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**Thomas F. Coleman** researched and contributed algorithms for constrained and unconstrained minimization, nonlinear least squares and curve fitting, constrained linear least squares, quadratic programming, and nonlinear equations.

Dr. Coleman is Dean of Faculty of Mathematics and Professor of Combinatorics and Optimization at University of Waterloo.

Dr. Coleman has published 4 books and over 70 technical papers in the areas of continuous optimization and computational methods and tools for large-scale problems.

**Yin Zhang** researched and contributed the large-scale linear programming algorithm.

Dr. Zhang is Professor of Computational and Applied Mathematics on the faculty of the Keck Center for Interdisciplinary Bioscience Training at Rice University.

Dr. Zhang has published over 50 technical papers in the areas of interior-point methods for linear programming and computational mathematical programming.
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- “Example: Nonlinear Constrained Minimization” on page 1-4
- “Example: Linear Programming” on page 1-14
Product Overview

In this section...

“Introduction” on page 1-2
“Optimization Functions” on page 1-2
“Optimization Tool GUI” on page 1-3

Introduction

Optimization Toolbox provides widely used algorithms for standard and large-scale optimization. These algorithms solve constrained and unconstrained continuous and discrete problems. The toolbox includes functions for linear programming, quadratic programming, binary integer programming, nonlinear optimization, nonlinear least squares, systems of nonlinear equations, and multiobjective optimization. You can use them to find optimal solutions, perform tradeoff analyses, balance multiple design alternatives, and incorporate optimization methods into algorithms and models.

Key features:

- Interactive tools for defining and solving optimization problems and monitoring solution progress
- Solvers for nonlinear and multiobjective optimization
- Solvers for nonlinear least squares, data fitting, and nonlinear equations
- Methods for solving quadratic and linear programming problems
- Methods for solving binary integer programming problems
- Parallel computing support in selected constrained nonlinear solvers

Optimization Functions

Most toolbox functions are MATLAB® function files, made up of MATLAB statements that implement specialized optimization algorithms. You can view the code for these functions using the statement

    type function_name
You can extend the capabilities of Optimization Toolbox software by writing your own functions, or by using the software in combination with other toolboxes, or with the MATLAB or Simulink® environments.

**Optimization Tool GUI**

Optimization Tool (optimtool) is a graphical user interface (GUI) for selecting a toolbox function, specifying optimization options, and running optimizations. It provides a convenient interface for all optimization routines, including those from Global Optimization Toolbox software, which is licensed separately.

Optimization Tool makes it easy to

- Define and modify problems quickly
- Use the correct syntax for optimization functions
- Import and export from the MATLAB workspace
- Generate code containing your configuration for a solver and options
- Change parameters of an optimization during the execution of certain Global Optimization Toolbox functions
Example: Nonlinear Constrained Minimization

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<tr>
<td>“Interpreting the Result” on page 1-12</td>
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Problem Formulation: Rosenbrock’s Function

Consider the problem of minimizing Rosenbrock’s function

\[ f(x) = 100 \left( x_2 - x_1^2 \right)^2 + (1 - x_1)^2, \]

over the unit disk, i.e., the disk of radius 1 centered at the origin. In other words, find \( x \) that minimizes the function \( f(x) \) over the set \( x_1^2 + x_2^2 \leq 1 \). This problem is a minimization of a nonlinear function with a nonlinear constraint.

Note  Rosenbrock’s function is a standard test function in optimization. It has a unique minimum value of 0 attained at the point (1,1). Finding the minimum is a challenge for some algorithms since it has a shallow minimum inside a deeply curved valley.

Here are two views of Rosenbrock’s function in the unit disk. The vertical axis is log-scaled; in other words, the plot shows \( \log(1+f(x)) \). Contour lines lie beneath the surface plot.
The function $f(x)$ is called the *objective function*. This is the function you wish to minimize. The inequality $x_1^2 + x_2^2 \leq 1$ is called a *constraint*. Constraints limit the set of $x$ over which you may search for a minimum. You can have any number of constraints, which are inequalities or equations.

All Optimization Toolbox optimization functions minimize an objective function. To maximize a function $f$, apply an optimization routine to minimize $-f$. For more details about maximizing, see “Maximizing an Objective” on page 2-27.

**Defining the Problem in Toolbox Syntax**

To use Optimization Toolbox software, you need to
1 Define your objective function in the MATLAB language, as a function file or anonymous function. This example will use a function file.

2 Define your constraint(s) as a separate file or anonymous function.

**Function File for Objective Function**
A function file is a text file containing MATLAB commands with the extension .m. Create a new function file in any text editor, or use the built-in MATLAB Editor as follows:

1 At the command line enter:

   ```
   edit rosenbrock
   ```

   The MATLAB Editor opens.

2 In the editor enter:

   ```
   function f = rosenbrock(x)
   f = 100*(x(2) - x(1)^2)^2 + (1 - x(1))^2;
   ```

3 Save the file by selecting **File > Save**.

**File for Constraint Function**
Constraint functions must be formulated so that they are in the form \( c(x) \leq 0 \) or \( ceq(x) = 0 \). The constraint \( x_1^2 + x_2^2 \leq 1 \) needs to be reformulated as \( x_1^2 + x_2^2 - 1 \leq 0 \) in order to have the correct syntax.

Furthermore, toolbox functions that accept nonlinear constraints need to have both equality and inequality constraints defined. In this example there is only an inequality constraint, so you must pass an empty array [ ] as the equality constraint function \( ceq \).

With these considerations in mind, write a function file for the nonlinear constraint:

1 Create a file named `unitdisk.m` containing the following code:
function [c, ceq] = unitdisk(x)
c = x(1)^2 + x(2)^2 - 1;
ceq = [ ];

2 Save the file unitdisk.m.

**Running the Optimization**

There are two ways to run the optimization:

- Using the “Optimization Tool” on page 1-7 Graphical User Interface (GUI)
- Using command line functions; see “Minimizing at the Command Line” on page 1-11.

**Optimization Tool**

1 Start the Optimization Tool by typing `optimtool` at the command line. The following GUI opens.
For more information about this tool, see Chapter 5, “Graphical Optimization Tool”.

The default **Solver** `fmincon` - Constrained nonlinear minimization is selected. This solver is appropriate for this problem, since Rosenbrock’s function is nonlinear, and the problem has a constraint. For more information about how to choose a solver, see “Choosing a Solver” on page 2-4.
3 In the **Algorithm** pop-up menu choose **Active set**—the default **Trust region reflective** algorithm doesn’t handle nonlinear constraints.

4 For **Objective function** enter `@rosenbrock`. The `@` character indicates that this is a function handle of the file `rosenbrock.m`.

5 For **Start point** enter `[0 0]`. This is the initial point where `fmincon` begins its search for a minimum.

6 For **Nonlinear constraint function** enter `@unitdisk`, the function handle of `unitdisk.m`.

Your **Problem Setup and Results** pane should match this figure.

![Solver and Algorithm Selection](image)

7 In the Options pane (center bottom), select **iterative** in the **Level of display** pop-up menu. (If you don’t see the option, click **Display to command window**.) This shows the progress of `fmincon` in the command window.
8 Click Start under Run solver and view results.

The following message appears in the box below the Start button:

Optimization running.
Objective function value: 0.045674808692966654
Local minimum possible. Constraints satisfied.

fmincon stopped because the predicted change in the objective function
is less than the default value of the function tolerance and constraints
are satisfied to within the default value of the constraint tolerance.

Your objective function value may differ slightly, depending on your computer
system and version of Optimization Toolbox software.

The message tells you that:

• The search for a constrained optimum ended because the derivative of the
  objective function is nearly 0 in directions allowed by the constraint.

• The constraint is very nearly satisfied.

“Exit Flags and Exit Messages” on page 3-3 discusses exit messages such
as these.

The minimizer \( x \) appears under Final point.
Minimizing at the Command Line

You can run the same optimization from the command line, as follows.

1. Create an options structure to choose iterative display and the active-set algorithm:

   ```matlab
   options = optimset('Display','iter','Algorithm','active-set');
   ```

2. Run the `fmincon` solver with the `options` structure, reporting both the location `x` of the minimizer, and value `fval` attained by the objective function:

   ```matlab
   [x,fval] = fmincon(@rosenbrock,[0 0],...
                   [],[],[],[],[],[],@unitdisk,options)
   ```

The six sets of empty brackets represent optional constraints that are not being used in this example. See the `fmincon` function reference pages for the syntax.

MATLAB outputs a table of iterations, and the results of the optimization:

```
Local minimum possible. Constraints satisfied.

fmincon stopped because the predicted change in the objective function
is less than the default value of the function tolerance and constraints
are satisfied to within the default value of the constraint tolerance.

<stopping criteria details>

Active inequalities (to within options.TolCon = 1e-006):
lower upper ineqlin ineqnonlin

1

x =
 0.7864   0.6177
```
fval =
  0.0457

The message tells you that the search for a constrained optimum ended because the derivative of the objective function is nearly 0 in directions allowed by the constraint, and that the constraint is very nearly satisfied. Several phrases in the message contain links that give you more information about the terms used in the message. For more details about these links, see “Enhanced Exit Messages” on page 3-5.

**Interpreting the Result**

The iteration table in the command window shows how MATLAB searched for the minimum value of Rosenbrock’s function in the unit disk. This table is the same whether you use Optimization Tool or the command line. MATLAB reports the minimization as follows:

<table>
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<th>Iter</th>
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<td>-Inf</td>
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<td>1</td>
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<td>71</td>
<td>0.0456825</td>
<td>-5.897e-005</td>
<td>0.5</td>
</tr>
<tr>
<td>18</td>
<td>75</td>
<td>0.0456785</td>
<td>-2.948e-005</td>
<td>0.5</td>
</tr>
<tr>
<td>19</td>
<td>79</td>
<td>0.0456766</td>
<td>-1.474e-005</td>
<td>0.5</td>
</tr>
</tbody>
</table>
This table might differ from yours depending on toolbox version and computing platform. The following description applies to the table as displayed.

- The first column, labeled **Iter**, is the iteration number from 0 to 19. *fmincon* took 19 iterations to converge.

- The second column, labeled **F-count**, reports the cumulative number of times Rosenbrock’s function was evaluated. The final row shows an **F-count** of 79, indicating that *fmincon* evaluated Rosenbrock’s function 79 times in the process of finding a minimum.

- The third column, labeled **f(x)**, displays the value of the objective function. The final value, 0.0456766, is the minimum that is reported in the Optimization Tool **Run solver and view results** box, and at the end of the exit message in the command window.

- The fourth column, **Max constraint**, goes from a value of –1 at the initial value, to very nearly 0, –1.474e–005, at the final iteration. This column shows the value of the constraint function *unitdisk* at each iteration. Since the value of *unitdisk* was nearly 0 at the final iteration, $x_1^2 + x_2^2 = 1$ there.

The other columns of the iteration table are described in “Iterative Display” on page 3-16.
Example: Linear Programming

In this section...

- “Example of Converting to Solver Form” on page 1-14
- “Model Description” on page 1-15
- “Solution Method” on page 1-16
- “Bibliography” on page 1-24

Example of Converting to Solver Form

This example demonstrates how to convert a problem from mathematical form into Optimization Toolbox solver syntax. While the problem is a linear program, the techniques apply to all solvers.

The variables and expressions in the problem represent a model of operating a chemical plant, from an example in Edgar and Himmelblau [1]. There are two video demos that describe the problem.

- Optimization Modeling 1 shows the problem in pictorial form. It demonstrates how to generate the mathematical expressions of “Model Description” on page 1-15 from the picture. To view the demo, enter the following command at the MATLAB command line:

  \[
  \text{playbackdemo('Optimization-Modeling-1','toolbox/optim/web/demos');}
  \]

- Optimization Modeling 2 describes how to convert these mathematical expressions into Optimization Toolbox solver syntax. This video shows how to solve the problem, and how to interpret the results. To view the demo, enter the following command at the MATLAB command line:

  \[
  \text{playbackdemo('Optimization-Modeling-2-Converting-To-Solver-Form','toolbox/optim/web/demos');}
  \]

The remainder of this example is concerned solely with transforming the problem to solver syntax. The example closely follows the video demo Optimization Modeling 2. The main difference between the video and the example is that this example shows how to use named variables, or index variables, which are similar to hash keys. This difference is in “Combine Variables Into One Vector” on page 1-17.
Model Description

The video demo Optimization Modeling 1 suggests that one way to convert a problem into mathematical form is to:

1. Get an overall idea of the problem
2. Identify the goal (maximizing or minimizing something)
3. Identify (name) variables
4. Identify constraints
5. Determine which variables you can control
6. Specify all quantities in mathematical notation
7. Check the model for completeness and correctness

For the meaning of the variables in this section, see the video demo Optimization Modeling 1.

The optimization problem is to minimize the objective function, subject to all the other expressions as constraints.

The objective function is:

\[ 0.002614 \text{ HPS} + 0.0239 \text{ PP} + 0.009825 \text{ EP} \]

The constraints are:

\[
\begin{align*}
2500 & \leq P1 \leq 6250 \\
I1 & \leq 192,000 \\
C & \leq 62,000 \\
I1 - HE1 & \leq 132,000 \\
I1 &= LE1 + HE1 + C \\
1359.8 \times I1 &= 1267.8 \times HE1 + 1251.4 \times LE1 + 192 \times C + 3413 \times P1 \\
3000 & \leq P2 \leq 9000 \\
I2 & \leq 244,000 \\
LE2 & \leq 142,000 \\
I2 &= LE2 + HE2 \\
1359.8 \times I2 &= 1267.8 \times HE2 + 1251.4 \times LE2 + 3413 \times P2
\end{align*}
\]
Getting Started

HPS = I1 + I2 + BF1
HPS = C + MPS + LPS
LPS = LE1 + LE2 + BF2
MPS = HE1 + HE2 + BF1 - BF2
P1 + P2 + PP ≥ 24,550
EP + PP ≥ 12,000
MPS ≥ 271,536
LPS ≥ 100,623
All variables are positive.

Solution Method
To solve the optimization problem, take the following steps.

1 “Choose a Solver” on page 1-16
2 “Combine Variables Into One Vector” on page 1-17
3 “Write Bound Constraints” on page 1-19
4 “Write Linear Inequality Constraints” on page 1-20
5 “Write Linear Equality Constraints” on page 1-21
6 “Write the Objective” on page 1-22
7 “Solve the Problem with linprog” on page 1-22
8 “Examine the Solution” on page 1-23

The steps are also demonstrated in the video Optimization Modeling 2.

Choose a Solver
To find the appropriate solver for this problem, consult the “Optimization Decision Table” on page 2-4. The table asks you to categorize your problem by type of objective function and types of constraints. For this problem, the objective function is linear, and the constraints are linear. The decision table recommends using the linprog solver.
As you see in “Problems Handled by Optimization Toolbox Functions” on page 2-12 or the \texttt{linprog} function reference page, the \texttt{linprog} solver solves problems of the form

$$\min_{x} f^T x \text{ such that } \begin{cases} A \cdot x \leq b, \\ Aeq \cdot x = beq, \\ lb \leq x \leq ub. \end{cases} \quad (1-1)$$

- $f^T x$ means a row vector of constants $f$ multiplying a column vector of variables $x$. In other words,

$$f^T x = f(1)x(1) + f(2)x(2) + \ldots + f(n)x(n),$$

where $n$ is the length of $f$.

- $A \leq x$ represents linear inequalities. $A$ is a $k$-by-$n$ matrix, where $k$ is the number of inequalities and $n$ is the number of variables (size of $x$). $b$ is a vector of length $k$. For more information, see “Linear Inequality Constraints” on page 2-32.

- $Aeq \cdot x = beq$ represents linear equalities. $Aeq$ is an $m$-by-$n$ matrix, where $m$ is the number of equalities and $n$ is the number of variables (size of $x$). $beq$ is a vector of length $m$. For more information, see “Linear Equality Constraints” on page 2-33.

- $lb \leq x \leq ub$ means each element in the vector $x$ must be greater than the corresponding element of $lb$, and must be smaller than the corresponding element of $ub$. For more information, see “Bound Constraints” on page 2-31.

The syntax of the \texttt{linprog} solver, as shown in its function reference page, is

$$[x \ fval] = \text{linprog}(f,A,b,Aeq,beq,lb,ub);$$

The inputs to the \texttt{linprog} solver are the matrices and vectors in Equation 1-1.

**Combine Variables Into One Vector**

There are 16 variables in the equations of “Model Description” on page 1-15. Put these variables into one vector. The name of the vector of variables is $x$ in Equation 1-1. Decide on an order, and construct the components of $x$ out of the variables.
The following code constructs the vector using a cell array of strings. Each string is the name of a variable.

```matlab
variables = {'I1','I2','HE1','HE2','LE1','LE2','C','BF1',...
             'BF2','HPS','MPS','LPS','P1','P2','PP','EP'};
N = length(variables);
% create variables for indexing
for v = 1:N
    eval([variables{v},' = ', num2str(v),';']);
end
```

Executing these commands creates the following named variables in your workspace:
These named variables represent index numbers for the components of \( x \). You do not have to create named variables. The video Optimization Modeling 2 shows how to solve the problem simply using the index numbers of the components of \( x \).

**Write Bound Constraints**

There are four variables with lower bounds, and six with upper bounds in the equations of “Model Description” on page 1-15. The lower bounds:

\[
\begin{align*}
P1 & \geq 2500 \\
P2 & \geq 3000
\end{align*}
\]
MPS \geq 271,536 
LPS \geq 100,623.

Also, all the variables are positive, which means they have a lower bound of zero.

Create the lower bound vector \( \mathbf{lb} \) as a vector of 0, then add the four other lower bounds.

\[
\mathbf{lb} = \text{zeros(size(variables))}; \\
\mathbf{lb}([P1,P2,MPS,LPS]) = ... \\
\qquad [2500,3000,271536,100623];
\]

The variables with upper bounds are:

\[
P1 \leq 6250 \\
P2 \leq 9000 \\
I1 \leq 192,000 \\
I2 \leq 244,000 \\
C \leq 62,000 \\
LE2 \leq 142000.
\]

Create the upper bound vector as a vector of \( \text{Inf} \), then add the six upper bounds.

\[
\mathbf{ub} = \text{Inf(size(variables))}; \\
\mathbf{ub}([P1,P2,I1,I2,C,LE2]) = ... \\
\qquad [6250,9000,192000,244000,62000,142000];
\]

**Write Linear Inequality Constraints**

There are three linear inequalities in the equations of “Model Description” on page 1-15:

\[
I1 - HE1 \leq 132,000 \\
EP + PP \geq 12,000 \\
P1 + P2 + PP \geq 24,550.
\]

In order to have the equations in the form \( A \mathbf{x} \leq b \), put all the variables on the left side of the inequality. All these equations already have that form.
Ensure that each inequality is in “less than” form by multiplying through by \(-1\) wherever appropriate:

\[
\begin{align*}
I_1 - HE_1 & \leq 132,000 \\
-EP - PP & \leq -12,000 \\
-P_1 - P_2 - PP & \leq -24,550.
\end{align*}
\]

In your MATLAB workspace, create the \(A\) matrix as a 3-by-16 zero matrix, corresponding to 3 linear inequalities in 16 variables. Create the \(b\) vector with three components.

\[
A = \text{zeros}(3,16);
A(1,I_1) = 1; A(1,HE_1) = -1; b(1) = 132000;
A(2,EP) = -1; A(2,PP) = -1; b(2) = -12000;
A(3,[P_1,P_2,PP]) = [-1,-1,-1];
b(3) = -24550;
\]

**Write Linear Equality Constraints**

There are eight linear equations in the equations of “Model Description” on page 1-15:

\[
\begin{align*}
I_2 &= LE_2 + HE_2 \\
LPS &= LE_1 + LE_2 + BF_2 \\
HPS &= I_1 + I_2 + BF_1 \\
HPS &= C + MPS + LPS \\
I_1 &= LE_1 + HE_1 + C \\
MPS &= HE_1 + HE_2 + BF_1 - BF_2 \\
1359.8 \ I_1 &= 1267.8 \ HE_1 + 1251.4 \ LE_1 + 192 \ C + 3413 \ P_1 \\
1359.8 \ I_2 &= 1267.8 \ HE_2 + 1251.4 \ LE_2 + 3413 \ P_2.
\end{align*}
\]

In order to have the equations in the form \(Aeq \ x = beq\), put all the variables on one side of the equation. The equations become:

\[
\begin{align*}
LE_2 + HE_2 - I_2 &= 0 \\
LE_1 + LE_2 + BF_2 - LPS &= 0 \\
I_1 + I_2 + BF_1 - HPS &= 0 \\
C + MPS + LPS - HPS &= 0 \\
LE_1 + HE_1 + C - I_1 &= 0 \\
HE_1 + HE_2 + BF_1 - BF_2 - MPS &= 0
\end{align*}
\]
1267.8 HE1 + 1251.4 LE1 + 192 C + 3413 P1 - 1359.8 I1 = 0
1267.8 HE2 + 1251.4 LE2 + 3413 P2 - 1359.8 I2 = 0.

Now write the Aeq matrix and beq vector corresponding to these equations. In your MATLAB workspace, create the Aeq matrix as an 8-by-16 zero matrix, corresponding to 8 linear equations in 16 variables. Create the beq vector with eight components, all zero.

\[
Aeq = \text{zeros}(8, 16); \quad \text{beq} = \text{zeros}(8, 1);
\]
\[
Aeq(1, [\text{LE2, HE2, I2}]) = [1, 1, -1];
Aeq(2, [\text{LE1, LE2, BF2, LPS}]) = [1, 1, 1, -1];
Aeq(3, [\text{I1, I2, BF1, HPS}]) = [1, 1, 1, -1];
Aeq(4, [\text{C, MPS, LPS, HPS}]) = [1, 1, 1, -1];
Aeq(5, [\text{LE1, HE1, C, I1}]) = [1, 1, 1, -1];
Aeq(6, [\text{HE1, HE2, BF1, BF2, MPS}]) = [1, 1, 1, -1, -1];
Aeq(7, [\text{HE1, LE1, C, P1, I1}]) = [1267.8, 1251.4, 192, 3413, -1359.8];
Aeq(8, [\text{HE2, LE2, P2, I2}]) = [1267.8, 1251.4, 3413, -1359.8];
\]

**Write the Objective**

The objective function is

\[
f^T x = 0.002614 \text{ HPS} + 0.0239 \text{ PP} + 0.009825 \text{ EP}.
\]

Write this expression as a vector \( f \) of multipliers of the \( x \) vector:

\[
f = \text{zeros(size(variables))};
\]
\[
f([\text{HPS, PP, EP}]) = [0.002614, 0.0239, 0.009825];
\]

**Solve the Problem with linprog**

You now have inputs required by the linprog solver. Call the solver and print the outputs in formatted form:

\[
[x \ fval] = \text{linprog}(f, A, b, Aeq, beq, lb, ub);
\]
\[
\text{for } d = 1: N
\]
\[
\text{fprintf(’%12.2f \t%s
’, x(d), variables{d})}
\]
\[
\text{end}
\]
\[
fval
\]

The result:
Optimization terminated.

136328.74 I1
244000.00 I2
128159.00 HE1
143377.00 HE2
0.00 LE1
100623.00 LE2
8169.74 C
0.00 BF1
0.00 BF2
380328.74 HPS
271536.00 MPS
100623.00 LPS
6250.00 P1
7060.71 P2
11239.29 PP
760.71 EP

fval =
1.2703e+003

Examine the Solution
The fval output gives the smallest value of the objective function at any feasible point.

The solution vector x is the point where the objective function has the smallest value. Notice that:

- BF1, BF2, and LE1 are 0, their lower bounds.
- I2 is 244,000, its upper bound.
- The nonzero components of the f vector are
  - HPS — 380,328.74
  - PP — 11,239.29
  - EP — 760.71

The video demo Optimization Modeling 2 gives interpretations of these characteristics in terms of the original problem.
Bibliography

Setting Up an Optimization

- “Introduction to Optimization Toolbox Solvers” on page 2-2
- “Choosing a Solver” on page 2-4
- “Writing Objective Functions” on page 2-16
- “Writing Constraints” on page 2-29
- “Passing Extra Parameters” on page 2-38
- “Setting Options” on page 2-43
Introduction to Optimization Toolbox Solvers

There are four general categories of Optimization Toolbox solvers:

- **Minimizers**
  This group of solvers attempts to find a local minimum of the objective function near a starting point \( x_0 \). They address problems of unconstrained optimization, linear programming, quadratic programming, and general nonlinear programming.

- **Multiobjective minimizers**
  This group of solvers attempts to either minimize the maximum value of a set of functions (\( \text{fminimax} \)), or to find a location where a collection of functions is below some prespecified values (\( \text{fgoalattain} \)).

- **Equation solvers**
  This group of solvers attempts to find a solution to a scalar- or vector-valued nonlinear equation \( f(x) = 0 \) near a starting point \( x_0 \). Equation-solving can be considered a form of optimization because it is equivalent to finding the minimum norm of \( f(x) \) near \( x_0 \).

- **Least-Squares (curve-fitting) solvers**
  This group of solvers attempts to minimize a sum of squares. This type of problem frequently arises in fitting a model to data. The solvers address problems of finding nonnegative solutions, bounded or linearly constrained solutions, and fitting parameterized nonlinear models to data.

For more information see “Problems Handled by Optimization Toolbox Functions” on page 2-12. See “Optimization Decision Table” on page 2-4 for aid in choosing among solvers for minimization.

Minimizers formulate optimization problems in the form

\[
\min_x f(x),
\]

possibly subject to constraints. \( f(x) \) is called an **objective function**. In general, \( f(x) \) is a scalar function of type `double`, and \( x \) is a vector or scalar of type `double`. However, multiobjective optimization, equation solving, and some sum-of-squares minimizers, can have vector or matrix objective functions \( F(x) \).
of type double. To use Optimization Toolbox solvers for maximization instead of minimization, see “Maximizing an Objective” on page 2-27.

Write the objective function for a solver in the form of a function file or anonymous function handle. You can supply a gradient $\nabla f(x)$ for many solvers, and you can supply a Hessian for several solvers. See “Writing Objective Functions” on page 2-16. Constraints have a special form, as described in “Writing Constraints” on page 2-29.
Choosing a Solver

In this section...

“Optimization Decision Table” on page 2-4
“Choosing the Algorithm” on page 2-7
“Problems Handled by Optimization Toolbox Functions” on page 2-12

Optimization Decision Table

The following table is designed to help you choose a solver. It does not address multiobjective optimization or equation solving. There are more details on all the solvers in “Problems Handled by Optimization Toolbox Functions” on page 2-12.

Use the table as follows:

1 Identify your objective function as one of five types:
   - Linear
   - Quadratic
   - Sum-of-squares (Least squares)
   - Smooth nonlinear
   - Nonsmooth

2 Identify your constraints as one of five types:
   - None (unconstrained)
   - Bound
   - Linear (including bound)
   - General smooth
   - Discrete (integer)

3 Use the table to identify a relevant solver.

In this table:
• * means relevant solvers are found in Global Optimization Toolbox functions (licensed separately from Optimization Toolbox solvers).

• `fmincon` applies to most smooth objective functions with smooth constraints. It is not listed as a preferred solver for least squares or linear or quadratic programming because the listed solvers are usually more efficient.

• The table has suggested functions, but it is not meant to unduly restrict your choices. For example, `fmincon` can be effective on some nonsmooth problems.

• The Global Optimization Toolbox `ga` function can address mixed integer programming problems.
# Solvers by Objective and Constraint

<table>
<thead>
<tr>
<th>Constraint Type</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Least Squares</th>
<th>Smooth nonlinear</th>
<th>Nonsmooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>n/a ((f = \text{const, or min} = -\infty))</td>
<td>quadprog, Theory, Examples</td>
<td>(\)</td>
<td>fminsearch, fminunc, Theory, Examples</td>
<td>fminsearch, *</td>
</tr>
<tr>
<td>Bound</td>
<td>linprog, Theory, Examples</td>
<td>quadprog, Theory, Examples</td>
<td>lsqcurvefit, lsqnonlin, Theory, Examples</td>
<td>fminbnd, fmincon, fseminf, Theory, Examples</td>
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<td>quadprog, Theory, Examples</td>
<td>lsqcurvefit, lsqnonlin, lsqnonneg, Theory, Examples</td>
<td>fmincon, fseminf, Theory, Examples</td>
<td>*</td>
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<tr>
<td>General smooth</td>
<td>fmincon, Theory, Examples</td>
<td>fmincon, Theory, Examples</td>
<td>fmincon, Theory, Examples</td>
<td>fmincon, fseminf, Theory, Examples</td>
<td>*</td>
</tr>
<tr>
<td>Discrete</td>
<td>bintprog, *, Theory, Example</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

**Note**  This table does not list multiobjective solvers nor equation solvers. See “Problems Handled by Optimization Toolbox Functions” on page 2-12 for a complete list of problems addressed by Optimization Toolbox functions.
Note Some solvers have several algorithms. For help choosing, see “Choosing the Algorithm” on page 2-7.

Choosing the Algorithm

- “fmincon Algorithms” on page 2-7
- “fsolve Algorithms” on page 2-8
- “fminunc Algorithms” on page 2-9
- “Least Squares Algorithms” on page 2-10
- “Linear Programming Algorithms” on page 2-11
- “Quadratic Programming Algorithms” on page 2-12

fmincon Algorithms

fmincon has four algorithm options:

- 'interior-point'
- 'sqp'
- 'active-set'
- 'trust-region-reflective' (default)

Use optimset to set the Algorithm option at the command line.

Recommendations

- Use the 'interior-point' algorithm first.
  For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.

- To run an optimization again to obtain more speed on small- to medium-sized problems, try 'sqp' next, and 'active-set' last.

- Use 'trust-region-reflective' when applicable. Your problem must have: objective function includes gradient, only bounds, or only linear equality constraints (but not both).
Reasoning Behind the Recommendations.

• 'interior-point' handles large, sparse problems, as well as small dense problems. The algorithm satisfies bounds at all iterations, and can recover from NaN or Inf results. It is a large-scale algorithm; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48. The algorithm can use special techniques for large-scale problems. For details, see “Interior-Point Algorithm” on page 11-58.

• 'sqp' satisfies bounds at all iterations. The algorithm can recover from NaN or Inf results. It is not a large-scale algorithm; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48.

• 'active-set' can take large steps, which adds speed. The algorithm is effective on some problems with nonsmooth constraints. It is not a large-scale algorithm; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48.

• 'trust-region-reflective' requires you to provide a gradient, and allows only bounds or linear equality constraints, but not both. Within these limitations, the algorithm handles both large sparse problems and small dense problems efficiently. It is a large-scale algorithm; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48. The algorithm can use special techniques to save memory usage, such as a Hessian multiply function. For details, see “Trust-Region-Reflective Algorithm” on page 11-55.

  • 'trust-region-reflective' is the default algorithm for historical reasons. It is effective when applicable, but it has many restrictions, so is not always applicable.

fsolve Algorithms

fsolve has three algorithms:

• 'trust-region-dogleg' (default)
• 'trust-region-reflective'
• 'levenberg-marquardt'

Use optimset to set the Algorithm option at the command line.
Choosing a Solver

Recommendations

- Use the 'trust-region-dogleg' algorithm first.
  For help if fsolve fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.
- To solve equations again if you have a Jacobian multiply function, or want to tune the internal algorithm (see “Trust-Region-Reflective Algorithm Only” on page 11-132), try 'trust-region-reflective'.
- Try timing all the algorithms, including 'levenberg-marquardt', to find the algorithm that works best on your problem.

Reasoning Behind the Recommendations.

- 'trust-region-dogleg' is the only algorithm that is specially designed to solve nonlinear equations. The others attempt to minimize the sum of squares of the function.
- The 'trust-region-reflective' algorithm is effective on sparse problems. It can use special techniques such as a Jacobian multiply function for large-scale problems.

fminunc Algorithms
fminunc has two algorithms:

- Large-scale
- Medium-scale

Choose between them at the command line by using optimset to set the LargeScale option to:

- 'on' (default) for Large-scale
- 'off' for Medium-scale
**Recommendations**

- If your objective function includes a gradient, use 'LargeScale' = 'on'.
- Otherwise, use 'LargeScale' = 'off'.

For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.

**Least Squares Algorithms**

**lsqlin.**  
lsqlin has two algorithms:

- Large-scale
- Medium-scale

Choose between them at the command line by using `optimset` to set the `LargeScale` option to:

- 'on' (default) for Large-scale
- 'off' for Medium-scale

**Recommendations**

- If you have no constraints or only bound constraints, use 'LargeScale' = 'on'.
- If you have linear constraints, use 'LargeScale' = 'off'.

For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.

**lsqcurvefit and lsqnonlin.**  
lsqcurvefit and lsqnonlin have two algorithms:

- 'trust-region-reflective' (default)
- 'levenberg-marquardt'

Use `optimset` to set the `Algorithm` option at the command line.
**Recommendations**

- If you have no constraints or only bound constraints, use `'trust-region-reflective'`.
- If your problem is underdetermined (fewer equations than dimensions), use `'levenberg-marquardt'`.

For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.

**Linear Programming Algorithms**

`linprog` has three algorithms:

- Large-scale interior-point
- Medium-scale active set
- Medium-scale Simplex

Choose between them at the command line by using `optimset` to set the `LargeScale` option to:

- `'on'` (default) for large-scale interior-point
- `'off'` for one of the other two

When `LargeScale` is `'off'`, choose between the two remaining algorithms by setting the `Simplex` option to:

- `'on'` for Simplex
- `'off'` (default) for active set

**Recommendations**

Use `'LargeScale' = 'on'`

For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.
**Quadratic Programming Algorithms**

quadprog has three algorithms:

- trust-region-reflective (formerly LargeScale = 'on'), the default
- active-set (formerly LargeScale = 'off')
- interior-point-convex

Use optimset to set the Algorithm option at the command line.

<table>
<thead>
<tr>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• If you have a convex problem, or if you don’t know whether your problem is convex, use interior-point-convex.</td>
</tr>
<tr>
<td>• If you have only bounds, or only linear equalities, use trust-region-reflective.</td>
</tr>
<tr>
<td>• If you have a nonconvex problem that does not satisfy the restrictions of trust-region-reflective, use active-set.</td>
</tr>
</tbody>
</table>

For help if the minimization fails, see “When the Solver Fails” on page 4-3 or “When the Solver Might Have Succeeded” on page 4-14.

**Problems Handled by Optimization Toolbox Functions**

The following tables show the functions available for minimization, equation solving, multiobjective optimization, and solving least-squares or data-fitting problems.

**Minimization Problems**

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar minimization</td>
<td>$\min_x f(x)$</td>
<td>fminbnd</td>
</tr>
</tbody>
</table>
### Minimization Problems (Continued)

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained minimization</td>
<td>[ \min_{x} f(x) ] such that ( l &lt; x &lt; u ) (( x ) is scalar)</td>
<td>fminunc, fminsearch</td>
</tr>
<tr>
<td>Linear programming</td>
<td>[ \min_{x} \left( x^T A \right) ] such that ( Ax \leq b ), ( Aeq x = beq ), ( l \leq x \leq u )</td>
<td>linprog</td>
</tr>
<tr>
<td>Quadratic programming</td>
<td>[ \min_{x} \frac{1}{2} x^T H x + c^T x ] such that ( Ax \leq b ), ( Aeq x = beq ), ( l \leq x \leq u )</td>
<td>quadprog</td>
</tr>
<tr>
<td>Constrained minimization</td>
<td>[ \min_{x} f(x) ] such that ( c(x) \leq 0 ), ( ceq(x) = 0 ), ( Ax \leq b ), ( Aeq x = beq ), ( l \leq x \leq u )</td>
<td>fmincon</td>
</tr>
<tr>
<td>Semi-infinite minimization</td>
<td>[ \min_{x} f(x) ] such that ( K(x,w) \leq 0 ) for all ( w ), ( c(x) \leq 0 ), ( ceq(x) = 0 ), ( Ax \leq b ), ( Aeq x = beq ), ( l \leq x \leq u )</td>
<td>fseminf</td>
</tr>
<tr>
<td>Binary integer programming</td>
<td>[ \min_{x} f^T x ] such that ( Ax \leq b ), ( Aeq x = beq ), ( x ) binary</td>
<td>bintprog</td>
</tr>
</tbody>
</table>
### Multiobjective Problems

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
</table>
| Goal attainment    | \[
\min_{x, \gamma} \gamma \quad \text{such that } \quad F(x) - w \gamma \leq \text{goal}, \quad c(x) \leq 0, \quad ceq(x) = 0, \quad A x \leq b, \quad Aeq x = beq, \quad l \leq x \leq u
\] | fgoalattain              |
| Minimax            | \[
\min_{x} \max_{i} F_i(x) \quad \text{such that } \quad c(x) \leq 0, \quad ceq(x) = 0, \quad A x \leq b, \quad Aeq x = beq, \quad l \leq x \leq u
\] | fminimax               |

### Equation Solving Problems

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear equations</td>
<td>[C x = d, n \text{ equations, } n \text{ variables}]</td>
<td>\ (matrix left division)</td>
</tr>
<tr>
<td>Nonlinear equation of one variable</td>
<td>[f(x) = 0]</td>
<td>fzero</td>
</tr>
<tr>
<td>Nonlinear equations</td>
<td>[F(x) = 0, n \text{ equations, } n \text{ variables}]</td>
<td>fsolve</td>
</tr>
</tbody>
</table>

### Least-Squares (Model-Fitting) Problems

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
</table>
| Linear least-squares                 | \[
\min_{x} \frac{1}{2} \| C x - d \|_2^2 \quad m \text{ equations, } n \text{ variables}
\] | \ (matrix left division) |
| Nonnegative linear-least-squares     | \[
\min_{x} \frac{1}{2} \| C x - d \|_2^2 \quad \text{such that } x \geq 0
\] | lsqnonneg                    |
### Least-Squares (Model-Fitting) Problems (Continued)

<table>
<thead>
<tr>
<th>Type</th>
<th>Formulation</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constrained linear-least-squares</td>
<td>[ \min_x \frac{1}{2} | C \cdot x - d |_2^2 ] such that [ A x \leq b, \quad Aeq x = beq, \quad lb \leq x \leq ub ]</td>
<td>\text{lsqlin}</td>
</tr>
<tr>
<td>Nonlinear least-squares</td>
<td>[ \min_x | F(x) |_2^2 = \min_x \sum_i F_i^2(x) ] such that [ lb \leq x \leq ub ]</td>
<td>\text{lsqnonlin}</td>
</tr>
<tr>
<td>Nonlinear curve fitting</td>
<td>[ \min_x | F(x,xdata) - ydata |_2^2 ] such that [ lb \leq x \leq ub ]</td>
<td>\text{lsqcurvefit}</td>
</tr>
</tbody>
</table>
# Writing Objective Functions

## In this section...

- “Types of Objective Functions” on page 2-16
- “Writing Scalar Objective Functions” on page 2-17
- “Writing Vector and Matrix Objective Functions” on page 2-23
- “Writing Objective Functions for Linear or Quadratic Problems” on page 2-27
- “Maximizing an Objective” on page 2-27

## Types of Objective Functions

Many Optimization Toolbox solvers minimize a scalar function of a multidimensional vector. The *objective* function is the function the solvers attempt to minimize. Several solvers accept vector-valued objective functions, and some solvers use objective functions you specify by vectors or matrices.

<table>
<thead>
<tr>
<th>Objective Type</th>
<th>Solvers</th>
<th>How to Write Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td>fmincon</td>
<td>“Writing Scalar Objective Functions” on page 2-17</td>
</tr>
<tr>
<td></td>
<td>fminunc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fminbnd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fminsearch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fseminf</td>
<td></td>
</tr>
<tr>
<td>Nonlinear least squares</td>
<td>lsqcurvefit</td>
<td>“Writing Vector and Matrix Objective Functions” on page 2-23</td>
</tr>
<tr>
<td></td>
<td>lsqnonlin</td>
<td></td>
</tr>
<tr>
<td>Multivariable equation</td>
<td>fsolve</td>
<td></td>
</tr>
<tr>
<td>solving</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiobjective</td>
<td>fgoalattain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fminimax</td>
<td></td>
</tr>
</tbody>
</table>
### Writing Scalar Objective Functions

- “Function Files” on page 2-17
- “Anonymous Function Objectives” on page 2-19
- “Including Derivatives” on page 2-20

#### Function Files

A scalar objective function file accepts one input, say \( x \), and returns one scalar output, say \( f \). The input \( x \) can be a scalar, vector, or matrix. A function file can return more outputs (see “Including Derivatives” on page 2-20).

For example, suppose your objective is a function of three variables, \( x, y, \) and \( z \):

\[
  f(x) = 3^* (x - y)^4 + 4^* (x + z)^2 / (1 + x^2 + y^2 + z^2) + \cosh(x - 1) + \tanh(y + z).
\]

1. Write this function as a file that accepts the vector \( \text{xin} = [x; y; z] \) and returns \( f \):

   ```matlab
   function f = myObjective(xin)
   f = 3*(xin(1)-xin(2))^4 + 4*(xin(1)+xin(3))^2/(1+norm(xin)^2) ... 
      + cosh(xin(1)-1) + tanh(xin(2)+xin(3));
   ```

2. Save it as a file named `myObjective.m` to a folder on your MATLAB path.

3. Check that the function evaluates correctly:

   ```matlab
   myObjective([1;2;3])
   ```
ans =
9.2666

For information on how to include extra parameters, see “Passing Extra Parameters” on page 2-38. For more complex examples of function files, see “Example: Nonlinear Minimization with Gradient and Hessian Sparsity Pattern” on page 6-18 or “Example: Nonlinear Minimization with Bound Constraints and Banded Preconditioner” on page 6-62.

Subfunctions and Nested Functions. Functions can exist inside other files as subfunctions or nested functions. Using subfunctions or nested functions can lower the number of distinct files you save. Using nested functions also lets you access extra parameters, as shown in “Nested Functions” on page 2-41.

For example, suppose you want to minimize the myObjective.m objective function, described in “Function Files” on page 2-17, subject to the ellipseparabola.m constraint, described in “Nonlinear Constraints” on page 2-33. Instead of writing two files, myObjective.m and ellipseparabola.m, write one file that contains both functions as subfunctions:

```matlab
function [x fval] = callObjConstr(x0,options)
% Using a subfunction for just one file
if nargin < 2
    options = optimset('Algorithm','interior-point');
end
[x fval] = fmincon(@myObjective,x0,[],[],[],[],[],[],
    @ellipseparabola,options);

function f = myObjective(xin)
f = 3*(xin(1)-xin(2))^4 + 4*(xin(1)+xin(3))^2/(1+sum(xin.^2)) ...
    + cosh(xin(1)-1) + tanh(xin(2)+xin(3));

function [c,ceq] = ellipseparabola(x)
c(1) = (x(1)^2)/9 + (x(2)^2)/4 - 1;
c(2) = x(1)^2 - x(2) - 1;
ceq = [];
```
Writing Objective Functions

Solve the constrained minimization starting from the point \([1;1;1]\):

\[
[x \ fval] = \text{callObjConstr(ones(3,1))}
\]

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

\[
x = \\
1.1835 \\
0.8345 \\
-1.6439 \\
\]

\[
fval = \\
0.5383 \\
\]

Anonymous Function Objectives

Use anonymous functions to write simple objective functions. For more information about anonymous functions, see “Constructing an Anonymous Function” in the MATLAB Programming Fundamentals documentation. Rosenbrock’s function is simple enough to write as an anonymous function:

\[
anonrosen = @(x)(100*(x(2) - x(1)^2)^2 + (1-x(1))^2);
\]

Check that \(anonrosen\) evaluates correctly at \([-1 \ 2]\):

\[
anonrosen([-1 \ 2])
\]

\[
ans = \\
104
\]

Minimizing \(anonrosen\) with \(fminunc\) yields the following results:

\[
\text{options} = \text{optimset('LargeScale','off')}; \\
[x \ fval] = \text{fminunc(anonrosen,[-1;2],options)}
\]

Local minimum found.
Setting Up an Optimization

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

\[
x = \\
1.0000 \\
1.0000
\]

\[
fval = \\
1.2262 \times 10^{-10}
\]

Including Derivatives

For `fmincon` and `fminunc`, you can include gradients in the objective function. You can also include Hessians, depending on the algorithm. The Hessian matrix \( H_{ij}(x) = \frac{\partial^2 f}{\partial x_i \partial x_j} \).

The following table shows which algorithms can use gradients and Hessians.

<table>
<thead>
<tr>
<th>Solver</th>
<th>Algorithm</th>
<th>Gradient</th>
<th>Hessian</th>
</tr>
</thead>
<tbody>
<tr>
<td>fmincon</td>
<td>active-set</td>
<td>Optional</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>interior-point</td>
<td>Optional</td>
<td>Optional separate function (see “Hessian” on page 11-47)</td>
</tr>
<tr>
<td></td>
<td>sqp</td>
<td>Optional</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>trust-region-reflective</td>
<td>Required</td>
<td>Optional</td>
</tr>
<tr>
<td>fminunc</td>
<td>LargeScale = 'on'</td>
<td>Required</td>
<td>Optional</td>
</tr>
<tr>
<td></td>
<td>LargeScale = 'off'</td>
<td>Optional</td>
<td>No</td>
</tr>
</tbody>
</table>

Benefits of Including Derivatives. If you do not provide gradients, solvers estimate gradients via finite differences. If you provide gradients, your solver need not perform this finite difference estimation, so can save time and be more accurate. Furthermore, solvers use an approximate Hessian, which can be far from the true Hessian. Providing a Hessian can yield a solution in fewer iterations.

For constrained problems, providing a gradient has another advantage. A solver can reach a point \( x \) such that \( x \) is feasible, but, for this \( x \), finite
Writing Objective Functions

differences around \( x \) always lead to an infeasible point. Suppose further that the objective function at an infeasible point returns a complex output, \( \text{Inf} \), \( \text{NaN} \), or error. In this case, a solver can fail or halt prematurely. Providing a gradient allows a solver to proceed. To obtain this benefit, you might also need to include the gradient of a nonlinear constraint function, and set the \( \text{GradConstr} \) option to ‘on’. See “Nonlinear Constraints” on page 2-33.

**How to Include Derivatives.**

1. Write code that returns:
   - The objective function (scalar) as the first output
   - The gradient (vector) as the second output
   - Optionally, the Hessian (matrix) as the third output

2. Set the \( \text{GradObj} \) option to ‘on’ with \( \text{optimset} \).

3. Optionally, set the \( \text{Hessian} \) option to ‘on’ or ‘user-supplied’.

   For the \( \text{fmincon} \) interior-point solver, set the \( \text{Hessian} \) option to ‘user-supplied’ and set the \( \text{HessFcn} \) option to \( @\text{hessianfcn} \), where \( \text{hessianfcn} \) is a function that computes the Hessian of the Lagrangian. For details, see “Hessian” on page 11-47. For an example, see “Example: Constrained Minimization Using \( \text{fmincon} \)’s Interior-Point Algorithm with Analytic Hessian” on page 6-53.

4. Optionally, check if your gradient function matches a finite-difference approximation. See “Checking Validity of Gradients or Jacobians” on page 2-50.

**Tip** For most flexibility, write *conditionalized* code. Conditionalized means that the number of function outputs can vary, as shown in the following example. Conditionalized code does not error depending on the value of the \( \text{GradObj} \) or \( \text{Hessian} \) option. Unconditionalized code requires you to set these options appropriately.

For example, consider Rosenbrock’s function
\[ f(x) = 100 \left( x_2 - x_1^2 \right)^2 + (1 - x_1)^2, \]

which is described and plotted in “Example: Nonlinear Constrained Minimization” on page 1-4. The gradient of \( f(x) \) is

\[
\nabla f(x) = \begin{bmatrix}
-400 \left( x_2 - x_1^2 \right) x_1 - 2(1 - x_1) \\
200 \left( x_2 - x_1^2 \right)
\end{bmatrix},
\]

and the Hessian \( H(x) \) is

\[
H(x) = \begin{bmatrix}
1200 x_1^2 - 400 x_2 + 2 & -400 x_1 \\
-400 x_1 & 200
\end{bmatrix}.
\]

rosenthree is an unconditionalized function that returns the Rosenbrock function with its gradient and Hessian:

```matlab
function [f g H] = rosenthree(x)
% Calculate objective f, gradient g, Hessian H
f = 100*(x(2) - x(1)^2)^2 + (1-x(1))^2;
g = [-400*(x(2)-x(1)^2)*x(1)-2*(1-x(1));
     200*(x(2)-x(1)^2)];
H = [1200*x(1)^2-400*x(2)+2, -400*x(1);
     -400*x(1), 200];
```

rosenboth is a conditionalized function that returns whatever the solver requires:

```matlab
function [f g H] = rosenboth(x)
% Calculate objective f
f = 100*(x(2) - x(1)^2)^2 + (1-x(1))^2;
if nargout > 1 % gradient required
    g = [-400*(x(2)-x(1)^2)*x(1)-2*(1-x(1));
         200*(x(2)-x(1)^2)];
if nargout > 2 % Hessian required
```
\[ H = \begin{bmatrix} 1200x(1)^2 - 400x(2) + 2, & -400x(1) \\ -400x(1), & 200 \end{bmatrix}; \]

\[ \text{nargout checks the number of arguments that a calling function specifies. See 
“Checking the Number of Input Arguments” in the MATLAB Programming Fundamentals documentation.} \]

The \text{fminunc} solver, designed for unconstrained optimization, allows you to minimize Rosenbrock’s function. Tell \text{fminunc} to use the gradient and Hessian by setting \text{options}:

\[ \text{options} = \text{optimset('GradObj','on','Hessian','on');} \]

Run \text{fminunc} starting at \([-1;2] \):

\[ [x \text{ fval}] = \text{fminunc(@rosenboth,[-1;2],options)} \]

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

\[ x = \]

\[ \begin{bmatrix} 1.0000 \\ 1.0000 \end{bmatrix} \]

\[ \text{fval} = \]

\[ 1.9310e-017 \]

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians automatically, as described in “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.

**Writing Vector and Matrix Objective Functions**

Some solvers, such as \text{fsolve} and \text{lsqcurvefit}, have objective functions that are vectors or matrices. The main difference in usage between these types of objective functions and scalar objective functions is the way to write their derivatives. The first-order partial derivatives of a vector-valued or
matrix-valued function is called a Jacobian; the first-order partial derivatives of a scalar function is called a gradient.

- “Jacobians of Vector Functions” on page 2-24
- “Jacobians of Matrix Functions” on page 2-25
- “Jacobians with Matrix-Valued Independent Variables” on page 2-26

**Jacobians of Vector Functions**

If \( x \) is a vector of independent variables, and \( F(x) \) is a vector function, the Jacobian \( J(x) \) is

\[
J_{ij}(x) = \frac{\partial F_i(x)}{\partial x_j}.
\]

If \( F \) has \( m \) components, and \( x \) has \( k \) components, \( J \) is an \( m \)-by-\( k \) matrix.

For example, if

\[
F(x) = \begin{bmatrix}
    x_1^2 + x_2 x_3 \\
    \sin(x_1 + 2x_2 - 3x_3)
\end{bmatrix},
\]

then \( J(x) \) is

\[
J(x) = \begin{bmatrix}
    2x_1 & x_3 & x_2 \\
    \cos(x_1 + 2x_2 - 3x_3) & 2\cos(x_1 + 2x_2 - 3x_3) & -3\cos(x_1 + 2x_2 - 3x_3)
\end{bmatrix}.
\]

The function file associated with this example is:

```matlab
function [F jacF] = vectorObjective(x)
    F = [x(1)^2 + x(2)*x(3); ...]
        sin(x(1) + 2*x(2) - 3*x(3))];
    if nargout > 1 % need Jacobian
        jacF = [2*x(1), x(3), x(2); ...]
            cos(x(1)+2*x(2)-3*x(3)), 2*cos(x(1)+2*x(2)-3*x(3)), ...]
                -3*cos(x(1)+2*x(2)-3*x(3))];
    end
```
Jacobians of Matrix Functions

The Jacobian of a matrix $F(x)$ is defined by changing the matrix to a vector, column by column. For example, rewrite the matrix

$$ F = \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \\ F_{31} & F_{32} \end{bmatrix} $$

as a vector $f$:

$$ f = \begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \\ F_{12} \\ F_{22} \\ F_{32} \end{bmatrix} $$

The Jacobian of $F$ is as the Jacobian of $f$,

$$ J_{ij} = \frac{\partial f_i}{\partial x_j}. $$

If $F$ is an $m$-by-$n$ matrix, and $x$ is a $k$-vector, the Jacobian is an $mn$-by-$k$ matrix.

For example, if

$$ F(x) = \begin{bmatrix} x_1 x_2 & x_1^3 + 3x_2^2 \\ 5x_2 - x_1^4 & x_2 / x_1 \\ 4 - x_2^2 & x_1^3 - x_2^4 \end{bmatrix}, $$

then the Jacobian of $F$ is
Jacobians with Matrix-Valued Independent Variables

If \( x \) is a matrix, define the Jacobian of \( F(x) \) by changing the matrix \( x \) to a vector, column by column. For example, if

\[
X = \begin{bmatrix}
  x_{11} & x_{12} \\
x_{21} & x_{22}
\end{bmatrix},
\]

then the gradient is defined in terms of the vector

\[
x = \begin{bmatrix}
x_{11} \\
x_{21} \\
x_{12} \\
x_{22}
\end{bmatrix}.
\]

With

\[
F = \begin{bmatrix}
  F_{11} & F_{12} \\
  F_{21} & F_{22} \\
  F_{31} & F_{32}
\end{bmatrix},
\]

and with \( f \) the vector form of \( F \) as above, the Jacobian of \( F(X) \) is defined as the Jacobian of \( f(x) \):

\[
J_{ij} = \frac{\partial f_i}{\partial x_j}.
\]

So, for example,
Writing Objective Functions

\[ J(3,2) = \frac{\partial f(3)}{\partial x(2)} = \frac{\partial F_{31}}{\partial X_{21}}, \quad \text{and} \quad J(5,4) = \frac{\partial f(5)}{\partial x(4)} = \frac{\partial F_{22}}{\partial X_{22}}. \]

If \( F \) is an \( m \)-by-\( n \) matrix and \( x \) is a \( j \)-by-\( k \) matrix, then the Jacobian is an \( mn \)-by-\( jk \) matrix.

Writing Objective Functions for Linear or Quadratic Problems

The following solvers handle linear or quadratic objective functions:

- \texttt{bintprog} and \texttt{linprog}: minimize
  \[ f'x = f(1)*x(1) + f(2)*x(2) + \ldots + f(n)*x(n). \]

  Input the vector \( f \) for the objective. See “Linear Programming Examples” on page 6-107, “Example: Linear Programming” on page 1-14, or “Example: Investments with Constraints” on page 6-140.

- \texttt{lsqlin} and \texttt{lsqnonneg}: minimize
  \[ \|Cx - d\|. \]

  Input the matrix \( C \) and the vector \( d \) for the objective. See “Example: Linear Least-Squares with Bound Constraints” on page 6-161.

- \texttt{quadprog}: minimize
  \[ \frac{1}{2} \cdot x'Hx + f'x = \frac{1}{2} \cdot (x(1)*H(1,1)*x(1) + 2*x(1)*H(1,2)*x(2) + \ldots + x(n)*H(n,n)*x(n)) + f(1)*x(1) + f(2)*x(2) + \ldots + f(n)*x(n). \]

  Input both the vector \( f \) and the symmetric matrix \( H \) for the objective. See “Quadratic Programming Examples” on page 6-125.

Maximizing an Objective

All solvers attempt to minimize an objective function. If you have a maximization problem, that is, a problem of the form

\[ \max_{x} f(x), \]
then define $g(x) = -f(x)$, and minimize $g$.

For example, to find the maximum of $\tan(\cos(x))$ near $x = 5$, evaluate:

```matlab
[x fval] = fminunc(@(x)-tan(cos(x)),5)
```

> Warning: Gradient must be provided for trust-region method; using line-search method instead.

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

```matlab
x = 
  6.2832

fval = 
  -1.5574
```

The maximum is 1.5574 (the negative of the reported `fval`), and occurs at $x = 6.2832$. This answer is correct since, to five digits, the maximum is $\tan(1) = 1.5574$, which occurs at $x = 2\pi = 6.2832$. 

Writing Constraints

In this section...

“Types of Constraints” on page 2-29
“Iterations Can Violate Constraints” on page 2-30
“Bound Constraints” on page 2-31
“Linear Inequality Constraints” on page 2-32
“Linear Equality Constraints” on page 2-33
“Nonlinear Constraints” on page 2-33
“Example: Using All Types of Constraints” on page 2-36

Types of Constraints

Optimization Toolbox solvers have special forms for constraints:

- “Bound Constraints” on page 2-31 — Lower and upper bounds on individual components: \( x \geq l \) and \( x \leq u \).

- “Linear Inequality Constraints” on page 2-32 — \( A \cdot x \leq b \). \( A \) is an \( m \)-by-\( n \) matrix, which represents \( m \) constraints for an \( n \)-dimensional vector \( x \). \( b \) is \( m \)-dimensional.

- “Linear Equality Constraints” on page 2-33 — \( Aeq \cdot x = beq \). Equality constraints have the same form as inequality constraints.

- “Nonlinear Constraints” on page 2-33 — \( c(x) \leq 0 \) and \( ceq(x) = 0 \). Both \( c \) and \( ceq \) are scalars or vectors representing several constraints.

Optimization Toolbox functions assume that inequality constraints are of the form \( c_i(x) \leq 0 \) or \( A \cdot x \leq b \). Express greater-than constraints as less-than constraints by multiplying them by \(-1\). For example, a constraint of the form \( c_i(x) \geq 0 \) is equivalent to the constraint \(-c_i(x) \leq 0\). A constraint of the form \( A \cdot x \geq b \) is equivalent to the constraint \(-A \cdot x \leq -b\). For more information, see “Linear Inequality Constraints” on page 2-32 and “Nonlinear Constraints” on page 2-33.

You can sometimes write constraints in several ways. For best results, use the lowest numbered constraints possible:
1 Bounds
2 Linear equalities
3 Linear inequalities
4 Nonlinear equalities
5 Nonlinear inequalities

For example, with a constraint $5x \leq 20$, use a bound $x \leq 4$ instead of a linear inequality or nonlinear inequality.

For information on how to pass extra parameters to constraint functions, see “Passing Extra Parameters” on page 2-38.

**Iterations Can Violate Constraints**

Be careful when writing your objective and constraint functions. Intermediate iterations can lead to points that are infeasible (do not satisfy constraints). If you write objective or constraint functions that assume feasibility, these functions can error or give unexpected results.

For example, if you take a square root or logarithm of $x$, and $x < 0$, the result is not real. You can try to avoid this error by setting 0 as a lower bound on $x$. Nevertheless, an intermediate iteration can violate this bound.

**Algorithms That Satisfy Bound Constraints**

Some solver algorithms satisfy bound constraints at every iteration:

- `fmincon` interior-point, sqp, and trust-region-reflective algorithms
- `lsqcurvefit` trust-region-reflective algorithm
- `lsqnonlin` trust-region-reflective algorithm
- `fminbnd`

**Solvers and Algorithms That Can Violate Bound Constraints**

The following solvers and algorithms can violate bound constraints at intermediate iterations:
• fmincon active-set algorithm
• fgoalattain solver
• fminimax solver
• fsminf solver

Bound Constraints

Lower and upper bounds limit the components of the vector \( x \). You need not give gradients for this type of constraint; solvers calculate them automatically. Bounds do not affect Hessians.

If you know bounds on the location of an optimum, you can obtain faster and more reliable solutions by explicitly including these bounds in your problem formulation.

Give bounds as vectors with the same length as \( x \).

• If a particular component has no lower bound, use –Inf as the bound; similarly, use \( \text{Inf} \) if a component has no upper bound.
• If you have only bounds of one type (upper or lower), you do not need to write the other type. For example, if you have no upper bounds, you do not need to supply a vector of \( \text{Inf} \)s. Also, if only the first \( m \) out of \( n \) components have bounds, then you need only supply a vector of length \( m \) containing bounds.

For example, suppose your bounds are:

\[
x_3 \geq 8
\]
\[
x_2 \leq 3.
\]

Write the constraint vectors as

\[
1 = [-\text{Inf}; -\text{Inf}; 8] \\
u = [\text{Inf}; 3] \text{ or } u = [\text{Inf}; 3; \text{Inf}].
\]

For a more complex example of bounds, see “Example: Linear Programming” on page 1-14.
Linear Inequality Constraints

Linear inequality constraints have the form \( Ax \leq b \). When \( A \) is \( m \)-by-\( n \), there are \( m \) constraints on a variable \( x \) with \( n \) components. You supply the \( m \)-by-\( n \) matrix \( A \) and the \( m \)-component vector \( b \). You do not need to give gradients for this type of constraint; solvers calculate them automatically. Linear inequalities do not affect Hessians.

For example, suppose that you have the following linear inequalities as constraints:

\[
\begin{align*}
    x_1 + x_3 & \leq 4, \\
    2x_2 - x_3 & \geq -2, \\
    x_1 - x_2 + x_3 - x_4 & \geq 9. 
\end{align*}
\]

Here \( m = 3 \) and \( n = 4 \).

Write these using the following matrix \( A \) and vector \( b \):

\[
A = \begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & -2 & 1 & 0 \\
-1 & 1 & -1 & 1
\end{bmatrix}
\]

\[
b = \begin{bmatrix}
4 \\
2 \\
-9
\end{bmatrix}
\]

Notice that the “greater than” inequalities were first multiplied by \(-1\) in order to get them into “less than” inequality form. In MATLAB syntax:

\[
A = [1 0 1 0; \\
0 -2 1 0; \\
-1 1 -1 1];
\]

\[
b = [4;2;-9];
\]

For a more complex example of linear constraints, see “Example: Linear Programming” on page 1-14.
**Linear Equality Constraints**

Linear equalities have the form \( Aeq \cdot x = beq \), which represents \( m \) equations with \( n \)-component vector \( x \). You supply the \( m \)-by-\( n \) matrix \( Aeq \) and the \( m \)-component vector \( beq \). You do not need to give a gradient for this type of constraint; solvers calculate them automatically. Linear equalities do not affect Hessians. The form of this type of constraint is the same as for “Linear Inequality Constraints” on page 2-32.

**Nonlinear Constraints**

Nonlinear inequality constraints have the form \( c(x) \leq 0 \), where \( c \) is a vector of constraints, one component for each constraint. Similarly, nonlinear equality constraints are of the form \( ceq(x) = 0 \).

Nonlinear constraint functions must return both inequality and equality constraints, even if they do not both exist. Return empty [] for a nonexistent constraint.

If you provide gradients for \( c \) and \( ceq \), your solver can run faster and give more reliable results.

Providing a gradient has another advantage. A solver can reach a point \( x \) such that \( x \) is feasible, but finite differences around \( x \) always lead to an infeasible point. In this case, a solver can fail or halt prematurely. Providing a gradient allows a solver to proceed.

For example, suppose that you have the following inequalities as constraints:

\[
\frac{x_1^2}{9} + \frac{x_2^2}{4} \leq 1,
\]

\[
x_2 \geq x_1^2 - 1.
\]

Write these constraints in a function file as follows:

```matlab
function [c,ceq]=ellipseparabola(x)
    c(1) = (x(1)^2)/9 + (x(2)^2)/4 - 1;
    c(2) = x(1)^2 - x(2) - 1;
    ceq = [];
end
```
ellipseparabola returns empty [] as the nonlinear equality function. Also, both inequalities were put into \( \leq 0 \) form.

### Including Gradients in Constraint Functions

To include gradient information, write a conditionalized function as follows:

```matlab
function [c,ceq,gradc,gradceq]=ellipseparabola(x)
c(1) = x(1)^2/9 + x(2)^2/4 - 1;
c(2) = x(1)^2 - x(2) - 1;
ceq = [];
if nargout > 2
    gradc = [2*x(1)/9, 2*x(1); x(2)/2, -1];
    gradceq = [];
end
```

See “Writing Scalar Objective Functions” on page 2-17 for information on conditionalized functions. The gradient matrix has the form

\[
\text{gradc}_{i,j} = \left[ \frac{\partial c(j)}{\partial x_i} \right].
\]

The first column of the gradient matrix is associated with \( c(1) \), and the second column is associated with \( c(2) \). This is the transpose of the form of Jacobians.

To have a solver use gradients of nonlinear constraints, indicate that they exist by using `optimset`:

```matlab
options=optimset('GradConstr','on');
```

Make sure to pass the options structure to your solver:

```matlab
[x,fval] = fmincon(@myobj,x0,A,b,Aeq,beq,lb,ub, ... 
                 @ellipseparabola,options)
```

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians automatically, as described in “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.
Anonymous Nonlinear Constraint Functions

For information on anonymous objective functions, see “Anonymous Function Objectives” on page 2-19.

Nonlinear constraint functions must return two outputs. The first output corresponds to nonlinear inequalities, and the second corresponds to nonlinear equalities.

Anonymous functions return just one output. So how can you write an anonymous function as a nonlinear constraint?

The `deal` function distributes multiple outputs. For example, suppose your nonlinear inequalities are

\[
\frac{x_1^2}{9} + \frac{x_2^2}{4} \leq 1, \\
x_2 \geq x_1^2 - 1.
\]

Suppose that your nonlinear equality is

\[x_2 = \tanh(x_1)\]

Write a nonlinear constraint function as follows:

\[
c = @(x)[x(1)^2/9 + x(2)^2/4 - 1; \\
x(1)^2 - x(2) - 1];
\]

\[
\text{ceq} = @(x)\tanh(x(1)) - x(2);
\]

\[
\text{nonlinfcn} = @(x)\text{deal}(c(x),\text{ceq}(x));
\]

To minimize the function \(\cosh(x_1) + \sinh(x_2)\) subject to the constraints in `nonlinfcn`, use `fmincon`:

\[
\text{obj} = @(x)\cosh(x(1))+\sinh(x(2));
\]

\[
\text{opts} = \text{optimset}(\text{'Algorithm','sqp'});
\]

\[
\text{z} = \text{fmincon(obj,[0;0],[],[],[],[],[],[],\text{nonlinfcn},\text{opts})}
\]

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is
non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

\[ z = \begin{bmatrix} -0.6530 \\ -0.5737 \end{bmatrix} \]

To check how well the resulting point \( z \) satisfies the constraints, use \texttt{nonlincf}:

\[
\begin{align*}
\texttt{[cout,ceqout]} &= \texttt{nonlincf}(z) \\
cout &= \\
&= \begin{bmatrix} -0.8704 \\ 0 \end{bmatrix} \\
\text{ceqout} &= \\
&= 1.1102 \times 10^{-16}
\end{align*}
\]

\( z \) indeed satisfies all the constraints to within the default value of the \texttt{TolCon} constraint tolerance, \( 1 \times 10^{-6} \).

**Example: Using All Types of Constraints**

This section contains an example of a nonlinear minimization problem with all possible types of constraints. The objective function is in the subfunction \texttt{myobj(x)}. The nonlinear constraints are in the subfunction \texttt{myconstr(x)}. This example does not use gradients.

```matlab
function [x fval exitflag] = fullexample
x0 = [1; 4; 5; 2; 5];
lb = [-Inf; -Inf; 0; -Inf; 1];
ub = [ Inf; Inf; 20];
Aeq = [1 -0.3 0 0 0];
beq = 0;
A = [0 0 0 -1 0.1 0 0 0 1 -0.5 0 0 -1 0 0.9];
b = [0; 0; 0];
opts = optimset('Algorithm','sqp');
```
% Writing Constraints

[x, fval, exitflag] = fmincon(@myobj, x0, A, b, Aeq, beq, lb, ub, ...
    @myconstr, opts)

%-------------------------------------------------------------
function f = myobj(x)

f = 6*x(2)*x(5) + 7*x(1)*x(3) + 3*x(2)^2;

%-------------------------------------------------------------
function [c, ceq] = myconstr(x)

    c = [x(1) - 0.2*x(2)*x(5) - 71
         0.9*x(3) - x(4)^2 - 67];
     ceq = 3*x(2)^2*x(5) + 3*x(1)^2*x(3) - 20.875;

Calling fullexample produces the following display in the Command Window:

[x fval exitflag] = fullexample;

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

x =
   0.6114
   2.0380
   1.3948
   0.1572
   1.5498

fval =
   37.3806

exitflag =
   1
Passing Extra Parameters

Extra Parameters, Fixed Variables, or Data

Sometimes objective or constraint functions have parameters in addition to the independent variable. The extra parameters can be data, or can represent variables that do not change during the optimization. There are three methods of passing these parameters:

- “Anonymous Functions” on page 2-38
- “Nested Functions” on page 2-41
- “Global Variables” on page 2-41

Global variables are troublesome because they do not allow names to be reused among functions. It is better to use one of the other two methods.

For example, suppose you want to minimize the function

\[ f(x) = \left( a - bx_1^2 + \frac{x_1^4}{3} \right) x_1^2 + x_1 x_2 + \left( -c + cx_2^2 \right) x_2^2 \] (2-1)

for different values of \( a, b, \) and \( c. \) Solvers accept objective functions that depend only on a single variable (\( x \) in this case). The following sections show how to provide the additional parameters \( a, b, \) and \( c. \) The solutions are for parameter values \( a = 4, b = 2.1, \) and \( c = 4 \) near \( x_0 = [0.5 0.5] \) using \texttt{fminunc}.

Anonymous Functions

To pass parameters using anonymous functions:

1. Write a file containing the following code:

   ```matlab
   function y = parameterfun(x,a,b,c)
   y = (a - b*x(1)^2 + x(1)^4/3)*x(1)^2 + x(1)*x(2) + ... 
       (-c + c*x(2)^2)*x(2)^2;
   ```

2. Assign values to the parameters and define a function handle \( f \) to an anonymous function by entering the following commands at the MATLAB prompt:
a = 4; b = 2.1; c = 4; % Assign parameter values
x0 = [0.5, 0.5];
f = @(x)parameterfun(x, a, b, c)

3 Call the solver fminunc with the anonymous function:

[x, fval] = fminunc(f, x0)

The following output is displayed in the command window:

Warning: Gradient must be provided for trust-region algorithm;
using line-search algorithm instead.
> In fminunc at 347

Local minimum found.

Optimization completed because the size of the gradient is less than
the default value of the function tolerance.

x =
   -0.0898   0.7127

fval =
   -1.0316
Note The parameters passed in the anonymous function are those that exist at the time the anonymous function is created. Consider the example

\[
a = 4; \ b = 2.1; \ c = 4; \\
f = @(x)\text{parameterfun}(x,a,b,c)
\]

Suppose you subsequently change, a to 3 and run

\[
[x,fval] = \text{fminunc}(f,x0)
\]

You get the same answer as before, since parameterfun uses \(a = 4\), the value when parameterfun was created.

To change the parameters that are passed to the function, renew the anonymous function by reentering it:

\[
a = 3; \\
f = @(x)\text{parameterfun}(x,a,b,c)
\]

You can create anonymous functions of more than one argument. For example, to use \text{lsqcurvefit}, first create a function that takes two input arguments, \(x\) and \(xdata\):

\[
fh = @(x,xdata)(\sin(x)\cdot xdata +(x.^2)\cdot \cos(xdata)); \\
x = \pi; \ xdata = \pi*[4;2;3]; \\
fh(x, xdata)
\]

\[
\text{ans} = \\
9.8696 \\
9.8696 \\
-9.8696
\]

Now call \text{lsqcurvefit}:

\[
\% \text{Assume ydata exists} \\
x = \text{lsqcurvefit}(fh,x,xdata,ydata)
\]
Nested Functions

To pass the parameters for Equation 2-1 via a nested function, write a single file that

- Accepts a, b, c, and x0 as inputs
- Contains the objective function as a nested function
- Calls fminunc

Here is the code for the function file for this example:

```matlab
function [x,fval] = runnested(a,b,c,x0)
    [x,fval] = fminunc(@nestedfun,x0);
    % Nested function that computes the objective function
    function y = nestedfun(x)
        y = (a - b*x(1)^2 + x(1)^4/3)*x(1)^2 + x(1)*x(2) + ... 
           (-c + c*x(2)^2)*x(2)^2;
    end
end
```

The objective function is the nested function `nestedfun`, which has access to the variables a, b, and c.

To run the optimization, enter:

```matlab
a = 4; b = 2.1; c = 4;% Assign parameter values
x0 = [0.5,0.5];
[x,fval] = runnested(a,b,c,x0)
```

The output is the same as in “Anonymous Functions” on page 2-38.

Global Variables

Global variables can be troublesome, it is better to avoid using them. To use global variables, declare the variables to be global in the workspace and in the functions that use the variables.

1 Write a function file:

```matlab
function y = globalfun(x)
```
global a b c
y = (a - b*x(1)^2 + x(1)^4/3)*x(1)^2 + x(1)*x(2) + ...
   (-c + c*x(2)^2)*x(2)^2;

In your MATLAB workspace, define the variables and run fminunc:

global a b c;
  a = 4; b = 2.1; c = 4; % Assign parameter values
  x0 = [0.5,0.5];
  [x,fval] = fminunc(@globalfun,x0)

The output is the same as in “Anonymous Functions” on page 2-38.
Setting Options

**In this section...**

- “Default Options” on page 2-43
- “Changing the Default Settings” on page 2-43
- “Tolerances and Stopping Criteria” on page 2-49
- “Checking Validity of Gradients or Jacobians” on page 2-50

**Default Options**

The options structure contains options used in the optimization routines. If, on the first call to an optimization routine, the options structure is not provided, or is empty, a set of default options is generated. Some of the default options values are calculated using factors based on problem size, such as MaxFunEvals. Some options are dependent on the specific solver algorithms, and are documented on those solver function reference pages.

“Optimization Options Reference” on page 9-7 provides an overview of all the options in the options structure.

**Changing the Default Settings**

The optimset function creates or updates an options structure to pass to the various optimization functions. The arguments to the optimset function are option name and option value pairs, such as TolX and 1e-4. Any unspecified properties have default values. You need to type only enough leading characters to define the option name uniquely. Case is ignored for option names. For option values that are strings, however, case and the exact string are necessary.

help optimset provides information that defines the different options and describes how to use them.

Here are some examples of the use of optimset.
Returning All Options

`optimset` returns all the options that can be set with typical values and default values.

Determining Options Used by a Function

The `options` structure defines the options passed to solvers. Because functions do not use all the options, it can be useful to find which options are used by a particular function. There are several ways of determining the available options:

- Consult the combined “Optimization Options Reference” on page 9-7 table.
- To find detailed descriptions of the options and their default values, consult the Options table in the function reference pages. For example, the available options for `fmincon` appear in this table.
- To find available options at the command line, pass the name of the function (in this example, `fmincon`) to `optimset`:

  ```
  optimset('fmincon')
  ```

  or

  ```
  optimset fmincon
  ```

  or

  ```
  optimset(@fmincon)
  ```

This statement returns a structure. Generally, fields not used by the function have empty values ([]); fields used by the function are set to their default values for the given function. However, some solvers have different default values depending on the algorithm used. For example, `fmincon` has a default `MaxIter` value of 400 for the `trust-region-reflective`, `sqp`, and `active-set` algorithms, but a default value of 1000 for the `interior-point` algorithm. `optimset fmincon` returns [] for the `MaxIter` field.

- You can also check the available options and their defaults in the Optimization Tool. These can change depending on problem and algorithm settings. These three pictures show how the available options for derivatives change as the type of supplied derivatives change:
Setting More Than One Option
You can specify multiple options with one call to `optimset`. For example, to reset the `Display` option and the tolerance on $x$, enter

```matlab
options = optimset('Display','iter','TolX',1e-6);
```

Updating an options Structure
To update an existing options structure, call `optimset` and pass the existing structure name as the first argument:

```matlab
options = optimset(options,'Display','iter','TolX',1e-6);
```

Retrieving Option Values
Use the `optimget` function to get option values from an options structure. For example, to get the current display option, enter the following:

```matlab
verbosity = optimget(options,'Display');
```
Displaying Output
To display output at each iteration, enter

```matlab
options = optimset('Display','iter');
```

This command sets the value of the \texttt{Display} option to \texttt{'iter'}, which causes the solver to display output at each iteration. You can also turn off any output display (\texttt{'off'}), display output only at termination (\texttt{'final'}), or display output only if the problem fails to converge (\texttt{'notify'}).

Choosing an Algorithm
Some solvers explicitly use an option called \texttt{LargeScale} for choosing which algorithm to use: \texttt{fminunc}, \texttt{linprog}, and others. Other solvers do not use the \texttt{LargeScale} attribute explicitly, but have an option called \texttt{Algorithm} instead: \texttt{fmincon}, \texttt{fsolve}, and others. All algorithms in \texttt{Algorithm} solvers are large scale, unless otherwise noted in their function reference pages. The term large-scale is explained in “Large-Scale vs. Medium-Scale Algorithms” on page \pageref{large-scale-vs-medium-scale}. For all solvers that have a large-scale algorithm, the default is for the function to use a large-scale algorithm (e.g., \texttt{LargeScale} is set to \texttt{'on'} by default).

For help deciding which algorithm to use, see “Choosing the Algorithm” on page \pageref{choosing-the-algorithm}.

To use a medium-scale algorithm in a solver that takes the \texttt{LargeScale} option, enter

```matlab
options = optimset('LargeScale','off');
```

For solvers that use the \texttt{Algorithm} option, choose the algorithm by entering

```matlab
options = optimset('Algorithm','algorithm-name');
```

\textit{algorithm-name} is the name of the chosen algorithm. You can find the choices in the function reference pages for each solver.
Large-Scale vs. Medium-Scale Algorithms. An optimization algorithm is large scale when it uses linear algebra that does not need to store, nor operate on, full matrices. This may be done internally by storing sparse matrices, and by using sparse linear algebra for computations whenever possible. Furthermore, the internal algorithms either preserve sparsity, such as a sparse Cholesky decomposition, or do not generate matrices, such as a conjugate gradient method. Large-scale algorithms are accessed by setting the LargeScale option to on, or setting the Algorithm option appropriately (this is solver-dependent).

In contrast, medium-scale methods internally create full matrices and use dense linear algebra. If a problem is sufficiently large, full matrices take up a significant amount of memory, and the dense linear algebra may require a long time to execute. Medium-scale algorithms are accessed by setting the LargeScale option to off, or setting the Algorithm option appropriately (this is solver-dependent).

Don’t let the name “large-scale” mislead you; you can use a large-scale algorithm on a small problem. Furthermore, you do not need to specify any sparse matrices to use a large-scale algorithm. Choose a medium-scale algorithm to access extra functionality, such as additional constraint types, or possibly for better performance.

Defining Output Functions and Plot Functions
Output functions and plot functions give information on the progress of a solver. They report results after each iteration of a solver. Additionally, they can halt a solver. For more information and examples of their use, see “Output Functions” on page 3-36 and “Plot Functions” on page 3-30.

Call output or plot functions by passing a function handle, or a cell array of function handles. For output functions, the syntax is

\[
\text{options} = \text{optimset}('\text{OutputFcn}',@\text{outfun});
\]

or

\[
\text{options} = \text{optimset}('\text{OutputFcn}',...
\{@\text{outfun1},@\text{outfun2},...\});
\]

For plot functions, the syntax is
options = optimset('PlotFcns',@plotfun);

or

options = optimset('PlotFcns',... 
                {@plotfun1,@plotfun2,...});

There are several predefined plot functions. See the solver function reference pages for a list, or view a list in the PlotFcns entry of the Options Structure table.

**Tolerances and Stopping Criteria**

The number of iterations in an optimization depends on a solver’s stopping criteria. These criteria include several tolerances you can set. Generally, a tolerance is a threshold which, if crossed, stops the iterations of a solver.

Set tolerances and other criteria using `optimset` as explained in “Setting Options” on page 2-43.

- **TolX** is a lower bound on the size of a step, meaning the norm of $(x_i - x_{i+1})$. If the solver attempts to take a step that is smaller than TolX, the iterations end. TolX is sometimes used as a relative bound, meaning iterations end when $|x_i - x_{i+1}| < \text{TolX}(1 + |x_i|)$, or a similar relative measure.

- **TolFun** is a lower bound on the change in the value of the objective function during a step. If $|f(x_i) - f(x_{i+1})| < \text{TolFun}$, the iterations end. TolFun
is sometimes used as a relative bound, meaning iterations end when 
\[ |f(x_i) - f(x_{i+1})| < \text{TolFun}(1 + |f(x_i)|), \]
or a similar relative measure.

- \text{TolFun} is also a bound on the first-order optimality measure. If the
  optimality measure is less than \text{TolFun}, the iterations end. \text{TolFun}
  can also be a relative bound. First-order optimality measure is defined in
  “First-Order Optimality Measure” on page 3-11.

- \text{TolCon} is an upper bound on the magnitude of any constraint functions.
  If a solver returns a point \( x \) with \( c(x) > \text{TolCon} \) or \( |ceq(x)| > \text{TolCon} \), the
  solver reports that the constraints are violated at \( x \). \text{TolCon}
  can also be a relative bound.

**Note** \text{TolCon} operates differently from other tolerances. If \text{TolCon}

is not satisfied (i.e., if the magnitude of the constraint function exceeds
\text{TolCon},

the solver attempts to continue, unless it is halted for another reason. A

solver does not halt simply because \text{TolCon} is satisfied.

- \text{MaxIter} is a bound on the number of solver iterations. \text{MaxFunEvals}
  is a bound on the number of function evaluations. Iterations and function
  evaluations are discussed in “Iterations and Function Counts” on page 3-10.

There are two other tolerances that apply to particular solvers: \text{TolPCG}

and \text{MaxPCGIter}. These relate to preconditioned conjugate gradient steps. For

more information, see “Preconditioned Conjugate Gradient Method” on page

6-24.

There are several tolerances that apply only to the \text{fmincon} interior-point

algorithm. For more information, see “Optimization Options Reference” on

page 9-7.

**Checking Validity of Gradients or Jacobians**

- “How to Check Derivatives” on page 2-51
- “Example: Checking Derivatives of Objective and Constraint Functions”
  on page 2-52
Many solvers allow you to supply a function that calculates first derivatives (gradients or Jacobians) of objective or constraint functions. You can check whether the derivatives calculated by your function match finite-difference approximations. This check can help you diagnose whether your derivative function is correct.

- If a component of the gradient function is less than 1, “match” means the absolute difference of the gradient function and the finite-difference approximation of that component is less than 1e-6.
- Otherwise, “match” means that the relative difference is less than 1e-6.

The DerivativeCheck option causes the solver to check the supplied derivative against a finite-difference approximation at just one point. If the finite-difference and supplied derivatives do not match, the solver errors. If the derivatives match to within 1e-6, the solver reports the calculated differences, and continues iterating without further derivative checks.

Solvers check the match at a point that is a small random perturbation of the initial point $x_0$, modified to be within any bounds. Solvers do not include the computations for DerivativeCheck in the function count; see “Iterations and Function Counts” on page 3-10.

**How to Check Derivatives**

- At the MATLAB command line:
  1. Set the GradObj, GradConstr, or Jacobian options to 'on' with optimset. Make sure your objective or constraint functions supply the appropriate derivatives.
  2. Set the DerivativeCheck option to 'on'.

- Using the Optimization Tool:
  1. In the Problem Setup and Results pane, choose Derivatives: Objective function: Gradient supplied or Nonlinear constraint function: Derivatives: Gradient supplied. Make sure your objective or constraint functions supply the appropriate derivatives.
  2. In the Options pane, check User-supplied derivatives > Validate user-supplied derivatives
Central finite differences are more accurate than the default forward finite differences. To use central finite differences:

- At the MATLAB command line, set `FinDiffType` option to 'central' with `optimset`.
- Using the Optimization Tool, in the **Approximated derivatives** pane, set **Type** to **central differences**.

**Example: Checking Derivatives of Objective and Constraint Functions**

- “Objective and Constraint Functions” on page 2-52
- “Checking Derivatives at the Command Line” on page 2-53
- “Checking Derivatives with the Optimization Tool” on page 2-55

**Objective and Constraint Functions.** Consider the problem of minimizing the Rosenbrock function within the unit disk as described in “Example: Nonlinear Constrained Minimization” on page 1-4. The `rosenboth` function calculates the objective function and its gradient:

```matlab
function [f g H] = rosenboth(x)
    f = 100*(x(2) - x(1)^2)^2 + (1-x(1))^2;
    if nargout > 1
        g = [-400*(x(2)-x(1)^2)*x(1)-2*(1-x(1));
             200*(x(2)-x(1)^2)];
        if nargout > 2
            if nargout > 2
                H = [1200*x(1)^2-400*x(2)+2, -400*x(2)+200;
                     -400*x(1), 200];
                end
        end
    end
end
```

`rosenboth` calculates the Hessian, too, but this example does not use the Hessian.
The `unitdisk2` function correctly calculates the constraint function and its gradient:

```matlab
function [c,ceq,gc,gceq] = unitdisk2(x)
c = x(1)^2 + x(2)^2 - 1;
ceq = [];
if nargout > 2
    gc = [2*x(1);2*x(2)];
gceq = [];
end
```

The `unitdiskb` function incorrectly calculates gradient of the constraint function:

```matlab
function [c ceq gc gceq] = unitdiskb(x)
c = x(1)^2 + x(2)^2 - 1;
ceq = [];
if nargout > 2
    gc = [x(1);x(2)]; % Gradient incorrect: off by a factor of 2
    gceq = [];
end
```

**Checking Derivatives at the Command Line.**

1. Set the options to use the interior-point algorithm, gradient of objective and constraint functions, and the `DerivativeCheck` option:

   ```matlab
   rng(0,'twister'); % for reproducibility--DerivativeCheck
   options = optimset('Algorithm','interior-point','DerivativeCheck','on','GradObj','on','GradConstr','on');
   ```

2. Solve the minimization with `fmincon` using the erroneous `unitdiskb` constraint function:

   ```matlab
   [x fval exitflag output] = fmincon(@rosenboth,...
   [-1;2],[],[],[],[],[],[],[],@unitdiskb,options);
   ```

**Derivative Check Information**
Objective function derivatives:
Maximum relative difference between user-supplied and finite-difference derivatives = 1.84768e-008.

Nonlinear inequality constraint derivatives:
Maximum relative difference between user-supplied and finite-difference derivatives = 1.
User-supplied constraint derivative element (2,1): 1.99838
Finite-difference constraint derivative element (2,1): 3.99675

Error using validateFirstDerivatives
Derivative Check failed:
User-supplied and forward finite-difference derivatives do not match within 1e-006 relative tolerance.

Error in fmincon at 805
validateFirstDerivatives(funfcn,confcn,X, ...)

The constraint function does not match the calculated gradient, encouraging you to check the function for an error.

3 Replace the unitdiskb constraint function with unitdisk2 and run the minimization again:

[x fval exitflag output] = fmincon(@rosenboth,...
[-1;2],[],[],[],[],[],[],[],@unitdisk2,options);

Derivative Check Information

Objective function derivatives:
Maximum relative difference between user-supplied and finite-difference derivatives = 1.28553e-008.

Nonlinear inequality constraint derivatives:
Maximum relative difference between user-supplied and finite-difference derivatives = 1.46443e-008.
Derivative Check successfully passed.

Local minimum found that satisfies the constraints...

**Checking Derivatives with the Optimization Tool.** To set up the example using correct derivative functions, but starting from \([0 \ 0]\), using the Optimization Tool:

1. Launch the Optimization Tool by entering `optimtool` at the command line.

2. Set the **Problem Setup and Results** pane to match the following figure:

   ![Problem Setup and Results Pane](image)

3. Set the **Options** pane to match the following figure:
4 Press the **Start** button under **Run solver and view results**.

The output screen displays
The forward finite difference approximation is inaccurate enough near \([0, 0]\) that the derivative check fails.

5 To use the more accurate central differences, select central differences in the Approximated derivatives > Type pane:

6 Click Run solver and view results > Clear Results, then Start. This time the derivative check is successful:
The derivative check also succeeds when you select the initial point \([-1 \ 2]\), or most random points.
Examining Results

- “Current Point and Function Value” on page 3-2
- “Exit Flags and Exit Messages” on page 3-3
- “Iterations and Function Counts” on page 3-10
- “First-Order Optimality Measure” on page 3-11
- “Iterative Display” on page 3-16
- “Output Structures” on page 3-25
- “Lagrange Multiplier Structures” on page 3-26
- “Hessian” on page 3-27
- “Plot Functions” on page 3-30
- “Output Functions” on page 3-36
Current Point and Function Value

The current point and function value are the first two outputs of all Optimization Toolbox solvers.

- The current point is the final point in the solver iterations. It is the best point the solver found in its run.
  - If you call a solver without assigning a value to the output, the default output, ans, is the current point.
- The function value is the value of the objective function at the current point.
  - The function value for least-squares solvers is the sum of squares, also known as the residual norm.
  - fgoalattain, fminimax, and fsolve return a vector function value.
  - Sometimes fval or Fval denotes function value.
Exit Flags and Exit Messages

<table>
<thead>
<tr>
<th>In this section...</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Exit Flags&quot; on page 3-3</td>
</tr>
<tr>
<td>&quot;Exit Messages&quot; on page 3-5</td>
</tr>
<tr>
<td>&quot;Enhanced Exit Messages&quot; on page 3-5</td>
</tr>
<tr>
<td>&quot;Exit Message Options&quot; on page 3-8</td>
</tr>
</tbody>
</table>

**Exit Flags**
When an optimization solver completes its task, it sets an exit flag. An exit flag is an integer that is a code for the reason the solver halted its iterations. In general:

- Positive exit flags correspond to successful outcomes.
- Negative exit flags correspond to unsuccessful outcomes.
- The zero exit flag corresponds to the solver being halted by exceeding an iteration limit or limit on the number of function evaluations (see “Iterations and Function Counts” on page 3-10, and also see “Tolerances and Stopping Criteria” on page 2-49).

A table of solver outputs in the solver’s function reference section lists the meaning of each solver’s exit flags.

**Note** Exit flags are not infallible guides to the quality of a solution. Many other factors, such as tolerance settings, can affect whether a solution is satisfactory to you. You are responsible for deciding whether a solver returns a satisfactory answer. Sometimes a negative exit flag does not correspond to a “bad” solution. Similarly, sometimes a positive exit flag does not correspond to a “good” solution.

You obtain an exit flag by calling a solver with the `exitflag` syntax. This syntax depends on the solver. For details, see the solver function reference pages. For example, for `fsolve`, the calling syntax to obtain an exit flag is
The following example uses this syntax. Suppose you want to solve the system of nonlinear equations

\[
\begin{align*}
2x_1 - x_2 &= e^{-x_1} \\
-x_1 + 2x_2 &= e^{-x_2}.
\end{align*}
\]

Write these equations as an anonymous function that gives a zero vector at a solution:

\[
\text{myfcn} = @(x)[2*x(1) - x(2) - \exp(-x(1));
-x(1) + 2*x(2) - \exp(-x(2))];
\]

Call \text{fsolve} with the \text{exitflag} syntax at the initial point \([-5 -5]\):

\[
[x_{\text{final}} \text{ fval exitflag}] = \text{fsolve}(\text{myfcn},[-5 -5])
\]

Equation solved.

\text{fsolve} completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

\[
\begin{align*}
x_{\text{final}} &= \\
&\quad 0.5671 \quad 0.5671
\end{align*}
\]

\[
\begin{align*}
f\text{val} &= \\
&\quad 1.0e-006 \ *
\end{align*}
\]

\[
\begin{align*}
&\quad -0.4059 \\
&\quad -0.4059
\end{align*}
\]

\[
\text{exitflag} = \\
1
\]

In the table for \text{fsolve} under “Output Arguments” on page 11-95, you find that an exit flag value 1 means “Function converged to a solution \(x\).” In other words, \text{fsolve} reports \text{myfcn} is nearly zero at \(x = [0.5671 \ 0.5671]\).
Exit Messages

Each solver issues a message to the MATLAB command window at the end of its iterations. This message explains briefly why the solver halted. The message might give more detail than the exit flag.

Many examples in this documentation show exit messages. For example, see “Minimizing at the Command Line” on page 1-11, or “Step 2: Invoke one of the unconstrained optimization routines.” on page 6-15. The example in the previous section, “Exit Flags” on page 3-3, shows the following exit message:

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

This message is more informative than the exit flag. The message indicates that the gradient is relevant. The message also states that the function tolerance controls how near 0 the vector of function values must be for fsolve to regard the solution as completed.

Enhanced Exit Messages

Some solvers have exit messages that contain links for more information. There are two types of links:

- Links on words or phrases. If you click such a link, a window opens that displays a definition of the term, or gives other information. The new window can contain links to the Help browser documentation for more detailed information.
- A link as the last line of the display saying <stopping criteria details>. If you click this link, MATLAB displays more detail about the reason the solver halted.

The fminunc solver has enhanced exit messages:

```matlab
opts = optimset('LargeScale','off'); % LargeScale needs gradient
[xfinal fval exitflag] = fminunc(@sin,0,opts)
```

This yields the following results:
Examining Results

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

<stopping criteria details>

xfinal =

-1.5708

fval =

-1.0000

exitflag =

1

Each of the underlined words or phrases contains a link that provides more information.

- The <stopping criteria details> link prints the following to the MATLAB command line:

  Optimization completed: The first-order optimality measure, 0.000000e+000, is less than the default value of options.TolFun = 1.000000e-006.

<table>
<thead>
<tr>
<th>Optimization Metric</th>
<th>User Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative norm(gradient) = 0.00e+000</td>
<td>TolFun = 1e-006 (default)</td>
</tr>
</tbody>
</table>

- The other links bring up a help window with term definitions. For example, clicking the Local minimum found link opens the following window:
Exit Flags and Exit Messages

Clicking the first-order optimality measure expander link brings up the definition of first-order optimality measure for fminunc:
Examining Results

The expander link is a way to obtain more information in the same window. Clicking the first-order optimality measure expander link again closes the definition.

- The other links open the Help Viewer.

**Exit Message Options**

Set the Display option to control the appearance of both exit messages and iterative display. For more information, see “Iterative Display” on page 3-16. The following table shows the effect of the various settings of the Display option.
<table>
<thead>
<tr>
<th>Value of the Display Option</th>
<th>Output to Command Window</th>
<th>Iterative Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>'none', or the synonymous 'off'</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>'final' (default for most solvers)</td>
<td>Default</td>
<td>None</td>
</tr>
<tr>
<td>'final-detailed'</td>
<td>Detailed</td>
<td>None</td>
</tr>
<tr>
<td>'iter'</td>
<td>Default</td>
<td>Yes</td>
</tr>
<tr>
<td>'iter-detailed'</td>
<td>Detailed</td>
<td>Yes</td>
</tr>
<tr>
<td>'notify'</td>
<td>Default only if exitflag ≤ 0</td>
<td>None</td>
</tr>
<tr>
<td>'notify-detailed'</td>
<td>Detailed only if exitflag ≤ 0</td>
<td>None</td>
</tr>
</tbody>
</table>

For example,

```matlab
opts = optimset('Display','iter-detailed','LargeScale','off');
[xfinal fval] = fminunc(@cos,1,opts);
```

yields the following display:

```
>> opts = optimset('Display','iter-detailed','LargeScale','off');
[xfinal fval] = fminunc(@cos,1,opts)

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>Step-size</th>
<th>optimality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>0.540302</td>
<td></td>
<td>0.841</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>-0.990628</td>
<td>2.38223</td>
<td>0.137</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>-1</td>
<td>0.351894</td>
<td>0.000328</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>-1</td>
<td>1</td>
<td>1.03e-006</td>
</tr>
</tbody>
</table>
```

Optimization completed: The **first-order optimality measure**, 5.602276e-007, is less than the default value of **options.TolFun** = 1.000000e-006.

Optimization Metric
relative norm(gradient) = 5.60e-007

User Options
TolFun = 1e-006 (default)
Iterations and Function Counts

In general, Optimization Toolbox solvers iterate to find an optimum. This means a solver begins at an initial value \( x_0 \), performs some intermediate calculations that eventually lead to a new point \( x_1 \), and then repeats the process to find successive approximations \( x_2, x_3, \ldots \) of the local minimum. Processing stops after some number of iterations \( k \).

At any step, intermediate calculations may involve evaluating the objective function and constraints, if any, at points near the current iterate \( x_i \). For example, the solver may estimate a gradient by finite differences. At each of these nearby points, the function count (F-count) is increased by one.

- If there are no constraints, the F-count reports the total number of objective function evaluations.
- If there are constraints, the F-count reports only the number of points where function evaluations took place, not the total number of evaluations of constraint functions.
- If there are many constraints, the F-count can be significantly less than the total number of function evaluations.

F-count is a header in the iterative display for many solvers. For an example, see “Interpreting the Result” on page 1-12.

The F-count appears in the output structure as output.funcCount. This enables you to access the evaluation count programmatically. For more information on output structures, see “Output Structures” on page 3-25.

Sometimes a solver attempts a step, and rejects the attempt. The LargeScale, trust-region-reflective, and trust-region-dogleg algorithms count these failed attempts as iterations, and report the (unchanged) result in the iterative display. The interior-point, active-set, and levenberg-marquardt algorithms do not count such an attempt as an iteration, and do not report the attempt in the iterative display. All attempted steps increase the F-count, regardless of the algorithm.
First-Order Optimality Measure

What Is First-Order Optimality Measure?
First-order optimality is a measure of how close a point \( x \) is to optimal. Most Optimization Toolbox solvers use this measure, though it has different definitions for different algorithms. First-order optimality is a necessary condition, but it is not a sufficient condition. In other words:

- The first-order optimality measure must be zero at a minimum.
- A point with first-order optimality equal to zero is not necessarily a minimum.

For general information about first-order optimality, see Nocedal and Wright [31]. For specifics about the first-order optimality measures for Optimization Toolbox solvers, see “Unconstrained Optimality” on page 3-12, “Constrained Optimality Theory” on page 3-12, and “Constrained Optimality in Solver Form” on page 3-14.

Stopping Rules Related to First-Order Optimality
The \( \text{TolFun} \) tolerance relates to the first-order optimality measure. Typically, if the first-order optimality measure is less than \( \text{TolFun} \), solver iterations end.

Some solvers or algorithms use relative first-order optimality as a stopping criterion. Solver iterations end if the first-order optimality measure is less than \( \mu \) times \( \text{TolFun} \), where \( \mu \) is either:

- The infinity norm (maximum) of the gradient of the objective function at \( x_0 \)
• The infinity norm (maximum) of inputs to the solver, such as \( f \) or \( b \) in \( \text{linprog} \) or \( H \) in \( \text{quadprog} \)

A relative measure attempts to account for the scale of a problem. Multiplying an objective function by a very large or small number does not change the stopping condition for a relative stopping criterion, but does change it for an unscaled one.

Solvers with enhanced exit messages state, in the stopping criteria details, when they use relative first-order optimality.

**Unconstrained Optimality**

For a smooth unconstrained problem,

\[
\min_{x} f(x),
\]

the first-order optimality measure is the infinity norm (meaning maximum absolute value) of \( \nabla f(x) \), which is:

\[
\text{first-order optimality measure} = \max_{i} |(\nabla f(x))_{i}| = \|\nabla f(x)\|_{\infty}.
\]

This measure of optimality is based on the familiar condition for a smooth function to achieve a minimum: its gradient must be zero. For unconstrained problems, when the first-order optimality measure is nearly zero, the objective function has gradient nearly zero, so the objective function could be near a minimum. If the first-order optimality measure is not small, the objective function is not minimal.

**Constrained Optimality Theory**

This section summarizes the theory behind the definition of first-order optimality measure for constrained problems. The definition as used in Optimization Toolbox functions is in “Constrained Optimality in Solver Form” on page 3-14.

For a smooth constrained problem, let \( g \) and \( h \) be vector functions representing all inequality and equality constraints respectively (meaning bound, linear, and nonlinear constraints):
min \( f(x) \) subject to \( g(x) \leq 0, \ h(x) = 0 \).

The meaning of first-order optimality in this case is more complex than for unconstrained problems. The definition is based on the Karush-Kuhn-Tucker (KKT) conditions. The KKT conditions are analogous to the condition that the gradient must be zero at a minimum, modified to take constraints into account. The difference is that the KKT conditions hold for constrained problems.

The KKT conditions use the auxiliary Lagrangian function:

\[
L(x, \lambda) = f(x) + \sum \lambda_{g,i} g_i(x) + \sum \lambda_{h,i} h_i(x).
\]

(3-1)

The vector \( \lambda \), which is the concatenation of \( \lambda_g \) and \( \lambda_h \), is the Lagrange multiplier vector. Its length is the total number of constraints.

The KKT conditions are:

\[
\nabla_x L(x, \lambda) = 0,
\]

(3-2)

\[
\lambda_{g,i} g_i(x) = 0 \ \forall i,
\]

(3-3)

\[
\begin{cases}
g(x) \leq 0, \\
h(x) = 0, \\
\lambda_{g,i} \geq 0.
\end{cases}
\]

(3-4)

Solvers do not use the three expressions in Equation 3-4 in the calculation of optimality measure.

The optimality measure associated with Equation 3-2 is

\[
\|\nabla_x L(x, \lambda)\| = \|\nabla f(x) + \sum \lambda_{g,i} \nabla g_i(x) + \sum \lambda_{h,i} \nabla h_i(x)\|.
\]

(3-5)

The optimality measure associated with Equation 3-3 is
where the norm in Equation 3-6 means infinity norm (maximum) of the vector $\lambda_{gi} g_i(x)$.

The combined optimality measure is the maximum of the values calculated in Equation 3-5 and Equation 3-6. Solvers that accept nonlinear constraint functions report constraint violations $g(x) > 0$ or $|h(x)| > 0$ as TolCon tolerance violations. See “Tolerances and Stopping Criteria” on page 2-49.

**Constrained Optimality in Solver Form**

Most constrained toolbox solvers separate their calculation of first-order optimality measure into bounds, linear functions, and nonlinear functions. The measure is the maximum of the following two norms, which correspond to Equation 3-5 and Equation 3-6:

$$
\| \nabla_L x L(x, \lambda) \| = \| \nabla f(x) + A^T \lambda_{ineqlin} + Aeq^T \lambda_{eqlin} + \sum \lambda_{ineqnonlin,i} \nabla c_i(x) + \sum \lambda_{eqnonlin,i} \nabla ceq_i(x) \|, \tag{3-7}
$$

$$
\| [x_i - x_i|_{\lambda_{lower,i}}, |x_i - u_i|_{\lambda_{upper,i}}, |Ax - b_i|_{\lambda_{ineqlin,i}}, |c_i(x)|_{\lambda_{ineqnonlin,i}}) \|, \tag{3-8}
$$

where the norm of the vectors in Equation 3-7 and Equation 3-8 is the infinity norm (maximum). The subscripts on the Lagrange multipliers correspond to solver Lagrange multiplier structures. See “Lagrange Multiplier Structures” on page 3-26. The summations in Equation 3-7 range over all constraints. If a bound is $\pm \text{Inf}$, that term is not constrained, so it is not part of the summation.

**Linear Equalities Only**

For some large-scale problems with only linear equalities, the first-order optimality measure is the infinity norm of the *projected* gradient. In other words, the first-order optimality measure is the size of the gradient projected onto the null space of $Aeq$. 

\[ \| \lambda_{g} g(x) \|, \] (3-6)
**Bounded Least-Squares and Trust-Region-Reflective Solvers**

For least-squares solvers and trust-region-reflective algorithms, in problems with bounds alone, the first-order optimality measure is the maximum over $i$ of $|v_i g_i|$. Here $g_i$ is the $i$th component of the gradient, $x$ is the current point, and

$$v_i = \begin{cases} 
|x_i - b_i| & \text{if the negative gradient points toward bound } b_i \\
1 & \text{otherwise.}
\end{cases}$$

If $x_i$ is at a bound, $v_i$ is zero. If $x_i$ is not at a bound, then at a minimizing point the gradient $g_i$ should be zero. Therefore the first-order optimality measure should be zero at a minimizing point.
Iterative Display

**In this section...**

| “Introduction” on page 3-16  |
| “Common Headings” on page 3-17 |
| “Function-Specific Headings” on page 3-17 |

**Introduction**

Iterative display is a table of statistics describing the calculations in each iteration of a solver. The statistics depend on both the solver and the solver algorithm. For more information about iterations, see “Iterations and Function Counts” on page 3-10. The table appears in the MATLAB Command Window when you run solvers with appropriate options.

Obtain iterative display by using `optimset` to create an options structure with the `Display` option set to 'iter' or 'iter-detailed'. For example:

```matlab
options = optimset('Display','iter','LargeScale','off');
[x fval exitflag output] = fminunc(@sin,0,options);
```

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>Step-size</th>
<th>optimality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>0</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>-0.841471</td>
<td>1</td>
<td>0.54</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>-1</td>
<td>0.484797</td>
<td>0.000993</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>-1</td>
<td>1</td>
<td>5.62e-005</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>-1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

You can also obtain iterative display by using the Optimization Tool. Select **Display to command window > Level of display > iterative or iterative with detailed message**.
Iterative display is available for all solvers except:

- linprog medium-scale active-set algorithm
- lsqlin
- lsqnonneg
- quadprog

**Common Headings**
The following table lists some common headings of iterative display.

<table>
<thead>
<tr>
<th>Heading</th>
<th>Information Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iteration or Iter</td>
<td>Iteration number; see “Iterations and Function Counts” on page 3-10</td>
</tr>
<tr>
<td>Func-count or F-count</td>
<td>Number of function evaluations; see “Iterations and Function Counts” on page 3-10</td>
</tr>
<tr>
<td>f(x)</td>
<td>Current objective function value</td>
</tr>
<tr>
<td>First-order optimality</td>
<td>First-order optimality measure (see “First-Order Optimality Measure” on page 3-11)</td>
</tr>
<tr>
<td>Norm of step</td>
<td>Size of the current step (size is the Euclidean norm, or 2-norm)</td>
</tr>
</tbody>
</table>

**Function-Specific Headings**
The following sections describe headings of iterative display whose meaning is specific to the optimization function you are using:

- “bintprog” on page 3-18
- “fgoalattain, fmincon, fminimax, and fseminf” on page 3-19
- “fminbnd and fzero” on page 3-20
• “fminsearch” on page 3-21
• “fminunc” on page 3-22
• “fsolve” on page 3-22
• “linprog” on page 3-22
• “lsqnonlin and lsqcurvefit” on page 3-24

**bintprog**
The following table describes the headings specific to bintprog.

<table>
<thead>
<tr>
<th><strong>bintprog Heading</strong></th>
<th><strong>Information Displayed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Explored nodes</td>
<td>Cumulative number of explored nodes.</td>
</tr>
<tr>
<td>Obj of LP relaxation</td>
<td>Objective function value of the linear programming (LP) relaxation problem.</td>
</tr>
<tr>
<td>Obj of best integer point</td>
<td>Objective function value of the best integer point found so far. This is an upper bound for the final objective function value.</td>
</tr>
<tr>
<td>Unexplored nodes</td>
<td>Number of nodes that have been set up but not yet explored.</td>
</tr>
<tr>
<td>Best lower bound on obj</td>
<td>Objective function value of LP relaxation problem that gives the best current lower bound on the final objective function value.</td>
</tr>
<tr>
<td>Relative gap between bounds</td>
<td>( \frac{100(b-a)}{</td>
</tr>
<tr>
<td></td>
<td>• ( b ) is the objective function value of the best integer point.</td>
</tr>
<tr>
<td></td>
<td>• ( a ) is the best lower bound on the objective function value.</td>
</tr>
</tbody>
</table>
**fgoalattain, fmincon, fminimax, and fseminf**

The following table describes the headings specific to `fgoalattain`, `fmincon`, `fminimax`, and `fseminf`.

<table>
<thead>
<tr>
<th><strong>fgoalattain, fmincon, fminimax, or fseminf Heading</strong></th>
<th><strong>Information Displayed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max constraint</td>
<td>Maximum violation among all constraints, both internally constructed and user-provided; can be negative when no constraint is binding.</td>
</tr>
<tr>
<td>CG-iterations</td>
<td>Number of conjugate gradient iterations taken in the current iteration (see “Preconditioned Conjugate Gradient Method” on page 6-24).</td>
</tr>
<tr>
<td>Trust-region radius</td>
<td>Current trust-region radius.</td>
</tr>
<tr>
<td>Line search steplength</td>
<td>Multiplicative factor that scales the search direction (see Equation 6-46).</td>
</tr>
<tr>
<td>Steplength</td>
<td>Multiplicative factor that scales the search direction (see Equation 6-46).</td>
</tr>
<tr>
<td>Attainment factor</td>
<td>Value of the attainment factor for <code>fgoalattain</code>.</td>
</tr>
<tr>
<td>Objective value</td>
<td>Objective function value of the nonlinear programming reformulation of the minimax problem for <code>fminimax</code>.</td>
</tr>
<tr>
<td>Directional derivative</td>
<td>Gradient of the objective function along the search direction.</td>
</tr>
<tr>
<td><strong>fgoalattain, fmincon, fminimax, or fseminf Heading</strong></td>
<td><strong>Information Displayed</strong></td>
</tr>
<tr>
<td>------------------------------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Procedure</td>
<td>Hessian update procedures:</td>
</tr>
<tr>
<td></td>
<td>- Infeasible start point</td>
</tr>
<tr>
<td></td>
<td>- Hessian not updated</td>
</tr>
<tr>
<td></td>
<td>- Hessian modified</td>
</tr>
<tr>
<td></td>
<td>- Hessian modified twice</td>
</tr>
<tr>
<td></td>
<td>For more information, see “Updating the Hessian Matrix” on page 6-30.</td>
</tr>
<tr>
<td></td>
<td>QP subproblem procedures:</td>
</tr>
<tr>
<td></td>
<td>- dependent — There are dependent (redundant) equality constraints that the solver detected and removed.</td>
</tr>
<tr>
<td></td>
<td>- Infeasible — The QP subproblem with linearized constraints is infeasible.</td>
</tr>
<tr>
<td></td>
<td>- Overly constrained — The QP subproblem with linearized constraints is infeasible.</td>
</tr>
<tr>
<td></td>
<td>- Unbounded — The QP subproblem is feasible with large negative curvature.</td>
</tr>
<tr>
<td></td>
<td>- Ill-posed — The QP subproblem search direction is too small.</td>
</tr>
<tr>
<td></td>
<td>- Unreliable — The QP subproblem seems to be ill-conditioned.</td>
</tr>
<tr>
<td>Feasibility</td>
<td>Maximum constraint violation, where satisfied inequality constraints count as 0.</td>
</tr>
</tbody>
</table>

**fminbnd and fzero**
The following table describes the headings specific to *fminbnd* and *fzero*. 
### fminbnd or fzero Heading

**Procedure**

- Initial (golden section search)
- Parabolic (parabolic interpolation)

**Information Displayed**

Procedures for fminbnd:

- initial
- golden (golden section search)
- parabolic (parabolic interpolation)

Procedures for fzero:

- initial (initial point)
- search (search for an interval containing a zero)
- bisection
- interpolation (linear interpolation or inverse quadratic interpolation)

### x

Current point for the algorithm

---

### fminsearch

The following table describes the headings specific to fminsearch.

<table>
<thead>
<tr>
<th>fminsearch Heading</th>
<th>Information Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>min f(x)</td>
<td>Minimum function value in the current simplex.</td>
</tr>
</tbody>
</table>

**Procedure**

Simplex procedure at the current iteration. Procedures include:

- initial simplex
- expand
- reflect
- shrink
- contract inside
- contract outside

For details, see “fminsearch Algorithm” on page 6-12.
**fminunc**

The following table describes the headings specific to *fminunc*.

<table>
<thead>
<tr>
<th>fminunc Heading</th>
<th>Information Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG-iterations</td>
<td>Number of conjugate gradient iterations taken in the current iteration (see “Preconditioned Conjugate Gradient Method” on page 6-24)</td>
</tr>
<tr>
<td>Step-size</td>
<td>Multiplicative factor that scales the search direction (see Equation 6-12)</td>
</tr>
</tbody>
</table>

The *fminunc* medium-scale algorithm can issue a **skipped update** message to the right of the First-order optimality column. This message means that *fminunc* did not update its Hessian estimate, because the resulting matrix would not have been positive definite. The message usually indicates that the objective function is not smooth at the current point.

**fsolve**

The following table describes the headings specific to *fsolve*.

<table>
<thead>
<tr>
<th>fsolve Heading</th>
<th>Information Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trust-region radius</td>
<td>Current trust-region radius (change in the norm of the trust-region radius)</td>
</tr>
<tr>
<td>CG-iterations</td>
<td>Number of conjugate gradient iterations taken in the current iteration (see “Preconditioned Conjugate Gradient Method” on page 6-24)</td>
</tr>
<tr>
<td>Residual</td>
<td>Residual (sum of squares) of the function</td>
</tr>
<tr>
<td>Directional derivative</td>
<td>Gradient of the function along the search direction</td>
</tr>
<tr>
<td>Lambda</td>
<td>$\lambda_k$ value defined in “Levenberg-Marquardt Method” on page 6-150</td>
</tr>
</tbody>
</table>

**linprog**

The following table describes the headings specific to *linprog*. 
<table>
<thead>
<tr>
<th><strong>linprog Heading</strong></th>
<th><strong>Information Displayed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primal Infeas A*x-b</td>
<td>Primal infeasibility.</td>
</tr>
<tr>
<td>Dual Infeas A'*y+z-w-f</td>
<td>Dual infeasibility.</td>
</tr>
<tr>
<td>Duality Gap x'*z+s'*w</td>
<td>Duality gap (see “Large Scale Linear Programming” on page 6-94) between the primal objective and the dual objective. s and w appear only in this equation if there are finite upper bounds.</td>
</tr>
<tr>
<td>Total Rel Error</td>
<td>Total relative error, described at the end of “Main Algorithm” on page 6-94.</td>
</tr>
<tr>
<td>Objective f'*x</td>
<td>Current objective value.</td>
</tr>
</tbody>
</table>
**lsqnonlin and lsqcurvefit**

The following table describes the headings specific to `lsqnonlin` and `lsqcurvefit`.

<table>
<thead>
<tr>
<th><strong>lsqnonlin or lsqcurvefit Heading</strong></th>
<th><strong>Information Displayed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resnorm</td>
<td>Value of the squared 2-norm of the residual at x</td>
</tr>
<tr>
<td>Residual</td>
<td>Residual vector of the function</td>
</tr>
<tr>
<td>CG-iterations</td>
<td>Number of conjugate gradient iterations taken in the current iteration (see “Preconditioned Conjugate Gradient Method” on page 6-24)</td>
</tr>
<tr>
<td>Directional derivative</td>
<td>Gradient of the function along the search direction</td>
</tr>
<tr>
<td>Lambda</td>
<td>$\lambda_k$ value defined in “Levenberg-Marquardt Method” on page 6-150</td>
</tr>
</tbody>
</table>
Output Structures

An output structure contains information on a solver’s result. All solvers can return an output structure. To obtain an output structure, invoke the solver with the output structure in the calling syntax. For example, to get an output structure from `lsqnonlin`, use the syntax

```
[x,resnorm,residual,exitflag,output] = lsqnonlin(...) 
```

You can also obtain an output structure by running a problem using the Optimization Tool. All results exported from Optimization Tool contain an output structure.

The contents of the output structure are listed in each solver’s reference pages. For example, the output structure returned by `lsqnonlin` contains `firstorderopt`, `iterations`, `funcCount`, `cgiterations`, `stepsize`, `algorithm`, and `message`. To access, for example, the message, enter `output.message`.

Optimization Tool exports results in a structure. The results structure contains the output structure. To access, for example, the number of iterations, use the syntax `optimresults.output.iterations`.

You can also see the contents of an output structure by double-clicking the output structure in the MATLAB Workspace pane.
Lagrange Multiplier Structures

Constrained optimization involves a set of Lagrange multipliers, as described in “First-Order Optimality Measure” on page 3-11. Solvers return estimated Lagrange multipliers in a structure. The structure is called \texttt{lambda}, since the conventional symbol for Lagrange multipliers is the Greek letter lambda (λ). The structure separates the multipliers into the following types, called fields:

- \texttt{lower}, associated with lower bounds
- \texttt{upper}, associated with upper bounds
- \texttt{eqlin}, associated with linear equalities
- \texttt{ineqlin}, associated with linear inequalities
- \texttt{eqnonlin}, associated with nonlinear equalities
- \texttt{ineqnonlin}, associated with nonlinear inequalities

To access, for example, the nonlinear inequality field of a Lagrange multiplier structure, enter \texttt{lambda.ineqnonlin}. To access the third element of the Lagrange multiplier associated with lower bounds, enter \texttt{lambda.lower(3)}.

The content of the Lagrange multiplier structure depends on the solver. For example, linear programming has no nonlinearities, so it does not have \texttt{eqnonlin} or \texttt{ineqnonlin} fields. Each applicable solver’s function reference pages contains a description of its Lagrange multiplier structure under the heading “Outputs.”
Hessian

In this section...

“fminunc Hessian” on page 3-27
“fmincon Hessian” on page 3-28

fminunc Hessian

The Hessian for an unconstrained problem is the matrix of second derivatives of the objective function $f$:

$$Hessian \ H_{ij} = \frac{\partial^2 f}{\partial x_i \partial x_j}.$$

- **Medium Scale Algorithm** — fminunc returns an estimated Hessian matrix at the solution. It computes the estimate by finite differences.

- **Large Scale Algorithm** — fminunc returns a Hessian matrix at the next-to-last iterate.
  - If you supply a Hessian in the objective function, fminunc returns this Hessian.
  - If you supply a HessMult function, fminunc returns the Hiinfo matrix from the HessMult function. For more information, see “Large-Scale Algorithm Only” on page 11-101.
  - Otherwise, fminunc returns an approximation from a sparse finite difference algorithm on the gradients.

This Hessian is accurate for the next-to-last iterate. However, the next-to-last iterate might not be close to the final point.

The reason the large-scale algorithm returns the Hessian at the next-to-last point is for efficiency. fminunc uses the Hessian internally to compute its next step. When fminunc reaches a stopping condition, it does not need to compute the next step, so does not compute the Hessian.
fmincon Hessian

The Hessian for a constrained problem is the Hessian of the Lagrangian. For an objective function \( f \), nonlinear inequality constraint vector \( c \), and nonlinear equality constraint vector \( ceq \), the Lagrangian is

\[
L = f + \sum_{i} \lambda_i c_i + \sum_{j} \lambda_j ceq_j.
\]

The \( \lambda_i \) are Lagrange multipliers; see “First-Order Optimality Measure” on page 3-11 and “Lagrange Multiplier Structures” on page 3-26. The Hessian of the Lagrangian is

\[
H = \nabla^2 L = \nabla^2 f + \sum_{i} \lambda_i \nabla^2 c_i + \sum_{j} \lambda_j \nabla^2 ceq_j.
\]

fmincon has four algorithms, with several options for Hessians, as described in “fmincon Trust Region Reflective Algorithm” on page 6-21, “fmincon Active Set Algorithm” on page 6-27, and “fmincon Interior Point Algorithm” on page 6-38. fmincon returns the following for the Hessian:

- **active-set or sqp Algorithm** — fmincon returns the Hessian approximation it computes at the next-to-last iterate. fmincon computes a quasi-Newton approximation of the Hessian matrix at the solution in the course of its iterations. This approximation does not, in general, match the true Hessian in every component, but only in certain subspaces. Therefore the Hessian that fmincon returns can be inaccurate. For more details of the active-set calculation, see “SQP Implementation” on page 6-30.

- **trust-region-reflective Algorithm** — fmincon returns the Hessian it computes at the next-to-last iterate.
  - If you supply a Hessian in the objective function, fmincon returns this Hessian.
  - If you supply a HessMult function, fmincon returns the Hinfo matrix from the HessMult function. For more information, see “Trust-Region-Reflective Algorithm” on page 11-55.
  - Otherwise, fmincon returns an approximation from a sparse finite difference algorithm on the gradients.
This Hessian is accurate for the next-to-last iterate. However, the next-to-last iterate might not be close to the final point.

The reason the trust-region-reflective algorithm returns the Hessian at the next-to-last point is for efficiency. fmincon uses the Hessian internally to compute its next step. When fmincon reaches a stopping condition, it does not need to compute the next step, so does not compute the Hessian.

- **interior-point Algorithm**
  - If the Hessian option is lbfgs or fin-diff-grads, or if you supply a Hessian multiply function (HessMult), fmincon returns [] for the Hessian.
  - If the Hessian option is bfgs (the default), fmincon returns a quasi-Newton approximation to the Hessian at the final point. This Hessian can be inaccurate, as in the active-set or sqp algorithm Hessian.
  - If the Hessian option is user-supplied, fmincon returns the user-supplied Hessian at the final point.
Plot Functions

The `PlotFcns` field of the `options` structure specifies one or more functions that an optimization function calls at each iteration to plot various measures of progress while the algorithm executes. Pass a function handle or cell array of function handles. The structure of a plot function is the same as the structure of an output function. For more information on this structure, see “Output Function” on page 9-18.

There are a variety of predefined plot functions available. Find them in the `PlotFcns` option description, in the solver function reference page, or in the Optimization Tool in the `Plot functions` pane of the `Options` pane.

Example: Using a Plot Function

This example shows how to use a plot function to view the progress of the `fmincon` interior-point algorithm. The problem is taken from the Getting Started “Example: Nonlinear Constrained Minimization” on page 1-4. The first part of the example shows how to run the optimization using the Optimization Tool. The second part shows how to run the optimization from the command line.

Running the Optimization Using the Optimization Tool

1 Write the nonlinear objective and constraint functions, including the derivatives:

```matlab
%% ROSENBOTH returns both the value y of Rosenbrock's function
% and also the value g of its gradient and H the Hessian.

function [f g H] = rosenboth(x)

f = 100*(x(2) - x(1)^2)^2 + (1-x(1))^2;

if nargout > 1
    g = [-400*(x(2)-x(1)^2)*x(1)-2*(1-x(1));
         200*(x(2)-x(1)^2)];
    if nargout > 2
```
\[ H = \begin{bmatrix} 1200*x(1)^2-400*x(2)+2, & -400*x(1); \\ -400*x(1), & 200 \end{bmatrix}; \]

end
end

Save this file as rosenboth.m.

function \[c,ceq,gc,gceq\] = unitdisk2(x)
% UNITDISK2 returns the value of the constraint
% function for the disk of radius 1 centered at
% [0 0]. It also returns the gradient.

c = x(1)^2 + x(2)^2 - 1;
ceq = [ ];

if nargout > 2
    gc = [2*x(1);2*x(2)];
gceq = [ ];
end

Save this file as unitdisk2.m.

2 Start the Optimization Tool by entering optimtool at the command line.

3 Set up the optimization:

- Choose the \texttt{fmincon} solver.
- Choose the \texttt{Interior point} algorithm.
- Set the objective function to \texttt{rosenboth}.
- Choose \texttt{Gradient supplied} for the objective function derivative.
- Set the start point to \texttt{[0 0]}.
- Set the nonlinear constraint function to \texttt{unitdisk2}.
- Choose \texttt{Gradient supplied} for the nonlinear constraint derivatives.

Your \textbf{Problem Setup and Results} panel should match the following figure.
4 Choose three plot functions in the Options pane: Current point, Function value, and First order optimality.

5 Click the Start button under Run solver and view results.

6 The output appears as follows in the Optimization Tool.
In addition, the following three plots appear in a separate window.
• The “Current Point” plot graphically shows the minimizer \([0.786, 0.618]\), which is reported as the **Final point** in the **Run solver and view results** pane. This plot updates at each iteration, showing the intermediate iterates.

• The “Current Function Value” plot shows the objective function value at all iterations. This graph is nearly monotone, showing \texttt{fmincon} reduces the objective function at almost every iteration.

• The “First-order Optimality” plot shows the first-order optimality measure at all iterations.
Running the Optimization from the Command Line

1 Write the nonlinear objective and constraint functions, including the derivatives, as shown in “Running the Optimization Using the Optimization Tool” on page 3-30.

2 Create an options structure that includes calling the three plot functions:

   ```matlab
   options = optimset('Algorithm','interior-point',
                     'GradObj','on','GradConstr','on','PlotFcns',{@optimplotx,...
                     @optimplotfval,@optimplotfirstorderopt});
   ```

3 Call `fmincon`:

   ```matlab
   x = fmincon(@rosenboth,[0 0],[],[],[],[],[],[],...
                @unitdisk2,options)
   ```

4 `fmincon` gives the following output:

   Local minimum found that satisfies the constraints.

   Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

   ```matlab
   x =
   0.7864   0.6177
   ```

   `fmincon` also displays the three plot functions, shown at the end of “Running the Optimization Using the Optimization Tool” on page 3-30.
Output Functions

Introduction
For some problems, you might want output from an optimization algorithm at each iteration. For example, you might want to find the sequence of points that the algorithm computes and plot those points. To do this, create an output function that the optimization function calls at each iteration. See “Output Function” on page 9-18 for details and syntax.

Generally, the solvers that can employ an output function are the ones that can take nonlinear functions as inputs. You can determine which solvers can have an output function by looking in the Options section of function reference pages, or by checking whether the Output function option is available in the Optimization Tool GUI for a solver.

Example: Using Output Functions

• “What the Example Contains” on page 3-36
• “Writing the Output Function” on page 3-37
• “Writing the Example Function File” on page 3-38
• “Running the Example” on page 3-40

What the Example Contains
The following example continues the one in “Example: Nonlinear Inequality Constraints” on page 6-47, which calls the function \texttt{fmincon} at the command line to solve a nonlinear, constrained optimization problem. The example in this section uses a function file to call \texttt{fmincon}. The file also contains all the functions needed for the example, including:

• The objective function
• The constraint function
• An output function that records the history of points computed by the algorithm for \texttt{fmincon}. At each iteration of the algorithm for \texttt{fmincon}, the output function:
Output Functions

- Plots the current point computed by the algorithm.
- Stores the point and its corresponding objective function value in a variable called `history`, and stores the current search direction in a variable called `searchdir`. The search direction is a vector that points in the direction from the current point to the next one.

The code for the file is here: “Writing the Example Function File” on page 3-38.

Writing the Output Function

You specify the output function in the `options` structure:

```matlab
options = optimset('OutputFcn', @outfun)
```

where `outfun` is the name of the output function. When you call an optimization function with `options` as an input, the optimization function calls `outfun` at each iteration of its algorithm.

In general, `outfun` can be any MATLAB function, but in this example, it is a nested subfunction of the function file described in “Writing the Example Function File” on page 3-38. The following code defines the output function:

```matlab
function stop = outfun(x, optimValues, state)
stop = false;

switch state
    case 'init'
        hold on
    case 'iter'
        % Concatenate current point and objective function value with history. x must be a row vector.
        history.fval = [history.fval; optimValues.fval];
        history.x = [history.x; x];
        % Concatenate current search direction with searchdir.
        searchdir = [searchdir;...optimValues.searchdirection'];
        plot(x(1),x(2),'o');
        % Label points with iteration number.
        text(x(1)+.15,x(2),num2str(optimValues.iteration));
```
Examining Results

```matlab
    case 'done'
        hold off
    otherwise
        end
    end
```

See “Using Function Handles with Nested Functions” in the MATLAB Programming Fundamentals documentation for more information about nested functions.

The arguments that the optimization function passes to `outfun` are:

- **x** — The point computed by the algorithm at the current iteration
- **optimValues** — Structure containing data from the current iteration
   - **optimValues.iteration** — Number of the current iteration
   - **optimValues.fval** — Current objective function value
   - **optimValues.searchdirection** — Current search direction
- **state** — The current state of the algorithm (‘init’, ‘interrupt’, ‘iter’, or ‘done’)

For more information about these arguments, see “Output Function” on page 9-18.

Writing the Example Function File

To create the function file for this example:

1. Open a new file in the MATLAB Editor.
2. Copy and paste the following code into the file:

   ```matlab
   function [history,searchdir] = runfmincon

   % Set up shared variables with OUTFUN
   history.x = [];
   history.fval = [];
   searchdir = [];
   ```
% call optimization
x0 = [-1 1];
options = optimset('outputfcn',@outfun,'display','iter',...
'Algorithm','active-set');
xsol = fmincon(@objfun,x0,[],[],[],[],[],[],@confun,options);

function stop = outfun(x,optimValues,state)
    stop = false;
    switch state
    case 'init'
        hold on
    case 'iter'
        % Concatenate current point and objective function
        % value with history. x must be a row vector.
        history.fval = [history.fval; optimValues.fval];
        history.x = [history.x; x];
        % Concatenate current search direction with
        % searchdir.
        searchdir = [searchdir;...
            optimValues.searchdirection'];
        plot(x(1),x(2),'o');
        % Label points with iteration number and add title.
        text(x(1)+.15,x(2),...
            num2str(optimValues.iteration));
        title('Sequence of Points Computed by fmincon');
    case 'done'
        hold off
    otherwise
    end
end

function f = objfun(x)
    f = exp(x(1))*(4*x(1)^2 + 2*x(2)^2 + 4*x(1)*x(2) +...
        2*x(2) + 1);
end

function [c, ceq] = confun(x)
    % Nonlinear inequality constraints
Examining Results

\[
c = [1.5 + x(1) \cdot x(2) - x(1) - x(2); \\
    -x(1) \cdot x(2) - 10];
\]
% Nonlinear equality constraints
ceq = [];

3 Save the file as runfmincon.m in a folder on the MATLAB path.

Running the Example
To run the example, enter:

\[
[\text{history searchdir}] = \text{runfmincon};
\]

This displays the following iterative output in the Command Window.

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>constraint</th>
<th>Max Line search</th>
<th>Directional First-order</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>1.8394</td>
<td>0.5</td>
<td></td>
<td>Infeasible</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>1.85127</td>
<td>-0.09197</td>
<td>1</td>
<td>0.109</td>
</tr>
<tr>
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<td>9</td>
<td>0.300167</td>
<td>9.33</td>
<td>1</td>
<td>-0.117</td>
</tr>
<tr>
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<td>12</td>
<td>0.529035</td>
<td>0.9209</td>
<td>1</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
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<td>-1.517</td>
<td>0.5</td>
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<td>-0.03303</td>
<td>1</td>
<td>-0.0542</td>
</tr>
<tr>
<td>7</td>
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<td>0.003184</td>
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<td>-0.0271</td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>0.0235504</td>
<td>9.032e-008</td>
<td>1</td>
<td>-0.0146</td>
</tr>
</tbody>
</table>

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

Active inequalities (to within options.TolCon = 1e-006):
lower upper ineqlin ineqnonlin
1
2

The output history is a structure that contains two fields:
history =

    x: [9x2 double]
   fval: [9x1 double]

The fval field contains the objective function values corresponding to the sequence of points computed by fmincon:

history.fval

ans =

    1.8394
   1.8513
    0.3002
    0.5298
    0.1870
    0.0729
    0.0353
    0.0236
    0.0236

These are the same values displayed in the iterative output in the column with header f(x).

The x field of history contains the sequence of points computed by the algorithm:

history.x

ans =

    -1.0000   1.0000
   -1.3679   1.2500
   -5.5708   3.4699
  -4.8000   2.2752
  -6.7054   1.2618
  -8.0679   1.0186
  -9.0230   1.0532
  -9.5471   1.0471
  -9.5474   1.0474
This example displays a plot of this sequence of points, in which each point is labeled by its iteration number.

The optimal point occurs at the eighth iteration. Note that the last two points in the sequence are so close that they overlap.

The second output argument, `searchdir`, contains the search directions for `fmincon` at each iteration. The search direction is a vector pointing from the point computed at the current iteration to the point computed at the next iteration:

```matlab
searchdir =
    -0.3679    0.2500
    -4.2029    2.2199
     0.7708   -1.1947
    -3.8108   -2.0268
    -1.3625   -0.2432
    -0.9552    0.0346
    -0.5241   -0.0061
    -0.0003    0.0003
```
Steps to Take After Running a Solver

- “Overview of Next Steps” on page 4-2
- “When the Solver Fails” on page 4-3
- “When the Solver Might Have Succeeded” on page 4-14
- “When the Solver Succeeds” on page 4-22
Overview of Next Steps

This chapter addresses questions you might have after running a solver. The questions include:

- Is the answer reliable?
- What can you do if the solver fails?
- Is the minimum smaller than all other minima, or only smaller than nearby minima? (“Local vs. Global Optima” on page 4-26)
- What can you do if the solver takes too long?

The list of questions is not exhaustive. It covers common or basic problems.

You can access relevant answers from many solvers’ default exit message. The first line of the exit message contains a link to a brief description of the result. This description contains a link leading to a relevant section of this chapter.
When the Solver Fails

When the Solver Fails

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Too Many Iterations or Function Evaluations

The solver stopped because it reached a limit on the number of iterations or function evaluations before it minimized the objective to the requested tolerance. To proceed, try one or more of the following.

1. Enable Iterative Display

   1. Enable Iterative Display” on page 4-3
   2. Relax Tolerances” on page 4-4
   3. Start the Solver From Different Points” on page 4-5
   4. Check Objective and Constraint Function Definitions” on page 4-5
   5. Center and Scale Your Problem” on page 4-5
   6. Provide Gradient or Jacobian” on page 4-6
   7. Provide Hessian” on page 4-7

1. Enable Iterative Display

Set the Display option to 'iter'. This setting shows the results of the solver iterations.

To enable iterative display:

- Using the Optimization Tool, choose Level of display to be iterative or iterative with detailed message.
- At the MATLAB command line, enter

  options = optimset('Display','iter');

Call the solver using the options structure.
For an example of iterative display, see “Interpreting the Result” on page 1-12.

**What to Look For in Iterative Display.**

- See if the objective function (\(F_{\text{val}}\) or \(f(x)\) or \(\text{Resnorm}\)) decreases. Decrease indicates progress.
- Examine constraint violation (\(\text{Max constraint}\)) to ensure that it decreases towards 0. Decrease indicates progress.
- See if the first-order optimality decreases towards 0. Decrease indicates progress.
- See if the Trust-region radius decreases to a small value. This decrease indicates that the objective might not be smooth.

**What to Do.**

- If the solver seemed to progress:
  1. Set \(\text{MaxIter}\) and/or \(\text{MaxFunEvals}\) to values larger than the defaults. You can see the default values in the Optimization Tool, or in the Options table in the solver’s Chapter 10, “Function Reference” pages.
  2. Start the solver from its last calculated point.
- If the solver is not progressing, try the other listed suggestions.

**2. Relax Tolerances**

If \(\text{TolX}\) or \(\text{TolFun}\), for example, are too small, the solver might not recognize when it has reached a minimum; it can make futile iterations indefinitely.

To change tolerances using the Optimization Tool, use the **Stopping criteria** list at the top of the **Options** pane.

To change tolerances at the command line, use **optimset** as described in “Setting Options” on page 2-43.

The \(\text{DiffMaxChange}\) and \(\text{DiffMinChange}\) options can affect a solver’s progress. These options control the step size in finite differencing for derivative estimation.
3. Start the Solver From Different Points
See Change the Initial Point.

4. Check Objective and Constraint Function Definitions
For example, check that your objective and nonlinear constraint functions return the correct values at some points. See Check your Objective and Constraint Functions. Check that an infeasible point does not cause an error in your functions; see “Iterations Can Violate Constraints” on page 2-30.

5. Center and Scale Your Problem
Solvers run more reliably when each coordinate has about the same effect on the objective and constraint functions. Multiply your coordinate directions with appropriate scalars to equalize the effect of each coordinate. Add appropriate values to certain coordinates to equalize their size.

Example: Centering and Scaling. Consider minimizing $1e6 \times x(1)^2 + 1e-6 \times x(2)^2$:

$$ f = @(x) 10^6 \times x(1)^2 + 10^{-6} \times x(2)^2; $$

Minimize $f$ using the medium-scale fminunc algorithm:

```matlab
opts = optimset('Display','none','LargeScale','off');
x = fminunc(f, [0.5; 0.5], opts)
x =
  0
  0.5000
```

The result is incorrect; poor scaling interfered with obtaining a good solution.

Scale the problem. Set

```matlab
D = diag([1e-3, 1e3]);
fr = @(y) f(D*y);
y = fminunc(fr, [0.5; 0.5], opts)
y =
  0
```
0 % the correct answer

Similarly, poor centering can interfere with a solution.

```matlab
fc = @(z)fr([z(1)-1e6 z(2)+1e6]); % poor centering
z = fminunc(fc,[.5 .5],opts)

z =
 1.0e+005 *
   10.0000  -10.0000 % looks good, but...

z - 1e6 % checking how close z is to 1e6
ans =
 1.0e+006 *
   -0.0000  -2.0000 % reveals quite a distance

fcc = @(w)fc([w(1)+1e6,w(2)-1e6]); % centered
w = fminunc(fcc,[.5 .5],opts)

w =
 0   0 % the correct answer
```

6. **Provide Gradient or Jacobian**

If you do not provide gradients or Jacobians, solvers estimate gradients and Jacobians by finite differences. Therefore, providing these derivatives can save computational time, and can lead to increased accuracy.

For constrained problems, providing a gradient has another advantage. A solver can reach a point $x$ such that $x$ is feasible, but finite differences around $x$ always lead to an infeasible point. In this case, a solver can fail or halt prematurely. Providing a gradient allows a solver to proceed.

Provide gradients or Jacobians in the files for your objective function and nonlinear constraint functions. For details of the syntax, see “Writing Scalar Objective Functions” on page 2-17, “Writing Vector and Matrix Objective Functions” on page 2-23, and “Nonlinear Constraints” on page 2-33.
To check that your gradient or Jacobian function is correct, use the DerivativeCheck option, as described in “Checking Validity of Gradients or Jacobians” on page 2-50.

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians programmatically. For an example, see “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.


7. **Provide Hessian**

Solvers often run more reliably and with fewer iterations when you supply a Hessian.

The following solvers and algorithms accept Hessians:

- **fmincon interior-point.** Write the Hessian as a separate function. For an example, see “Example: Constrained Minimization Using fmincon’s Interior-Point Algorithm with Analytic Hessian” on page 6-53.

- **fmincon trust-region-reflective.** Give the Hessian as the third output of the objective function. For an example, see “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68.

- **fminunc large-scale.** Give the Hessian as the third output of the objective function. For an example, see “Example: Nonlinear Minimization with Gradient and Hessian” on page 6-17.

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians programmatically. For an example, see “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.
No Feasible Point
The solver was unable to find a point satisfying all constraints to within the TolCon constraint tolerance. To proceed, try one or more of the following.

“1. Check Linear Constraints” on page 4-8
“2. Check Nonlinear Constraints” on page 4-8

1. Check Linear Constraints
Try finding a point that satisfies the bounds and linear constraints by solving a linear programming problem.

1 Define a linear programming problem with an objective function that is always zero:

\[ f = \text{zeros(size(x0))}; \% \text{assumes } x0 \text{ is the initial point} \]

2 Solve the linear programming problem to see if there is a feasible point:

\[ x\text{new} = \text{linprog}(f,A,b,Aeq,beq,lb,ub); \]

3 If there is a feasible point \( x\text{new} \), use \( x\text{new} \) as the initial point and rerun your original problem.

4 If there is no feasible point, your problem is not well-formulated. Check the definitions of your bounds and linear constraints.

2. Check Nonlinear Constraints
After ensuring that your bounds and linear constraints are feasible (contain a point satisfying all constraints), check your nonlinear constraints.

- Set your objective function to zero:

\[ @(x)0 \]

Run your optimization with the zero objective. If you find a feasible point \( x\text{new} \), set \( x0 = x\text{new} \) and rerun your original problem.

- If you do not find a feasible point using a zero objective function, use the zero objective function with several initial points.
- If you find a feasible point \( x_{\text{new}} \), set \( x_0 = x_{\text{new}} \) and rerun your original problem.
- If you do not find a feasible point, try relaxing the constraints, discussed next.

Try relaxing your nonlinear inequality constraints, then tightening them.

1 Change the nonlinear constraint function \( c \) to return \( c - \Delta \), where \( \Delta \) is a positive number. This change makes your nonlinear constraints easier to satisfy.

2 Look for a feasible point for the new constraint function, using either your original objective function or the zero objective function.

- If you find a feasible point,
  - Reduce \( \Delta \)  
  - Look for a feasible point for the new constraint function, starting at the previously found point.

- If you do not find a feasible point, try increasing \( \Delta \) and looking again.

If you find no feasible point, your problem might be truly infeasible, meaning that no solution exists. Check all your constraint definitions again.

**Problem Unbounded**
The solver reached a point whose objective function was less than the objective limit tolerance.

- Your problem might be truly unbounded. In other words, there is a sequence of points \( x_i \) with
  
  \[ \lim_{i \to \infty} f(x_i) = -\infty. \]

  and such that all the \( x_i \) satisfy the problem constraints.

- Check that your problem is formulated correctly. Solvers try to minimize objective functions; if you want a maximum, change your objective function to its negative. For an example, see “Maximizing an Objective” on page 2-27.
- Try scaling or centering your problem. See Center and Scale Your Problem.
- Relax the objective limit tolerance by using `optimset` to reduce the value of the `ObjectiveLimit` tolerance.

**fsolve Could Not Solve Equation**

`fsolve` can fail to solve an equation for various reasons. Here are some suggestions for how to proceed:

1. **Try Changing the Initial Point.** `fsolve` relies on an initial point. By giving it different initial points, you increase the chances of success.

2. **Check the definition of the equation to make sure that it is smooth.** `fsolve` might fail to converge for equations with discontinuous gradients, such as absolute value. `fsolve` can fail to converge for functions with discontinuities.

3. **Check that the equation is “square,” meaning equal dimensions for input and output (has the same number of unknowns as values of the equation).**

4. **Change tolerances, especially `TolFun` and `TolX`.** If you attempt to get high accuracy by setting tolerances to very small values, `fsolve` can fail to converge. If you set tolerances that are too high, `fsolve` can fail to solve an equation accurately.

5. **Check the problem definition.** Some problems have no real solution, such as \( x^2 + 1 = 0 \).

**Solver Takes Too Long**

Solvers can take excessive time for various reasons. To diagnose the reason, use one or more of the following techniques.

1. **Enable Iterative Display**

   Set the `Display` option to `'iter'`. This setting shows the results of the solver iterations.

   To enable iterative display:
• Using the Optimization Tool, choose **Level of display** to be **iterative** or **iterative with detailed message**.

• At the MATLAB command line, enter

\[
\text{options} = \text{optimset}('\text{Display}', '\text{iter}');
\]

Call the solver using the **options** structure.

For an example of iterative display, see “Interpreting the Result” on page 1-12. For more information, see “What to Look For in Iterative Display” on page 4-4.

2. **Enable FunValCheck**

Sometimes a solver fails because an objective function or nonlinear constraint function returns a complex value, infinity, or NaN. To halt solver iterations in these cases, enable the **FunValCheck** option.

• Using the Optimization Tool, check the box labeled **Error if user-supplied function returns Inf, NaN, or complex** in the **Function value check** pane.

• At the MATLAB command line, enter

\[
\text{options} = \text{optimset}('\text{FunValCheck}', 'on');
\]

Call the solver using the **options** structure.

3. **Use Appropriate Tolerances**

Solvers can fail to converge if tolerances are too small, especially **TolFun** and **TolX**.

To change tolerances using the Optimization Tool, use the **Stopping criteria** list at the top of the **Options** pane.

To change tolerances at the command line, use **optimset** as described in “Setting Options” on page 2-43.
4. **Use a Plot Function**

You can obtain more visual or detailed information about solver iterations using a plot function. For a list of the predefined plot functions, see Options > Plot functions in the Optimization Tool. The Options section of your solver’s function reference pages also lists the plot functions.

To use a plot function:

- Using the Optimization Tool, check the boxes next to each plot function you wish to use.
- At the MATLAB command line, enter
  
  ```matlab
  options = optimset('PlotFcns',{@plotfcn1,@plotfcn2,...});
  
  Call the solver using the options structure.
  ```

For an example of using a plot function, see “Example: Using a Plot Function” on page 3-30.

5. **Enable DerivativeCheck**

If you have supplied derivatives (gradients or Jacobians) to your solver, the solver can fail to converge if the derivatives are inaccurate. For more information about using the DerivativeCheck option, see “Checking Validity of Gradients or Jacobians” on page 2-50.

6. **Use an Output Function**

You can obtain detailed information about solver iterations using an output function. Solvers call output functions at each iteration. You write output functions using the syntax described in “Output Function” on page 9-18.

For an example of using an output function, see “Example: Using Output Functions” on page 3-36.

7. **Use a Sparse Solver or a Multiply Function**

Large problems can cause MATLAB to run out of memory or time. Here are some suggestions for using less memory:
• Use a large-scale algorithm if possible. These algorithms include trust-region-reflective algorithms, the fmincon interior-point algorithm, any LargeScale algorithm, the fsolve trust-region-dogleg algorithm, and the Levenberg-Marquardt algorithm.

Use sparse matrices for your linear constraints.

• Use a Jacobian multiply function or Hessian multiply function. For examples, see “Example: Jacobian Multiply Function with Linear Least Squares” on page 6-162, “Example: Quadratic Minimization with a Dense but Structured Hessian” on page 6-127, and “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68.

8. Use Parallel Computing
If you have a Parallel Computing Toolbox™ license, your solver might run faster using parallel computing. For more information, see Chapter 7, “Parallel Computing for Optimization”.
When the Solver Might Have Succeeded

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**Final Point Equals Initial Point**
The initial point seems to be a local minimum or solution because the first-order optimality measure is close to 0. You might be unhappy with this result, since the solver did not improve your initial point.

If you are unsure that the initial point is truly a local minimum, try:

1. Starting from different points — see Change the Initial Point.
2. Checking that your objective and constraints are defined correctly (for example, do they return the correct values at some points?) — see Check your Objective and Constraint Functions. Check that an infeasible point does not cause an error in your functions; see “Iterations Can Violate Constraints” on page 2-30.
3. Changing tolerances, such as TolFun, TolCon, and TolX — see Use Appropriate Tolerances.
4. Scaling your problem so each coordinate has about the same effect — see Rescale the Problem.
5. Providing gradient and Hessian information — see Provide Analytic Gradients or Jacobian and Provide a Hessian.

**Local Minimum Possible**
The solver might have reached a local minimum, but cannot be certain because the first-order optimality measure is not less than the TolFun tolerance. (To learn more about first-order optimality measure, see “First-Order Optimality Measure” on page 3-11.) To see if the reported solution is reliable, consider the following suggestions.

“1. Nonsmooth Functions” on page 4-15
“2. Rerun Starting At Final Point” on page 4-15
“3. Try a Different Algorithm” on page 4-16
“4. Change Tolerances” on page 4-18
“5. Rescale the Problem” on page 4-19
“6. Check Nearby Points” on page 4-19
“7. Change Finite Differencing Options” on page 4-19
“8. Provide Analytic Gradients or Jacobian” on page 4-20
“9. Provide a Hessian” on page 4-20

1. Nonsmooth Functions

If you try to minimize a nonsmooth function, or have nonsmooth constraints, “Local Minimum Possible” can be the best exit message. This is because the first-order optimality conditions do not apply at a nonsmooth point.

To satisfy yourself that the solution is adequate, try to Check Nearby Points.

2. Rerun Starting At Final Point

Restarting an optimization at the final point can lead to a solution with a better first-order optimality measure. A better (lower) first-order optimality measure gives you more reason to believe that the answer is reliable.

For example, consider the following minimization problem, taken from a demo (echodemo symbolic_optim_demo):

```matlab
options = optimset('LargeScale','off');
funh = @(x)log(1 + (x(1) - 4/3)^2 + 3*(x(2) - (x(1)^3 - x(1)))^2);
[xfinal fval exitflag] = fminunc(funh,[-1;2],options)
```

Local minimum possible.

fminunc stopped because it cannot decrease the objective function along the current search direction.

```
xfinal =
    1.3333
    1.0370
fval =
```

4-15
The exit flag value of 5 indicates that the first-order optimality measure was above the function tolerance. Run the minimization again starting from xfinal:

```matlab
[xfinal2 fval2 exitflag2] = fminunc(funh,xfinal,options)
```

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

```matlab
xfinal2 =
    1.3333
    1.0370
```

```matlab
fval2 =
    6.5281e-014
```

```matlab
exitflag2 =
    1
```

The local minimum is “found,” not “possible,” and the exitflag is 1, not 5. The two solutions are virtually identical. Yet the second run has a more satisfactory exit message, since the first-order optimality measure was low enough: 7.5996e-007, instead of 3.9674e-006.

### 3. Try a Different Algorithm

Many solvers give you a choice of algorithm. Different algorithms can lead to the use of different stopping criteria.

For example, Rerun Starting At Final Point returns exitflag 5 from the first run. This run uses the medium-scale algorithm.

The large-scale algorithm requires a user-supplied gradient. betopt.m contains a calculation of the objective function and gradient:
function [f gradf] = betopt(x)

    g = 1 + (x(1)-4/3)^2 + 3*(x(2) - (x(1)^3-x(1)))*2;
    f = log(g);
    gradf(1) = 2*(x(1)-4/3) + 6*(x(2) - (x(1)^3-x(1)))*(1-3*x(1)^2);
    gradf(1) = gradf(1)/g;
    gradf(2) = 6*(x(2) - (x(1)^3 -x(1)))/g;

Running the optimization using the large-scale algorithm results in a different exitflag:

    options = optimset('GradObj','on');
    [xfinal3 fval3 exitflag3] = fminunc(@betopt,[-1;2],options)

Local minimum possible.

fminunc stopped because the final change in function value relative to its initial value is less than the default value of the function tolerance.

    xfinal3 =
        1.3333
        1.0370

    fval3 =
        7.6659e-012

    exitflag3 =
        3

The exit condition is better than the medium-scale condition, though it is still not the best. Rerunning the algorithm from the final point produces a better point, with extremely small first-order optimality measure:

    [xfinal4 fval4 eflag4 output4] = fminunc(@betopt,xfinal3,options)

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.
4. Change Tolerances

Sometimes tightening or loosening tolerances leads to a more satisfactory result. For example, choose a smaller value of TolFun in the Try a Different Algorithm section:

```matlab
options = optimset('TolFun',1e-8,'GradObj','on'); % default=1e-6
[xfinal3 fval3 eflag3 output3] = fminunc(@betopt,[-1;2],options)
```

Local minimum found.

Optimization completed because the size of the gradient is less than the selected value of the function tolerance.

\[
\text{xfinal3} = \\
\begin{align*}
1.3333 \\
1.0370
\end{align*}
\]

\[
\text{fval3} = \\
0
\]
When the Solver Might Have Succeeded

\texttt{eflag3 = 1}

\texttt{output3 =}

\begin{verbatim}
iterations: 15
funcCount: 16
cgiterations: 12
firstorderopt: 7.5211e-011
algorithm: 'large-scale: trust-region Newton'
message: [1x500 char]
\end{verbatim}

\texttt{fminunc} took one more iteration than before, arriving at a better solution.

5. \textbf{Rescale the Problem}

Try to have each coordinate give about the same effect on the objective and constraint functions by scaling and centering. For examples, see Center and Scale Your Problem.

6. \textbf{Check Nearby Points}

Evaluate your objective function and constraints, if they exist, at points near the final point. If the final point is a local minimum, nearby feasible points have larger objective function values. See Check Nearby Points for an example.

If you have a Global Optimization Toolbox license, try running the \texttt{patternsearch} solver from the final point. \texttt{patternsearch} examines nearby points, and accepts all types of constraints.

7. \textbf{Change Finite Differencing Options}

Central finite differences are more time-consuming to evaluate, but are much more accurate. Use central differences when your problem can have high curvature.

To choose central differences at the command line, use \texttt{optimset} to set 'FinDiffType' to 'central', instead of the default 'forward'.

To choose central differences in the Optimization Tool, set \textbf{Options > Approximated derivatives > Type} to be central differences.
8. **Provide Analytic Gradients or Jacobian**

If you do not provide gradients or Jacobians, solvers estimate gradients and Jacobians by finite differences. Therefore, providing these derivatives can save computational time, and can lead to increased accuracy.

For constrained problems, providing a gradient has another advantage. A solver can reach a point \( x \) such that \( x \) is feasible, but finite differences around \( x \) always lead to an infeasible point. In this case, a solver can fail or halt prematurely. Providing a gradient allows a solver to proceed.

Provide gradients or Jacobians in the files for your objective function and nonlinear constraint functions. For details of the syntax, see “Writing Scalar Objective Functions” on page 2-17, “Writing Vector and Matrix Objective Functions” on page 2-23, and “Nonlinear Constraints” on page 2-33.

To check that your gradient or Jacobian function is correct, use the `DerivativeCheck` option, as described in “Checking Validity of Gradients or Jacobians” on page 2-50.

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians programmatically. For an example, see “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.


9. **Provide a Hessian**

Solvers often run more reliably and with fewer iterations when you supply a Hessian.

The following solvers and algorithms accept Hessians:

- `fmincon interior-point`. Write the Hessian as a separate function. For an example, see “Example: Constrained Minimization Using fmincon’s Interior-Point Algorithm with Analytic Hessian” on page 6-53.
• `fmincon trust-region-reflective`. Give the Hessian as the third output of the objective function. For an example, see “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68.

• `fminunc large-scale`. Give the Hessian as the third output of the objective function. For an example, see “Example: Nonlinear Minimization with Gradient and Hessian” on page 6-17.

If you have a Symbolic Math Toolbox license, you can calculate gradients and Hessians programmatically. For an example, see “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72.

The example in “Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72 shows `fmincon` taking 84 iterations without a Hessian, but only 26 iterations with a Hessian.
When the Solver Succeeds

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What Can Be Wrong If The Solver Succeeds?
A solver can report that a minimization succeeded, and yet the reported solution can be incorrect. For a rather trivial example, consider minimizing the function \( f(x) = x^3 \) for \( x \) between –2 and 2, starting from the point \( 1/3 \):

```matlab
options = optimset('Algorithm','active-set');
ffun = @(x)x^3;
xfinal = fmincon(ffun,1/3,[],[],[],[],-2,2,[],options)
```

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints were satisfied to within the default value of the constraint tolerance.

No active inequalities.

```matlab
xfinal =
-1.5056e-008
```

The true minimum occurs at \( x = -2 \). `fmincon` gives this report because the function \( f(x) \) is so flat near \( x = 0 \).

Another common problem is that a solver finds a local minimum, but you might want a global minimum. For more information, see “Local vs. Global Optima” on page 4-26.
Lesson: check your results, even if the solver reports that it “found” a local minimum, or “solved” an equation.

This section gives techniques for verifying results.

1. **Change the Initial Point**

The initial point can have a large effect on the solution. If you obtain the same or worse solutions from various initial points, you become more confident in your solution.

For example, minimize \( f(x) = x^3 + x^4 \) starting from the point 1/4:

```matlab
ffun = @(x)x^3 + x^4;
options = optimset('LargeScale','off');
[xfinal fval] = fminunc(ffun,1/4,options)
```

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

\[
x =
\begin{align*}
-1.6764e-008
\end{align*}
\]

\[
fval =
\begin{align*}
-4.7111e-024
\end{align*}
\]

Change the initial point by a small amount, and the solver finds a better solution:

```
[xfinal fval] = fminunc(ffun,1/4+.001,options)
```

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

\[
xfinal =
\begin{align*}
-0.7500
\end{align*}
\]
Steps to Take After Running a Solver

4

Steps to Take After Running a Solver

fval =
  -0.1055

x = -0.75 is the global solution; starting from other points cannot improve the solution.

For more information, see “Local vs. Global Optima” on page 4-26.

2. Check Nearby Points

to see if there are better values than a reported solution, evaluate your objective function and constraints at various nearby points.

For example, with the objective function ffun from “What Can Be Wrong If The Solver Succeeds?” on page 4-22, and the final point xfinal = -1.5056e-008, calculate ffun(xfinal–) for some δ:

delta = .1;
[ffun(xfinal),ffun(xfinal+delta),ffun(xfinal-delta)]

ans =
  -0.0000  0.0011 -0.0009

The objective function is lower at ffun(xfinal–), so the solver reported an incorrect solution.

A less trivial example:

    options = optimset('Algorithm','active-set');
    lb = [0,-1]; ub = [1,1];
    ffun = @(x)(x(1)-(x(1)-x(2))^2);
    [x fval exitflag] = fmincon(ffun,[1/2 1/3],[],[],[],...
                                lb,ub,[],options)

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints were satisfied to within the default value of the constraint tolerance.
Active inequalities (to within options.TolCon = 1e-006):
  lower  upper  ineqlin  ineqnonlin
    1

x =
  1.0e-007 *
     0    0.1614

fval =
  -2.6059e-016

exitflag =
      1

Evaluating ffun at nearby feasible points shows that the solution x is not a true minimum:

[ffun([0,.001]),ffun([0,-.001]),...
  ffun([.001,-.001]),ffun([.001,.001])]

ans =
  1.0e-003 *
     -0.0010   -0.0010   0.9960   1.0000

The first two listed values are smaller than the computed minimum fval.

If you have a Global Optimization Toolbox license, you can use the patternsearch function to check nearby points.

3. Check your Objective and Constraint Functions

Double-check your objective function and constraint functions to ensure that they correspond to the problem you intend to solve. Suggestions:

- Check the evaluation of your objective function at a few points.
- Check that each inequality constraint has the correct sign.
- If you performed a maximization, remember to take the negative of the reported solution. (This advice assumes that you maximized a function
by minimizing the negative of the objective.) For example, to maximize \( f(x) = x - x^2 \), minimize \( g(x) = -x + x^2 \):

```matlab
options = optimset('LargeScale','off');
[x fval] = fminunc(@(x)-x+x^2,0,options)
```

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.

```matlab
x =
    0.5000
fval =
   -0.2500
```

The maximum of \( f \) is 0.25, the negative of \( fval \).

- Check that an infeasible point does not cause an error in your functions; see “Iterations Can Violate Constraints” on page 2-30.

**Local vs. Global Optima**

- “Why Didn’t the Solver Find the Smallest Minimum?” on page 4-26
- “Searching for a Smaller Minimum” on page 4-27
- “Basins of Attraction” on page 4-28

**Why Didn’t the Solver Find the Smallest Minimum?**

In general, solvers return a local minimum. The result might be a global minimum, but there is no guarantee that it is. This section describes why solvers behave this way, and gives suggestions for ways to search for a global minimum, if needed.

- A *local* minimum of a function is a point where the function value is smaller than at nearby points, but possibly greater than at a distant point.

- A *global* minimum is a point where the function value is smaller than at all other feasible points.
Generally, Optimization Toolbox solvers find a local optimum. (This local optimum can be a global optimum.) They find the optimum in the basin of attraction of the starting point. For more information about basins of attraction, see “Basins of Attraction” on page 4-28.

There are some exceptions to this general rule.

- Linear programming and positive definite quadratic programming problems are convex, with convex feasible regions, so there is only one basin of attraction. Indeed, under certain choices of options, \texttt{linprog} ignores any user-supplied starting point, and \texttt{quadprog} does not require one, though supplying one can sometimes speed a minimization.

- Global Optimization Toolbox functions, such as \texttt{simulannealbnd}, attempt to search more than one basin of attraction.

**Searching for a Smaller Minimum**

If you need a global optimum, you must find an initial value for your solver in the basin of attraction of a global optimum.

Suggestions for ways to set initial values to search for a global optimum:

- Use a regular grid of initial points.

- Use random points drawn from a uniform distribution if your problem has all its coordinates bounded. Use points drawn from normal, exponential, or other random distributions if some components are unbounded. The less you know about the location of the global optimum, the more spread-out your random distribution should be. For example, normal distributions rarely sample more than three standard deviations away from their means, but a Cauchy distribution (density \(1/( (1 + x^2))\)) makes hugely disparate samples.
• Use identical initial points with added random perturbations on each coordinate, bounded, normal, exponential, or other.

• If you have a Global Optimization Toolbox license, use the `GlobalSearch` or `MultiStart` solvers. These solvers automatically generate random start points within bounds.

The more you know about possible initial points, the more focused and successful your search will be.

**Basins of Attraction**

If an objective function $f(x)$ is smooth, the vector $-\nabla f(x)$ points in the direction where $f(x)$ decreases most quickly. The equation of steepest descent, namely

$$\frac{d}{dt} x(t) = -\nabla f(x(t)),$$

yields a path $x(t)$ that goes to a local minimum as $t$ gets large. Generally, initial values $x(0)$ that are near to each other give steepest descent paths that tend to the same minimum point. The *basin of attraction* for steepest descent is the set of initial values that lead to the same local minimum.

The following figure shows two one-dimensional minima. The figure shows different basins of attraction with different line styles, and shows directions of steepest descent with arrows. For this and subsequent figures, black dots represent local minima. Every steepest descent path, starting at a point $x(0)$, goes to the black dot in the basin containing $x(0)$.
The following figure shows how steepest descent paths can be more complicated in more dimensions.

One basin of attraction, showing steepest descent paths from various starting points

The following figure shows even more complicated paths and basins of attraction.
Several basins of attraction

Constraints can break up one basin of attraction into several pieces. For example, consider minimizing $y$ subject to:

- $y \geq |x|$
- $y \geq 5 - 4(x-2)^2$.

The figure shows the two basins of attraction with the final points.
When the Solver Succeeds

The steepest descent paths are straight lines down to the constraint boundaries. From the constraint boundaries, the steepest descent paths travel down along the boundaries. The final point is either (0,0) or (11/4,11/4), depending on whether the initial x-value is above or below 2.
Steps to Take After Running a Solver
Graphical Optimization Tool

- “Getting Started with the Optimization Tool” on page 5-2
- “Running a Problem in the Optimization Tool” on page 5-6
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- “Importing and Exporting Your Work” on page 5-17
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Getting Started with the Optimization Tool

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**Introduction**

The Optimization Tool is a GUI for solving optimization problems. With the Optimization Tool, you select a solver from a list and set up your problem visually. If you are familiar with the optimization problem you want to solve, the Optimization Tool lets you select a solver, specify the optimization options, and run your problem. You can also import and export data from the MATLAB workspace, and generate files containing your configuration for the solver and options.

**Opening the Optimization Tool**

To open the tool, type

```
optimtool
```

in the Command Window. This opens the Optimization Tool, as shown in the following figure.
You can also open the Optimization Tool from the main MATLAB window as pictured:

The reference page for the Optimization Tool provides variations for starting the `optimtool` function.
Steps for Using the Optimization Tool
This is a summary of the steps to set up your optimization problem and view results with the Optimization Tool.

1. Select solver and algorithm
2. Specify function to minimize
3. Set problem parameters for selected solver
4. Specify options
5. Run solver
6. View solver status and results
7. Import and export problem, options, and results
Running a Problem in the Optimization Tool

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Introduction

After defining your problem and specifying the options, you are ready to run the solver.

To run the selected solver, click the Start button. For most solvers, as the algorithm runs, the Current iteration field updates. This field does not update for solvers for which the current iteration does not apply.
Pausing and Stopping the Algorithm
While the algorithm is running, you can

- Click **Pause** to temporarily suspend the algorithm. To resume the algorithm using the current iteration at the time you paused, click **Resume**.
- Click **Stop** to stop the algorithm. The **Run solver and view results** window displays information for the current iteration at the moment you clicked **Stop**.

You can export your results after stopping the algorithm. For details, see “Exporting Your Work” on page 5-17.

Viewing Results
When the algorithm terminates, the **Run solver and view results** window displays the reason the algorithm terminated. To clear the **Run solver and view results** window between runs, click **Clear Results**.

Sorting the Displayed Results
Depending on the solver and problem, results can be in the form of a table. If the table has multiple rows, sort the table by clicking a column heading. Click the heading again to sort the results in reverse.

For example, suppose you use the Optimization Tool to solve the **bintprog** problem described in “Example: Investments with Constraints” on page 6-140. The result appears as follows.
To sort the results by value, from lowest to highest, click **Value**.
To sort the results in reverse order, highest to lowest, click **Value** again.
To return to the original order, click **Index**. For an example of sorting a table returned by the Global Optimization Toolbox `gamultiobj` function, see “Example: Multiobjective Optimization”.

If you export results using **File > Export to Workspace**, the exported results do not depend on the sorted display.

**Displaying Plots**

In addition to the **Run solver and view results** window, you can also display measures of progress while the algorithm executes by generating plots. Each plot selected draws a separate axis in the figure window. You can select a predefined plot function from the Optimization Tool, or you can write your own. For more information on which plot functions are available, see “Plot Functions” on page 5-13.
Final Point
The Final point updates to show the coordinates of the final point when the algorithm terminated. If you don’t see the final point, click the upward-pointing triangle on the icon on the lower-left.

Starting a New Problem

Resetting Options and Clearing the Problem
Selecting File > Reset Optimization Tool resets the problem definition and options to the original default values. This action is equivalent to closing and restarting the optimtool.

To clear only the problem definition, select File > Clear Problem Fields. With this action, fields in the Problem Setup and Results pane are reset to the defaults, with the exception of the selected solver and algorithm choice. Any options that you have modified from the default values in the Options pane are not reset with this action.

Setting Preferences for Changing Solvers
To modify how your options are handled in the Optimization Tool when you change solvers, select File > Preferences, which opens the Preferences dialog box shown below.

![Preferences Dialog Box](image)
The default value, **Reset options to defaults**, discards any options you specified previously in the `optimtool`. Under this choice, you can select the option **Prompt before resetting options to defaults**.

Alternatively, you can select **Keep current options if possible** to preserve the values you have modified. Changed options that are not valid with the newly selected solver are kept but not used, while active options relevant to the new solver selected are used. This choice allows you to try different solvers with your problem without losing your options.

### Closing the Optimization Tool

To close the `optimtool` window, select **File > Close**.
Specifying Certain Options

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Plot Functions
You can select a plot function to easily plot various measures of progress while the algorithm executes. Each plot selected draws a separate axis in the figure window. If available for the solver selected, the Stop button in the Run solver and view results window to interrupt a running solver. You can select a predefined plot function from the Optimization Tool, or you can select Custom function to write your own. Plot functions not relevant to the solver selected are grayed out. The following lists the available plot functions:

- **Current point** — Select to show a bar plot of the point at the current iteration.
- **Function count** — Select to plot the number of function evaluations at each iteration.
- **Function value** — Select to plot the function value at each iteration.
- **Norm of residuals** — Select to show a bar plot of the current norm of residuals at the current iteration.
- **Max constraint** — Select to plot the maximum constraint violation value at each iteration.
- **Current step** — Select to plot the algorithm step size at each iteration.
- **First order optimality** — Select to plot the violation of the optimality conditions for the solver at each iteration.
- **Custom function** — Enter your own plot function as a function handle. To provide more than one plot function use a cell array, for example, by typing:

  `{@plotfcn,@plotfcn2}`
Write custom plot functions with the same syntax as output functions. For information, see “Output Function” on page 9-18.

The graphic above shows the plot functions available for the default \texttt{fmincon} solver.

**Output function**

\textbf{Output function} is a function or collection of functions the algorithm calls at each iteration. Through an output function you can observe optimization quantities such as function values, gradient values, and current iteration. Specify no output function, a single output function using a function handle, or multiple output functions. To provide more than one output function use a cell array of function handles in the \textbf{Custom function} field, for example by typing:

\{\texttt{@outputfcn,@outputfcn2}\}

For more information on writing an output function, see “Output Function” on page 9-18.

**Display to Command Window**

Select \textbf{Level of display} to specify the amount of information displayed when you run the algorithm. Choose from the following; depending on the solver, only some may be available:
• **off** (default) — Display no output.

• **final** — Display the reason for stopping at the end of the run.

• **final with detailed message** — Display the detailed reason for stopping at the end of the run.

• **notify** — Display output only if the function does not converge.

• **notify with detailed message** — Display a detailed output only if the function does not converge.

• **iterative** — Display information at each iteration of the algorithm and the reason for stopping at the end of the run.

• **iterative with detailed message** — Display information at each iteration of the algorithm and the detailed reason for stopping at the end of the run.

See “Enhanced Exit Messages” on page 3-5 for information on detailed messages.

Set **Node interval**, with the **bintprog** solver selected, to specify the interval of explored nodes you want to display output for. Note that integer feasible solution nodes are always shown.

Selecting **Show diagnostics** lists problem information and options that have changed from the defaults.

The graphic below shows the display options.
Getting Help in the Optimization Tool

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**Quick Reference**
The Optimization Tool provides extensive context-sensitive help directly in the GUI.

For assistance with the primary tasks in the Optimization Tool window, use the **Quick Reference** pane. To toggle between displaying or hiding the **Quick Reference** pane, do either of the following:

- Select **Help > Show Quick Reference**
- Click the `>` or `<` buttons in the upper right of the GUI

To resize the **Quick Reference** pane, drag the vertical divider to the left or to the right.

**Additional Help**
In addition to the **Quick Reference** pane, you can access the documentation for the Optimization Tool by selecting **Help > Optimization Tool Help**.
Importing and Exporting Your Work

In this section...

“Exporting Your Work” on page 5-17
“Importing Your Work” on page 5-19
“Generating a File” on page 5-19

Exporting Your Work

The Export to Workspace dialog box enables you to send your problem information to the MATLAB workspace as a structure that you may then manipulate in the Command Window.

To access the Export to Workspace dialog box shown below, select File > Export to Workspace.

You can specify a structure that contains:

- The problem and options information
- The problem and options information, and the state of the solver when stopped (this means the latest point for most solvers, the current population for Genetic Algorithms solvers, and the best point found for the Simulated Annealing solver)
• The states of random number generators rand and randn at the start of the previous run, by checking the Use random states from previous run box for applicable solvers

• The options information only

• The results of running your problem in optimtool

Exported results structures contain all optional information. For example, an exported results structure for lsqcurvefit contains the data x, resnorm, residual, exitflag, output, lambda, and jacobian.

After you have exported information from the Optimization Tool to the MATLAB workspace, you can see your data in the MATLAB Workspace browser or by typing the name of the structure at the Command Window. To see the value of a field in a structure, double-click on the structure in the Workspace window. Alternatively, see the values by entering structurename.fieldname at the command line. For example, so see the message in an output structure, enter output.message. If a structure contains structures, you can double-click again in the workspace browser, or enter structure1.structure2.fieldname at the command line. For example, to see the level of iterative display contained in the options structure of an exported problem structure, enter optimproblem.options.Display.

You can run a solver on an exported problem at the command line by typing

    solver(problem)

For example, if you have exported a fmincon problem named optimproblem, you can type

    fmincon(optimproblem)

This runs fmincon on the problem with the saved options structure contained in optimproblem. You can exercise more control over outputs by typing, for example,

    [x,fval,exitflag] = fmincon(optimproblem)

or use any other supported syntax.
Importing Your Work

Whether you saved options from Optimization Toolbox functions at the Command Window or if you exported options, or the problem and options, from the optimtool, you can resume work on your problem using the optimtool.

There are three ways to import your options, or problem and options, to optimtool.

- Call the optimtool function from the Command Window specifying your options, or problem and options, as the input, for example,

  optimtool(options)

- Select File > Import Options in the Optimization Tool.
- Select File > Import Problem in the Optimization Tool.

The methods described above require that the options, or problem and options, be present in the MATLAB workspace.

If you import a problem that was generated with the Include information needed to resume this run box checked, the initial point is the latest point generated in the previous run. (For Genetic Algorithm solvers, the initial population is the latest population generated in the previous run. For the Simulated Annealing solver, the initial point is the best point generated in the previous run.) If you import a problem that was generated with this box unchecked, the initial point (or population) is the initial point (or population) of the previous run.

Generating a File

You may want to generate a file to continue with your optimization problem in the Command Window at another time. You can run the file without modification to recreate the results that you created with the Optimization Tool. You can also edit and modify the file and run it from the Command Window.

To export data from the Optimization Tool to a file, select File > Generate Code.
The generated file captures the following:

- The problem definition, including the solver, information on the function to be minimized, algorithm specification, constraints, and start point
- The options (using `optimset`) with the currently selected option value

Running the file at the Command Window reproduces your problem results.

Although you cannot export your problem results to a generated file, you can save them in a MAT-file that you can use with your generated file, by exporting the results using the Export to Workspace dialog box, then saving the data to a MAT-file from the Command Window.


### Optimization Tool Examples

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### About Optimization Tool Examples

This section contains two examples showing how to use the Optimization Tool to solve representative problems. There are other examples available:


### Optimization Tool with the fmincon Solver

This example shows how to use the Optimization Tool with the `fmincon` solver to minimize a quadratic subject to linear and nonlinear constraints and bounds.

Consider the problem of finding \([x_1, x_2]\) that solves

\[
\min_x f(x) = x_1^2 + x_2^2
\]

subject to the constraints

\[
\begin{aligned}
0.5 &\leq x_1 & \quad \text{(bound)} \\
-x_1 - x_2 + 1 &\leq 0 & \quad \text{(linear inequality)} \\
-x_1^2 - x_2^2 + 1 &\leq 0 \quad \text{(linear inequality)} \\
-9x_1^2 - x_2^2 + 9 &\leq 0 & \quad \text{(nonlinear inequality)} \\
-x_1^2 + x_2 &\leq 0 \\
-x_2^2 + x_1 &\leq 0
\end{aligned}
\]
The starting guess for this problem is $x_1 = 3$ and $x_2 = 1$.

**Step 1: Write a file objecfun.m for the objective function.**

```matlab
function f = objecfun(x)
f = x(1)^2 + x(2)^2;
```

**Step 2: Write a file nonlconstr.m for the nonlinear constraints.**

```matlab
function [c,ceq] = nonlconstr(x)
c = [-x(1)^2 - x(2)^2 + 1;
    -9*x(1)^2 - x(2)^2 + 9;
    -x(1)^2 + x(2);
    -x(2)^2 + x(1)];
ceq = [];
```

**Step 3: Set up and run the problem with the Optimization Tool.**

1. Enter `optimtool` in the Command Window to open the Optimization Tool.

2. Select `fmincon` from the selection of solvers and change the **Algorithm** field to **Active set**.

3. Enter `@objecfun` in the **Objective function** field to call the `objecfun.m` file.

4. Enter `[3; 1]` in the **Start point** field.
5 Define the constraints.

- Set the bound \(0.5 \leq x_1\) by entering 0.5 in the **Lower** field.
- Set the linear inequality constraint by entering \([-1 -1]\) in the **A** field and enter -1 in the **b** field.
- Set the nonlinear constraints by entering @nonlconstr in the **Nonlinear constraint function** field.

6 In the **Options** pane, expand the **Display to command window** option if necessary, and select **Iterative** to show algorithm information at the Command Window for each iteration.

7 Click the **Start** button as shown in the following figure.

8 When the algorithm terminates, under **Run solver and view results** the following information is displayed:
• The **Current iteration** value when the algorithm terminated, which for this example is 7.

• The final value of the objective function when the algorithm terminated:

  Objective function value: 2.0000000268595803

• The algorithm termination message:

  Local minimum found that satisfies the constraints.

  Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

• The final point, which for this example is

  1
In the Command Window, the algorithm information is displayed for each iteration:

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Max constraint</th>
<th>Line search steplength</th>
<th>Max Directional derivative</th>
<th>First-order optimality</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>-5.22</td>
<td>1</td>
<td>1.74</td>
<td>Infeasible start point</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>4.84298</td>
<td>-0.1322</td>
<td>1</td>
<td>-4.39</td>
<td>4.08</td>
<td>Hessian modified twice</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>4.0251</td>
<td>-0.01168</td>
<td>1</td>
<td>-3.85</td>
<td>1.09</td>
<td>Hessian modified twice</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>2.42704</td>
<td>-0.03214</td>
<td>1</td>
<td>-3.04</td>
<td>0.995</td>
<td>Hessian modified twice</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>2.03615</td>
<td>-0.004728</td>
<td>1</td>
<td>-2.82</td>
<td>0.0664</td>
<td>Hessian modified twice</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>2.00033</td>
<td>-5.596e-005</td>
<td>1</td>
<td>-2.81</td>
<td>0.000522</td>
<td>Hessian modified twice</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>2</td>
<td>-5.327e-009</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

Active inequalities (to within options.TolCon = 1e-006):

<table>
<thead>
<tr>
<th>lower</th>
<th>upper</th>
<th>ineqlin</th>
<th>ineqnonlin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference


Optimization Tool with the lsqlin Solver

This example shows how to use the Optimization Tool to solve a constrained least-squares problem.
The Problem
The problem in this example is to find the point on the plane \( x_1 + 2x_2 + 4x_3 = 7 \) that is closest to the origin. The easiest way to solve this problem is to minimize the square of the distance from a point \( x = (x_1, x_2, x_3) \) on the plane to the origin, which returns the same optimal point as minimizing the actual distance. Since the square of the distance from an arbitrary point \( (x_1, x_2, x_3) \) to the origin is \( x_1^2 + x_2^2 + x_3^2 \), you can describe the problem as follows:

\[
\min_{x} f(x) = x_1^2 + x_2^2 + x_3^2,
\]

subject to the constraint

\[ x_1 + 2x_2 + 4x_3 = 7. \]

The function \( f(x) \) is called the objective function and \( x_1 + 2x_2 + 4x_3 = 7 \) is an equality constraint. More complicated problems might contain other equality constraints, inequality constraints, and upper or lower bound constraints.

Setting Up the Problem
This section shows how to set up the problem with the \texttt{lsqlin} solver in the Optimization Tool.

1 Enter \texttt{optimtool} in the Command Window to open the Optimization Tool.

2 Select \texttt{lsqlin} from the selection of solvers. Use the default large-scale algorithm.

3 Enter the following to create variables for the objective function:
   - In the \texttt{C} field, enter \texttt{eye(3)}.
   - In the \texttt{d} field, enter \texttt{zeros(3,1)}.

The \texttt{C} and \texttt{d} fields should appear as shown in the following figure.
4 Enter the following to create variables for the equality constraints:
   • In the \texttt{Aeq} field, enter \([1 \ 2 \ 4]\).
   • In the \texttt{beq} field, enter 7.

The \texttt{Aeq} and \texttt{beq} fields should appear as shown in the following figure.

5 Click the \textbf{Start} button as shown in the following figure.

6 When the algorithm terminates, under \textbf{Run solver and view results} the following information is displayed:
• The **Current iteration** value when the algorithm terminated, which for this example is 1.

• The final value of the objective function when the algorithm terminated:

  \[
  \text{Objective function value: } 2.3333333333333333
  \]

• The algorithm termination message:

  \[
  \text{Optimization terminated.}
  \]

• The final point, which for this example is

  \[
  \begin{align*}
  0.3333 \\
  0.6667 \\
  1.3333
  \end{align*}
  \]
Optimization Algorithms and Examples

- “Optimization Theory Overview” on page 6-2
- “Unconstrained Nonlinear Optimization Algorithms” on page 6-3
- “Unconstrained Nonlinear Optimization Examples” on page 6-15
- “Constrained Nonlinear Optimization Algorithms” on page 6-21
- “Constrained Nonlinear Optimization Examples” on page 6-47
- “Linear Programming Algorithms” on page 6-94
- “Linear Programming Examples” on page 6-107
- “Quadratic Programming Algorithms” on page 6-111
- “Quadratic Programming Examples” on page 6-125
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- “Binary Integer Programming Examples” on page 6-140
- “Least Squares (Model Fitting) Algorithms” on page 6-145
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- “Selected Bibliography” on page 6-202
Optimization Theory Overview

Optimization techniques are used to find a set of design parameters, \( x = \{x_1, x_2, \ldots, x_n\} \), that can in some way be defined as optimal. In a simple case this might be the minimization or maximization of some system characteristic that is dependent on \( x \). In a more advanced formulation the objective function, \( f(x) \), to be minimized or maximized, might be subject to constraints in the form of equality constraints, \( G_i(x) = 0 \) (\( i = 1, \ldots, m_e \)); inequality constraints, \( G_i(x) \leq 0 \) (\( i = m_e + 1, \ldots, m \)); and/or parameter bounds, \( x_l, x_u \).

A General Problem (GP) description is stated as

$$\min_{x} f(x),$$  \hspace{1cm} (6-1)

subject to

\[
G_i(x) = 0 \quad i = 1, \ldots, m_e,
\]
\[
G_i(x) \leq 0 \quad i = m_e + 1, \ldots, m,
\]

where \( x \) is the vector of length \( n \) design parameters, \( f(x) \) is the objective function, which returns a scalar value, and the vector function \( G(x) \) returns a vector of length \( m \) containing the values of the equality and inequality constraints evaluated at \( x \).

An efficient and accurate solution to this problem depends not only on the size of the problem in terms of the number of constraints and design variables but also on characteristics of the objective function and constraints. When both the objective function and the constraints are linear functions of the design variable, the problem is known as a Linear Programming (LP) problem. Quadratic Programming (QP) concerns the minimization or maximization of a quadratic objective function that is linearly constrained. For both the LP and QP problems, reliable solution procedures are readily available. More difficult to solve is the Nonlinear Programming (NP) problem in which the objective function and constraints can be nonlinear functions of the design variables. A solution of the NP problem generally requires an iterative procedure to establish a direction of search at each major iteration. This is usually achieved by the solution of an LP, a QP, or an unconstrained subproblem.
Unconstrained Nonlinear Optimization Algorithms

In this section...

“Definition” on page 6-3
“Large Scale fminunc Algorithm” on page 6-3
“Medium Scale fminunc Algorithm” on page 6-6
“fminsearch Algorithm” on page 6-12

Definition
Unconstrained minimization is the problem of finding a vector $x$ that is a local minimum to a scalar function $f(x)$:

$$\min_{x} f(x)$$

The term *unconstrained* means that no restriction is placed on the range of $x$.

Large Scale fminunc Algorithm

Trust-Region Methods for Nonlinear Minimization
Many of the methods used in Optimization Toolbox solvers are based on *trust regions*, a simple yet powerful concept in optimization.

To understand the trust-region approach to optimization, consider the unconstrained minimization problem, minimize $f(x)$, where the function takes vector arguments and returns scalars. Suppose you are at a point $x$ in $n$-space and you want to improve, i.e., move to a point with a lower function value. The basic idea is to approximate $f$ with a simpler function $q$, which reasonably reflects the behavior of function $f$ in a neighborhood $N$ around the point $x$. This neighborhood is the trust region. A trial step $s$ is computed by minimizing (or approximately minimizing) over $N$. This is the trust-region subproblem,
The key questions in defining a specific trust-region approach to minimizing \( f(x) \) are how to choose and compute the approximation \( q \) (defined at the current point \( x \)), how to choose and modify the trust region \( N \), and how accurately to solve the trust-region subproblem. This section focuses on the unconstrained problem. Later sections discuss additional complications due to the presence of constraints on the variables.

In the standard trust-region method ([48]), the quadratic approximation \( q \) is defined by the first two terms of the Taylor approximation to \( F \) at \( x \); the neighborhood \( N \) is usually spherical or ellipsoidal in shape. Mathematically the trust-region subproblem is typically stated

\[
\min \left\{ \frac{1}{2} s^T H s + s^T g \text{ such that } \|Ds\| \leq \Delta \right\},
\]

(6-3)

where \( g \) is the gradient of \( f \) at the current point \( x \), \( H \) is the Hessian matrix (the symmetric matrix of second derivatives), \( D \) is a diagonal scaling matrix, \( \Delta \) is a positive scalar, and \( \| \cdot \| \) is the 2-norm. Good algorithms exist for solving Equation 6-3 (see [48]); such algorithms typically involve the computation of a full eigensystem and a Newton process applied to the secular equation

\[
\frac{1}{\Delta} - \frac{1}{\|s\|} = 0.
\]

Such algorithms provide an accurate solution to Equation 6-3. However, they require time proportional to several factorizations of \( H \). Therefore, for large-scale problems a different approach is needed. Several approximation and heuristic strategies, based on Equation 6-3, have been proposed in the literature ([42] and [50]). The approximation approach followed in Optimization Toolbox solvers is to restrict the trust-region subproblem to a two-dimensional subspace \( S \) ([39] and [42]). Once the subspace \( S \) has been computed, the work to solve Equation 6-3 is trivial even if full.
eigenvalue/eigenvector information is needed (since in the subspace, the problem is only two-dimensional). The dominant work has now shifted to the determination of the subspace.

The two-dimensional subspace $S$ is determined with the aid of a preconditioned conjugate gradient process described below. The solver defines $S$ as the linear space spanned by $s_1$ and $s_2$, where $s_1$ is in the direction of the gradient $g$, and $s_2$ is either an approximate Newton direction, i.e., a solution to

$$H \cdot s_2 = -g,$$  \hspace{1cm} (6-4)

or a direction of negative curvature,

$$s_2^T H \cdot s_2 < 0.$$ \hspace{1cm} (6-5)

The philosophy behind this choice of $S$ is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence (via the Newton step, when it exists).

A sketch of unconstrained minimization using trust-region ideas is now easy to give:

1. Formulate the two-dimensional trust-region subproblem.
2. Solve Equation 6-3 to determine the trial step $s$.
3. If $f(x + s) < f(x)$, then $x = x + s$.
4. Adjust $\Delta$.

These four steps are repeated until convergence. The trust-region dimension $\Delta$ is adjusted according to standard rules. In particular, it is decreased if the trial step is not accepted, i.e., $f(x + s) \geq f(x)$. See [46] and [49] for a discussion of this aspect.

Optimization Toolbox solvers treat a few important special cases of $f$ with specialized functions: nonlinear least-squares, quadratic functions, and linear least-squares. However, the underlying algorithmic ideas are the same as for the general case. These special cases are discussed in later sections.
Preconditioned Conjugate Gradient Method

A popular way to solve large symmetric positive definite systems of linear equations $H p = -g$ is the method of Preconditioned Conjugate Gradients (PCG). This iterative approach requires the ability to calculate matrix-vector products of the form $H v$ where $v$ is an arbitrary vector. The symmetric positive definite matrix $M$ is a preconditioner for $H$. That is, $M = C^2$, where $C^{-1} H C^{-1}$ is a well-conditioned matrix or a matrix with clustered eigenvalues.

In a minimization context, you can assume that the Hessian matrix $H$ is symmetric. However, $H$ is guaranteed to be positive definite only in the neighborhood of a strong minimizer. Algorithm PCG exits when a direction of negative (or zero) curvature is encountered, i.e., $d^T H d \leq 0$. The PCG output direction, $p$, is either a direction of negative curvature or an approximate ($tol$ controls how approximate) solution to the Newton system $H p = -g$. In either case $p$ is used to help define the two-dimensional subspace used in the trust-region approach discussed in “Trust-Region Methods for Nonlinear Minimization” on page 6-3.

Medium Scale fminunc Algorithm

Basics of Unconstrained Optimization

Although a wide spectrum of methods exists for unconstrained optimization, methods can be broadly categorized in terms of the derivative information that is, or is not, used. Search methods that use only function evaluations (e.g., the simplex search of Nelder and Mead [30]) are most suitable for problems that are not smooth or have a number of discontinuities. Gradient methods are generally more efficient when the function to be minimized is continuous in its first derivative. Higher order methods, such as Newton’s method, are only really suitable when the second-order information is readily and easily calculated, because calculation of second-order information, using numerical differentiation, is computationally expensive.

Gradient methods use information about the slope of the function to dictate a direction of search where the minimum is thought to lie. The simplest of these is the method of steepest descent in which a search is performed in a direction, $-\nabla f(x)$, where $\nabla f(x)$ is the gradient of the objective function. This method is very inefficient when the function to be minimized has long narrow valleys as, for example, is the case for Rosenbrock’s function.
Unconstrained Nonlinear Optimization Algorithms

\[ f(x) = 100\left(x_2 - x_1^2\right)^2 + (1 - x_1)^2. \]  

(6-6)

The minimum of this function is at \( x = [1,1] \), where \( f(x) = 0 \). A contour map of this function is shown in the figure below, along with the solution path to the minimum for a steepest descent implementation starting at the point \([-1.9,2]\). The optimization was terminated after 1000 iterations, still a considerable distance from the minimum. The black areas are where the method is continually zigzagging from one side of the valley to another. Note that toward the center of the plot, a number of larger steps are taken when a point lands exactly at the center of the valley.

![Figure 6-1: Steepest Descent Method on Rosenbrock’s Function (Equation 6-6)](image)

This function, also known as the banana function, is notorious in unconstrained examples because of the way the curvature bends around the origin. Rosenbrock’s function is used throughout this section to illustrate the use of a variety of optimization techniques. The contours have been plotted in exponential increments because of the steepness of the slope surrounding the U-shaped valley.
For an animated version of this figure, enter `bandem` at the MATLAB command line.

**Quasi-Newton Methods**

Of the methods that use gradient information, the most favored are the quasi-Newton methods. These methods build up curvature information at each iteration to formulate a quadratic model problem of the form

\[
\min_x \frac{1}{2} x^T H x + c^T x + b,
\]

where the Hessian matrix, \( H \), is a positive definite symmetric matrix, \( c \) is a constant vector, and \( b \) is a constant. The optimal solution for this problem occurs when the partial derivatives of \( x \) go to zero, i.e.,

\[
\nabla f(x^*) = Hx^* + c = 0.
\]

The optimal solution point, \( x^* \), can be written as

\[
x^* = -H^{-1}c.
\]

Newton-type methods (as opposed to quasi-Newton methods) calculate \( H \) directly and proceed in a direction of descent to locate the minimum after a number of iterations. Calculating \( H \) numerically involves a large amount of computation. Quasi-Newton methods avoid this by using the observed behavior of \( f(x) \) and \( \nabla f(x) \) to build up curvature information to make an approximation to \( H \) using an appropriate updating technique.

A large number of Hessian updating methods have been developed. However, the formula of Broyden [3], Fletcher [12], Goldfarb [20], and Shanno [37] (BFGS) is thought to be the most effective for use in a general purpose method.

The formula given by BFGS is

\[
H_{k+1} = H_k + \frac{q_k q_k^T}{q_k^T s_k} - \frac{H_k^T s_k s_k^T H_k}{s_k^T H_k s_k},
\]

where
\[
\begin{align*}
  s_k &= x_{k+1} - x_k, \\
  q_k &= \nabla f(x_{k+1}) - \nabla f(x_k).
\end{align*}
\]

As a starting point, \( H_0 \) can be set to any symmetric positive definite matrix, for example, the identity matrix \( I \). To avoid the inversion of the Hessian \( H \), you can derive an updating method that avoids the direct inversion of \( H \) by using a formula that makes an approximation of the inverse Hessian \( H^{-1} \) at each update. A well-known procedure is the DFP formula of Davidon [7], Fletcher, and Powell [14]. This uses the same formula as the BFGS method (Equation 6-10) except that \( q_k \) is substituted for \( s_k \).

The gradient information is either supplied through analytically calculated gradients, or derived by partial derivatives using a numerical differentiation method via finite differences. This involves perturbing each of the design variables, \( x \), in turn and calculating the rate of change in the objective function.

At each major iteration, \( k \), a line search is performed in the direction

\[
d = -H_k^{-1} \cdot \nabla f(x_k).
\]

The quasi-Newton method is illustrated by the solution path on Rosenbrock’s function in Figure 6-2, BFGS Method on Rosenbrock’s Function. The method is able to follow the shape of the valley and converges to the minimum after 140 function evaluations using only finite difference gradients.
Line Search

Line search is a search method that is used as part of a larger optimization algorithm. At each step of the main algorithm, the line-search method searches along the line containing the current point, \( x_k \), parallel to the search direction, which is a vector determined by the main algorithm. That is, the method finds the next iterate \( x_{k+1} \) of the form

\[
x_{k+1} = x_k + \alpha^* d_k,
\]

where \( x_k \) denotes the current iterate, \( d_k \) is the search direction, and \( \alpha^* \) is a scalar step length parameter.

The line search method attempts to decrease the objective function along the line \( x_k + \alpha^* d_k \) by repeatedly minimizing polynomial interpolation models of the objective function. The line search procedure has two main steps:

- The bracketing phase determines the range of points on the line \( x_{k+1} = x_k + \alpha^* d_k \) to be searched. The bracket corresponds to an interval specifying the range of values of \( \alpha \).
• The *sectioning* step divides the bracket into subintervals, on which
the minimum of the objective function is approximated by polynomial
interpolation.

The resulting step length $\alpha$ satisfies the Wolfe conditions:

$$f(x_k + \alpha d_k) \leq f(x_k) + c_1 \alpha \nabla f_k^T d_k, \quad (6-13)$$

$$\nabla f(x_k + \alpha d_k)^T d_k \geq c_2 \nabla f_k^T d_k, \quad (6-14)$$

where $c_1$ and $c_2$ are constants with $0 < c_1 < c_2 < 1$.

The first condition (Equation 6-13) requires that $\alpha_k$ sufficiently decreases the
objective function. The second condition (Equation 6-14) ensures that the step
length is not too small. Points that satisfy both conditions (Equation 6-13 and
Equation 6-14) are called *acceptable points*.

The line search method is an implementation of the algorithm described in
Section 2-6 of [13]. See also [31] for more information about line search.

**Hessian Update**

Many of the optimization functions determine the direction of search by
updating the Hessian matrix at each iteration, using the BFGS method
(Equation 6-10). The function `fminunc` also provides an option to use the
DFP method given in “Quasi-Newton Methods” on page 6-8 (set `HessUpdate`
to ‘dfp’ in `options` to select the DFP method). The Hessian, $H$, is always
maintained to be positive definite so that the direction of search, $d$, is always
in a descent direction. This means that for some arbitrarily small step $\alpha$ in
the direction $d$, the objective function decreases in magnitude. You achieve
positive definiteness of $H$ by ensuring that $H$ is initialized to be positive
definite and thereafter $q_k^T s_k$ (from Equation 6-15) is always positive. The
term $q_k^T s_k$ is a product of the line search step length parameter $\alpha_k$ and
a combination of the search direction $d$ with past and present gradient
evaluations,
\[ q_k^T s_k = \alpha_k \left( \nabla f(x_{k+1})^T d - \nabla f(x_k)^T d \right). \]  

(6-15)

You always achieve the condition that \( q_k^T s_k \) is positive by performing a sufficiently accurate line search. This is because the search direction, \( d \), is a descent direction, so that \( \alpha_k \) and the negative gradient \( -\nabla f(x_k)^T d \) are always positive. Thus, the possible negative term \( -\nabla f(x_{k+1})^T d \) can be made as small in magnitude as required by increasing the accuracy of the line search.

**fminsearch Algorithm**

*fminsearch* uses the Nelder-Mead simplex algorithm as described in Lagarias et al. [57]. This algorithm uses a simplex of \( n + 1 \) points for \( n \)-dimensional vectors \( x \). The algorithm first makes a simplex around the initial guess \( x_0 \) by adding 5\% of each component \( x_0(i) \) to \( x_0 \), and using these \( n \) vectors as elements of the simplex in addition to \( x_0 \). (It uses 0.00025 as component \( i \) if \( x_0(i) = 0 \).) Then, the algorithm modifies the simplex repeatedly according to the following procedure.

---

**Note** The keywords for the *fminsearch* iterative display appear in bold after the description of the step.

1. Let \( x(i) \) denote the list of points in the current simplex, \( i = 1,...,n+1 \).

2. Order the points in the simplex from lowest function value \( f(x(1)) \) to highest \( f(x(n+1)) \). At each step in the iteration, the algorithm discards the current worst point \( x(n+1) \), and accepts another point into the simplex. [Or, in the case of step 7 below, it changes all \( n \) points with values above \( f(x(1)) \)].

3. Generate the *reflected* point

\[ r = 2m - x(n+1), \]

where

\[ m = \sum x(i)/n, \quad i = 1...n, \]

and calculate \( f(r) \).
4 If \( f(x(1)) \leq f(r) < f(x(n)) \), accept \( r \) and terminate this iteration. Reflect

5 If \( f(r) < f(x(1)) \), calculate the expansion point \( s \)

\[
s = m + 2(m - x(n+1)),
\]

and calculate \( f(s) \).

a If \( f(s) < f(r) \), accept \( s \) and terminate the iteration. Expand

b Otherwise, accept \( r \) and terminate the iteration. Reflect

6 If \( f(r) \geq f(x(n)) \), perform a contraction between \( m \) and the better of \( x(n+1) \) and \( r \):

a If \( f(r) < f(x(n+1)) \) (i.e., \( r \) is better than \( x(n+1) \)), calculate

\[
c = m + (r - m)/2
\]

and calculate \( f(c) \). If \( f(c) < f(r) \), accept \( c \) and terminate the iteration. Contract outside

b If \( f(r) \geq f(x(n+1)) \), calculate

\[
cc = m + (x(n+1) - m)/2
\]

and calculate \( f(cc) \). If \( f(cc) < f(x(n+1)) \), accept \( cc \) and terminate the iteration. Contract inside

Otherwise, continue with Step 7 (Shrink).

7 Calculate the \( n \) points

\[
v(i) = x(1) + (x(i) - x(1))/2
\]

and calculate \( f(v(i)), i = 2,...,n+1 \). The simplex at the next iteration is \( x(1), v(2),...,v(n+1) \). Shrink

The following figure shows the points that \texttt{fminsearch} might calculate in the procedure, along with each possible new simplex. The original simplex has a bold outline. The iterations proceed until they meet a stopping criterion.
In this section...

“Example: fminunc Unconstrained Minimization” on page 6-15
“Example: Nonlinear Minimization with Gradient and Hessian” on page 6-17
“Example: Nonlinear Minimization with Gradient and Hessian Sparsity Pattern” on page 6-18

Example: fminunc Unconstrained Minimization

Consider the problem of finding a set of values \([x_1, x_2]\) that solves

\[
\min_x f(x) = e^{x_1} \left(4x_1^2 + 2x_2^2 + 4x_1x_2 + 2x_2 + 1\right).
\]  

(6-16)

To solve this two-dimensional problem, write a file that returns the function value. Then, invoke the unconstrained minimization routine \texttt{fminunc}.

Step 1: Write a file \texttt{objfun.m}.

This code ships with the toolbox. To view, enter \texttt{type objfun}:

\begin{verbatim}
function f = objfun(x)
f = exp(x(1)) * (4*x(1)^2 + 2*x(2)^2 + 4*x(1)*x(2) + 2*x(2) + 1);
\end{verbatim}

Step 2: Invoke one of the unconstrained optimization routines.

\begin{verbatim}
x0 = [-1,1]; % Starting guess
options = optimset('LargeScale','off');
[x,fval,exitflag,output] = fminunc(@objfun,x0,options);
\end{verbatim}

This produces the following output:

Local minimum found.

Optimization completed because the size of the gradient is less than the default value of the function tolerance.
View the results:

\[ x, fval, \text{exitflag}, \text{output} \]

\[ x = \\
0.5000 \quad -1.0000 \\
\]

\[ fval = \\
3.6609e-015 \\
\]

\[ \text{exitflag} = \\
1 \\
\]

\[ \text{output} = \\
\text{iterations: 8} \\
\text{funcCount: 66} \\
\text{stepsize: 1} \\
\text{firstorderopt: 1.2284e-007} \\
\text{algorithm: 'medium-scale: Quasi-Newton line search'} \\
\text{message: [1x438 char]} \\
\]

The `exitflag` tells whether the algorithm converged. `exitflag = 1` means a local minimum was found. The meanings of `exitflags` are given in function reference pages.

The `output` structure gives more details about the optimization. For `fminunc`, it includes the number of iterations in `iterations`, the number of function evaluations in `funcCount`, the final step-size in `stepsize`, a measure of first-order optimality (which in this unconstrained case is the infinity norm of the gradient at the solution) in `firstorderopt`, the type of algorithm used in `algorithm`, and the exit message (the reason the algorithm stopped).

Pass the variable `options` to `fminunc` to change characteristics of the optimization algorithm, as in

\[ x = \text{fminunc(@objfun,x0,options);} \]

`options` is a structure that contains values for termination tolerances and algorithm choices. Create an `options` structure using the `optimset` function:

\[ \text{options} = \text{optimset('LargeScale','off');} \]
You can also create an options structure by exporting from the Optimization Tool.

In this example, we have turned off the default selection of the large-scale algorithm and so the medium-scale algorithm is used. Other options include controlling the amount of command line display during the optimization iteration, the tolerances for the termination criteria, whether a user-supplied gradient or Jacobian is to be used, and the maximum number of iterations or function evaluations. See `optimset`, the individual optimization functions, and “Optimization Options Reference” on page 9-7 for more options and information.

**Example: Nonlinear Minimization with Gradient and Hessian**

This example involves solving a nonlinear minimization problem with a tridiagonal Hessian matrix $H(x)$ first computed explicitly, and then by providing the Hessian’s sparsity structure for the finite-differencing routine.

The problem is to find $x$ to minimize

$$f(x) = \sum_{i=1}^{n-1} \left( x_i^2 (x_{i+1}^2+1) + x_{i+1}^2 (x_i^2+1) \right)$$

(6-17)

where $n = 1000$.

**Step 1: Write a file brownfgh.m that computes the objective function, the gradient of the objective, and the sparse tridiagonal Hessian matrix.**

The file is lengthy so is not included here. View the code with the command

```
  type brownfgh
```

Because `brownfgh` computes the gradient and Hessian values as well as the objective function, you need to use `optimset` to indicate that this information is available in `brownfgh`, using the `GradObj` and `Hessian` options.
Step 2: Call a nonlinear minimization routine with a starting point xstart.

```matlab
n = 1000;
xstart = -ones(n,1);
xstart(2:2:n,1) = 1;
options = optimset('GradObj','on','Hessian','on');
[x,fval,exitflag,output] = fminunc(@brownfgh,xstart,options);
```

This 1000 variable problem is solved in about 7 iterations and 7 conjugate gradient iterations with a positive `exitflag` indicating convergence. The final function value and measure of optimality at the solution x are both close to zero. For `fminunc`, the first order optimality is the infinity norm of the gradient of the function, which is zero at a local minimum:

```matlab
exitflag =
1
fval =
2.8709e-017
output =
    iterations: 7
    funcCount: 8
    cgiterations: 7
    firstorderopt: 4.7948e-010
    algorithm: 'large-scale: trust-region Newton'
    message: [1x498 char]
```

Example: Nonlinear Minimization with Gradient and Hessian Sparsity Pattern

Next, solve the same problem but the Hessian matrix is now approximated by sparse finite differences instead of explicit computation. To use the large-scale method in `fminunc`, you must compute the gradient in `fun`; it is not optional as in the medium-scale method.

The `brownfg` file computes the objective function and gradient.
Step 1: Write a file brownfg.m that computes the objective function and the gradient of the objective.

```matlab
function [f,g] = brownfg(x)
% BROWNFG Nonlinear minimization test problem
%
% Evaluate the function
n=length(x); y=zeros(n,1);
i=1:(n-1);
y(i)=(x(i).^2).^(x(i+1).^2+1) + ...
   (x(i+1).^2).^(x(i).^2+1);
f=sum(y);
% Evaluate the gradient if nargout > 1
if nargout > 1
    i=1:(n-1); g = zeros(n,1);
g(i) = 2*(x(i+1).^2+1).*x(i).* ...
      ((x(i).^2).^(x(i+1).^2)+ ... 
     2*x(i).*((x(i+1).^2).^(x(i).^2+1))).* ...
      log(x(i+1).^2);
g(i+1) = g(i+1) + ...
     2*x(i+1).*((x(i).^2).^(x(i+1).^2+1))).* ...
      log(x(i).^2) + ... 
     2*(x(i).^2+1).*x(i+1).* ...
      ((x(i+1).^2).^(x(i).^2));
end
```

To allow efficient computation of the sparse finite-difference approximation of the Hessian matrix $H(x)$, the sparsity structure of $H$ must be predetermined. In this case assume this structure, $Hstr$, a sparse matrix, is available in file brownhstr.mat. Using the spy command you can see that $Hstr$ is indeed sparse (only 2998 nonzeros). Use optimset to set the HessPattern option to $Hstr$. When a problem as large as this has obvious sparsity structure, not setting the HessPattern option requires a huge amount of unnecessary memory and computation because `fminunc` attempts to use finite differencing on a full Hessian matrix of one million nonzero entries.

You must also set the GradObj option to 'on' using optimset, since the gradient is computed in brownfg.m. Then execute `fminunc` as shown in Step 2.
Step 2: Call a nonlinear minimization routine with a starting point \( x_{\text{start}} \).

```matlab
fun = @brownfg;
load brownhstr % Get Hstr, structure of the Hessian
spy(Hstr) % View the sparsity structure of Hstr
n = 1000;
xstart = -ones(n,1);
xstart(2:2:n,1) = 1;
options = optimset('GradObj','on','HessPattern',Hstr);
[x,fval,exitflag,output] = fminunc(fun,xstart,options);
```

This 1000-variable problem is solved in seven iterations and seven conjugate gradient iterations with a positive \( \text{exitflag} \) indicating convergence. The final function value and measure of optimality at the solution \( x \) are both close to zero (for \text{fminunc}, the first-order optimality is the infinity norm of the gradient of the function, which is zero at a local minimum):

```matlab
exitflag,fval,output
exitflag =
    1
fval =
    7.4738e-017
output =
    iterations: 7
    funcCount: 8
    cgiterations: 7
    firstorderopt: 7.9822e-010
    algorithm: 'large-scale: trust-region Newton'
    message: [1x498 char]
    constrviolation: []
```
Constrained Nonlinear Optimization Algorithms

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**Definition**

Constrained minimization is the problem of finding a vector \( x \) that is a local minimum to a scalar function \( f(x) \) subject to constraints on the allowable \( x \):

\[
\min_{x} f(x)
\]

such that one or more of the following holds: \( c(x) \leq 0, \ c_{eq}(x) = 0, \ A \ x \leq b, \ A_{eq} \ x = b_{eq}, \ l \leq x \leq u \). There are even more constraints used in semi-infinite programming; see “fseminf Problem Formulation and Algorithm” on page 6-42.

**fmincon Trust Region Reflective Algorithm**

**Trust-Region Methods for Nonlinear Minimization**

Many of the methods used in Optimization Toolbox solvers are based on trust regions, a simple yet powerful concept in optimization.

To understand the trust-region approach to optimization, consider the unconstrained minimization problem, minimize \( f(x) \), where the function takes vector arguments and returns scalars. Suppose you are at a point \( x \) in \( n \)-space and you want to improve, i.e., move to a point with a lower function value. The basic idea is to approximate \( f \) with a simpler function \( q \), which reasonably
reflects the behavior of function \( f \) in a neighborhood \( N \) around the point \( x \). This neighborhood is the trust region. A trial step \( s \) is computed by minimizing (or approximately minimizing) over \( N \). This is the trust-region subproblem,

\[
\min_{s} \{ q(s), s \in N \}.
\] (6-18)

The current point is updated to be \( x + s \) if \( f(x + s) < f(x) \); otherwise, the current point remains unchanged and \( N \), the region of trust, is shrunk and the trial step computation is repeated.

The key questions in defining a specific trust-region approach to minimizing \( f(x) \) are how to choose and compute the approximation \( q \) (defined at the current point \( x \)), how to choose and modify the trust region \( N \), and how accurately to solve the trust-region subproblem. This section focuses on the unconstrained problem. Later sections discuss additional complications due to the presence of constraints on the variables.

In the standard trust-region method ([48]), the quadratic approximation \( q \) is defined by the first two terms of the Taylor approximation to \( F \) at \( x \); the neighborhood \( N \) is usually spherical or ellipsoidal in shape. Mathematically the trust-region subproblem is typically stated

\[
\min \left\{ \frac{1}{2} s^T H s + s^T g \text{ such that } \|D s\| \leq \Delta \right\},
\] (6-19)

where \( g \) is the gradient of \( f \) at the current point \( x \), \( H \) is the Hessian matrix (the symmetric matrix of second derivatives), \( D \) is a diagonal scaling matrix, \( \Delta \) is a positive scalar, and \( \| . \| \) is the 2-norm. Good algorithms exist for solving Equation 6-19 (see [48]); such algorithms typically involve the computation of a full eigensystem and a Newton process applied to the secular equation

\[
\frac{1}{\Delta} - \frac{1}{\|s\|} = 0.
\]

Such algorithms provide an accurate solution to Equation 6-19. However, they require time proportional to several factorizations of \( H \). Therefore, for large-scale problems a different approach is needed. Several approximation and heuristic strategies, based on Equation 6-19, have been proposed in
the literature ([42] and [50]). The approximation approach followed in Optimization Toolbox solvers is to restrict the trust-region subproblem to a two-dimensional subspace $S$ ([39] and [42]). Once the subspace $S$ has been computed, the work to solve Equation 6-19 is trivial even if full eigenvalue/eigenvector information is needed (since in the subspace, the problem is only two-dimensional). The dominant work has now shifted to the determination of the subspace.

The two-dimensional subspace $S$ is determined with the aid of a preconditioned conjugate gradient process described below. The solver defines $S$ as the linear space spanned by $s_1$ and $s_2$, where $s_1$ is in the direction of the gradient $g$, and $s_2$ is either an approximate Newton direction, i.e., a solution to

$$H \cdot s_2 = -g, \quad (6-20)$$

or a direction of negative curvature,

$$s_2^T \cdot H \cdot s_2 < 0. \quad (6-21)$$

The philosophy behind this choice of $S$ is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence (via the Newton step, when it exists).

A sketch of unconstrained minimization using trust-region ideas is now easy to give:

1. Formulate the two-dimensional trust-region subproblem.
2. Solve Equation 6-19 to determine the trial step $s$.
3. If $f(x + s) < f(x)$, then $x = x + s$.
4. Adjust $\Delta$.

These four steps are repeated until convergence. The trust-region dimension $\Delta$ is adjusted according to standard rules. In particular, it is decreased if the trial step is not accepted, i.e., $f(x + s) \geq f(x)$. See [46] and [49] for a discussion of this aspect.
Optimization Toolbox solvers treat a few important special cases of $f$ with specialized functions: nonlinear least-squares, quadratic functions, and linear least-squares. However, the underlying algorithmic ideas are the same as for the general case. These special cases are discussed in later sections.

**Preconditioned Conjugate Gradient Method**

A popular way to solve large symmetric positive definite systems of linear equations $Hp = -g$ is the method of Preconditioned Conjugate Gradients (PCG). This iterative approach requires the ability to calculate matrix-vector products of the form $Hv$ where $v$ is an arbitrary vector. The symmetric positive definite matrix $M$ is a preconditioner for $H$. That is, $M = C^2$, where $C^{-1}HC^{-1}$ is a well-conditioned matrix or a matrix with clustered eigenvalues.

In a minimization context, you can assume that the Hessian matrix $H$ is symmetric. However, $H$ is guaranteed to be positive definite only in the neighborhood of a strong minimizer. Algorithm PCG exits when a direction of negative (or zero) curvature is encountered, i.e., $d^THd \leq 0$. The PCG output direction, $p$, is either a direction of negative curvature or an approximate ($tol$ controls how approximate) solution to the Newton system $Hp = -g$. In either case $p$ is used to help define the two-dimensional subspace used in the trust-region approach discussed in “Trust-Region Methods for Nonlinear Minimization” on page 6-3.

**Linear Equality Constraints**

Linear constraints complicate the situation described for unconstrained minimization. However, the underlying ideas described previously can be carried through in a clean and efficient way. The large-scale methods in Optimization Toolbox solvers generate strictly feasible iterates.

The general linear equality constrained minimization problem can be written

$$\min \{f(x) \text{ such that } Ax = b\}, \quad (6-22)$$

where $A$ is an $m$-by-$n$ matrix ($m \leq n$). Some Optimization Toolbox solvers preprocess $A$ to remove strict linear dependencies using a technique based on the LU factorization of $A^T$ [46]. Here $A$ is assumed to be of rank $m$. 


The method used to solve Equation 6-22 differs from the unconstrained approach in two significant ways. First, an initial feasible point \( x_0 \) is computed, using a sparse least-squares step, so that \( Ax_0 = b \). Second, Algorithm PCG is replaced with Reduced Preconditioned Conjugate Gradients (RPCG), see [46], in order to compute an approximate reduced Newton step (or a direction of negative curvature in the null space of \( A \)). The key linear algebra step involves solving systems of the form

\[
\begin{bmatrix}
C & \tilde{A}^T \\
\tilde{A} & 0
\end{bmatrix}
\begin{bmatrix}
s \\
t
\end{bmatrix}
= \begin{bmatrix}
r \\
0
\end{bmatrix},
\tag{6-23}
\]

where \( \tilde{A} \) approximates \( A \) (small nonzeros of \( A \) are set to zero provided rank is not lost) and \( C \) is a sparse symmetric positive-definite approximation to \( H \), i.e., \( C = H \). See [46] for more details.

**Box Constraints**

The box constrained problem is of the form

\[
\min \{ f(x) \ \text{such that} \ l \leq x \leq u \},
\tag{6-24}
\]

where \( l \) is a vector of lower bounds, and \( u \) is a vector of upper bounds. Some (or all) of the components of \( l \) can be equal to \(-\infty\) and some (or all) of the components of \( u \) can be equal to \( \infty \). The method generates a sequence of strictly feasible points. Two techniques are used to maintain feasibility while achieving robust convergence behavior. First, a scaled modified Newton step replaces the unconstrained Newton step (to define the two-dimensional subspace \( S \)). Second, reflections are used to increase the step size.

The scaled modified Newton step arises from examining the Kuhn-Tucker necessary conditions for Equation 6-24,

\[
(D(x))^{-2} g = 0,
\tag{6-25}
\]

where

\[
D(x) = \text{diag}\left(|v_k|^{-1/2}\right),
\]
and the vector $v(x)$ is defined below, for each $1 \leq i \leq n$:

- If $g_i < 0$ and $u_i < \infty$ then $v_i = x_i - u_i$
- If $g_i \geq 0$ and $l_i > -\infty$ then $v_i = x_i - l_i$
- If $g_i < 0$ and $u_i = \infty$ then $v_i = -1$
- If $g_i \geq 0$ and $l_i = -\infty$ then $v_i = 1$

The nonlinear system Equation 6-25 is not differentiable everywhere. Nondifferentiability occurs when $v_i = 0$. You can avoid such points by maintaining strict feasibility, i.e., restricting $l < x < u$.

The scaled modified Newton step $s_k$ for the nonlinear system of equations given by Equation 6-25 is defined as the solution to the linear system

$$\hat{M}D^N s^N = -\hat{g}$$

(6-26)

at the $k$th iteration, where

$$\hat{g} = D^{-1}g = \text{diag}(|v|^{1/2})g,$$

(6-27)

and

$$\hat{M} = D^{-1}HD^{-1} + \text{diag}(g)J^v.$$  

(6-28)

Here $J^v$ plays the role of the Jacobian of $|v|$. Each diagonal component of the diagonal matrix $J^v$ equals 0, -1, or 1. If all the components of $l$ and $u$ are finite, $J^v = \text{diag}(\text{sign}(g))$. At a point where $g_i = 0$, $v_i$ might not be differentiable.

$J^v_{ii} = 0$ is defined at such a point. Nondifferentiability of this type is not a cause for concern because, for such a component, it is not significant which value $v_i$ takes. Further, $|v_i|$ will still be discontinuous at this point, but the function $|v_i|g_i$ is continuous.

Second, reflections are used to increase the step size. A (single) reflection step is defined as follows. Given a step $p$ that intersects a bound constraint, consider the first bound constraint crossed by $p$; assume it is the $i$th bound
constraint (either the $i$th upper or $i$th lower bound). Then the reflection step $p^R = p$ except in the $i$th component, where $p^R_i = -p_i$.

**fmincon Active Set Algorithm**

**Introduction**

In constrained optimization, the general aim is to transform the problem into an easier subproblem that can then be solved and used as the basis of an iterative process. A characteristic of a large class of early methods is the translation of the constrained problem to a basic unconstrained problem by using a penalty function for constraints that are near or beyond the constraint boundary. In this way the constrained problem is solved using a sequence of parameterized unconstrained optimizations, which in the limit (of the sequence) converge to the constrained problem. These methods are now considered relatively inefficient and have been replaced by methods that have focused on the solution of the Karush-Kuhn-Tucker (KKT) equations. The KKT equations are necessary conditions for optimality for a constrained optimization problem. If the problem is a so-called convex programming problem, that is, $f(x)$ and $G_i(x), i = 1,...,m$, are convex functions, then the KKT equations are both necessary and sufficient for a global solution point.

Referring to GP (Equation 6-1), the Kuhn-Tucker equations can be stated as

$$
\nabla f(x^*) + \sum_{i=1}^{m} \lambda_i \cdot \nabla G_i(x^*) = 0
$$

$$
\lambda_i \cdot G_i(x^*) = 0, \quad i = 1,...,m_e
$$

$$
\lambda_i \geq 0, \quad i = m_e + 1,...,m,
$$

(6-29)

in addition to the original constraints in Equation 6-1.

The first equation describes a canceling of the gradients between the objective function and the active constraints at the solution point. For the gradients to be canceled, Lagrange multipliers ($\lambda_i, i = 1,...,m$) are necessary to balance the deviations in magnitude of the objective function and constraint gradients. Because only active constraints are included in this canceling operation, constraints that are not active must not be included in this operation and so
are given Lagrange multipliers equal to 0. This is stated implicitly in the last two Kuhn-Tucker equations.

The solution of the KKT equations forms the basis to many nonlinear programming algorithms. These algorithms attempt to compute the Lagrange multipliers directly. Constrained quasi-Newton methods guarantee superlinear convergence by accumulating second-order information regarding the KKT equations using a quasi-Newton updating procedure. These methods are commonly referred to as Sequential Quadratic Programming (SQP) methods, since a QP subproblem is solved at each major iteration (also known as Iterative Quadratic Programming, Recursive Quadratic Programming, and Constrained Variable Metric methods).

The 'active-set' algorithm is not a large-scale algorithm; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48.

**Sequential Quadratic Programming (SQP)**

SQP methods represent the state of the art in nonlinear programming methods. Schittkowski [36], for example, has implemented and tested a version that outperforms every other tested method in terms of efficiency, accuracy, and percentage of successful solutions, over a large number of test problems.

Based on the work of Biggs [1], Han [22], and Powell ([32] and [33]), the method allows you to closely mimic Newton’s method for constrained optimization just as is done for unconstrained optimization. At each major iteration, an approximation is made of the Hessian of the Lagrangian function using a quasi-Newton updating method. This is then used to generate a QP subproblem whose solution is used to form a search direction for a line search procedure. An overview of SQP is found in Fletcher [13], Gill et al. [19], Powell [35], and Schittkowski [23]. The general method, however, is stated here.

Given the problem description in GP (Equation 6-1) the principal idea is the formulation of a QP subproblem based on a quadratic approximation of the Lagrangian function.
Here you simplify Equation 6-1 by assuming that bound constraints have been expressed as inequality constraints. You obtain the QP subproblem by linearizing the nonlinear constraints.

**Quadratic Programming (QP) Subproblem**

\[
\min_{d \in \mathbb{R}^n} \frac{1}{2} d^T H_k d + \nabla f(x_k)^T d \\
\nabla g_i(x_k)^T d + g_i(x_k) = 0, \quad i = 1, \ldots, m_e \\
\nabla g_i(x_k)^T d + g_i(x_k) \leq 0, \quad i = m_e + 1, \ldots, m.
\]  

(6-31)

This subproblem can be solved using any QP algorithm (see, for instance, “Quadratic Programming Solution” on page 6-32). The solution is used to form a new iterate

\[
x_{k+1} = x_k + \alpha_k d_k.
\]

The step length parameter \( \alpha_k \) is determined by an appropriate line search procedure so that a sufficient decrease in a merit function is obtained (see “Updating the Hessian Matrix” on page 6-30). The matrix \( H_k \) is a positive definite approximation of the Hessian matrix of the Lagrangian function (Equation 6-30). \( H_k \) can be updated by any of the quasi-Newton methods, although the BFGS method (see “Updating the Hessian Matrix” on page 6-30) appears to be the most popular.

A nonlinearly constrained problem can often be solved in fewer iterations than an unconstrained problem using SQP. One of the reasons for this is that, because of limits on the feasible area, the optimizer can make informed decisions regarding directions of search and step length.

Consider Rosenbrock’s function with an additional nonlinear inequality constraint, \( g(x) \),
\[ x_1^2 + x_2^2 - 1.5 \leq 0. \]  

(6-32)

This was solved by an SQP implementation in 96 iterations compared to 140 for the unconstrained case. SQP Method on Nonlinearly Constrained Rosenbrock’s Function (Equation 6-6) on page 6-30 shows the path to the solution point \( x = [0.9072, 0.8228] \) starting at \( x = [-1.9, 2.0] \).

![Figure 6-3: SQP Method on Nonlinearly Constrained Rosenbrock’s Function (Equation 6-6)](image)

**SQP Implementation**

The SQP implementation consists of three main stages, which are discussed briefly in the following subsections:

- “Updating the Hessian Matrix” on page 6-30
- “Quadratic Programming Solution” on page 6-32
- “Line Search and Merit Function” on page 6-36

**Updating the Hessian Matrix.** At each major iteration a positive definite quasi-Newton approximation of the Hessian of the Lagrangian function, \( H \), is calculated using the BFGS method, where \( \lambda_i, i = 1, \ldots, m \), is an estimate of the Lagrange multipliers.
\[
H_{k+1} = H_k + \frac{q_k q_k^T}{q_k^T s_k} - \frac{H_k^T s_k^T s_k H_k}{s_k^T H_k s_k},
\]

(6-33)

where

\[
s_k = x_{k+1} - x_k
\]

\[
q_k = \left[ \nabla f(x_{k+1}) + \sum_{i=1}^{m} \lambda_i \cdot \nabla g_i(x_{k+1}) \right] - \left[ \nabla f(x_k) + \sum_{i=1}^{m} \lambda_i \cdot \nabla g_i(x_k) \right].
\]

Powell [33] recommends keeping the Hessian positive definite even though it might be positive indefinite at the solution point. A positive definite Hessian is maintained providing \( q_k^T s_k \) is positive at each update and that \( H \) is initialized with a positive definite matrix. When \( q_k^T s_k \) is not positive, \( q_k \) is modified on an element-by-element basis so that \( q_k^T s_k > 0 \). The general aim of this modification is to distort the elements of \( q_k \), which contribute to a positive definite update, as little as possible. Therefore, in the initial phase of the modification, the most negative element of \( q_k^T s_k \) is repeatedly halved. This procedure is continued until \( q_k^T s_k \) is greater than or equal to a small negative tolerance. If, after this procedure, \( q_k^T s_k \) is still not positive, modify \( q_k \) by adding a vector \( v \) multiplied by a constant scalar \( w \), that is,

\[
q_k = q_k + wv,
\]

(6-34)

where

\[
v_i = \nabla g_i(x_{k+1}) \cdot g_i(x_{k+1}) - \nabla g_i(x_k) \cdot g_i(x_k)
\]

if \((q_k)_i \cdot w < 0\) and \((q_k)_i \cdot (s_k)_i < 0\), \(i = 1,...,m\)

\[
v_i = 0 \text{ otherwise},
\]

and increase \( w \) systematically until \( q_k^T s_k \) becomes positive.

The functions \texttt{fmincon}, \texttt{fminimax}, \texttt{fgoalattain}, and \texttt{fseminf} all use SQP. If \texttt{Display} is set to \textquoteleft iter\textquotefract; in options, then various information is given
such as function values and the maximum constraint violation. When the Hessian has to be modified using the first phase of the preceding procedure to keep it positive definite, then \textit{Hessian modified} is displayed. If the Hessian has to be modified again using the second phase of the approach described above, then \textit{Hessian modified twice} is displayed. When the QP subproblem is infeasible, then \textit{infeasible} is displayed. Such displays are usually not a cause for concern but indicate that the problem is highly nonlinear and that convergence might take longer than usual. Sometimes the message \textit{no update} is displayed, indicating that \( q_k^T s_k \) is nearly zero. This can be an indication that the problem setup is wrong or you are trying to minimize a noncontinuous function.

\textbf{Quadratic Programming Solution.} At each major iteration of the SQP method, a QP problem of the following form is solved, where \( A_i \) refers to the \( i \)th row of the \( m \)-by-\( n \) matrix \( A \).

\[
\min_{d \in \mathbb{R}^n} q(d) = \frac{1}{2} d^T H d + c^T d,
\]

\[
A_i d = b_i, \quad i = 1, \ldots, m_e
\]

\[
A_i d \leq b_i, \quad i = m_e + 1, \ldots, m. \tag{6-35}
\]

The method used in Optimization Toolbox functions is an active set strategy (also known as a projection method) similar to that of Gill et al., described in [18] and [17]. It has been modified for both Linear Programming (LP) and Quadratic Programming (QP) problems.

The solution procedure involves two phases. The first phase involves the calculation of a feasible point (if one exists). The second phase involves the generation of an iterative sequence of feasible points that converge to the solution. In this method an active set, \( \bar{A}_k \), is maintained that is an estimate of the active constraints (i.e., those that are on the constraint boundaries) at the solution point. Virtually all QP algorithms are active set methods. This point is emphasized because there exist many different methods that are very similar in structure but that are described in widely different terms.

\( \bar{A}_k \) is updated at each iteration \( k \), and this is used to form a basis for a search direction \( \hat{d}_k \). Equality constraints always remain in the active set \( \bar{A}_k \). The
notation for the variable $\hat{d}_k$ is used here to distinguish it from $d_k$ in the major iterations of the SQP method. The search direction $\hat{d}_k$ is calculated and minimizes the objective function while remaining on any active constraint boundaries. The feasible subspace for $\hat{d}_k$ is formed from a basis $Z_k$ whose columns are orthogonal to the estimate of the active set $\bar{A}_k$ (i.e., $\bar{A}_k Z_k = 0$). Thus a search direction, which is formed from a linear summation of any combination of the columns of $Z_k$, is guaranteed to remain on the boundaries of the active constraints.

The matrix $Z_k$ is formed from the last $m - l$ columns of the QR decomposition of the matrix $\bar{A}_k^T$, where $l$ is the number of active constraints and $l < m$. That is, $Z_k$ is given by

$$Z_k = Q[:,l+1:m],$$  \hfill (6-36)

where

$$Q^T \bar{A}_k^T = \begin{bmatrix} R \\ 0 \end{bmatrix}.$$  

Once $Z_k$ is found, a new search direction $\hat{d}_k$ is sought that minimizes $q(d)$ where $\hat{d}_k$ is in the null space of the active constraints. That is, $\hat{d}_k$ is a linear combination of the columns of $Z_k$: $\hat{d}_k = Z_k p$ for some vector $p$.

Then if you view the quadratic as a function of $p$, by substituting for $\hat{d}_k$, you have

$$q(p) = \frac{1}{2} p^T Z_k^T H Z_k p + c^T Z_k p.$$  \hfill (6-37)

Differentiating this with respect to $p$ yields
\[ \nabla q(p) = Z_k^T H Z_k p + Z_k^T c. \]  

(6-38)

\( \nabla q(p) \) is referred to as the projected gradient of the quadratic function because it is the gradient projected in the subspace defined by \( Z_k \). The term \( Z_k^T H Z_k \) is called the projected Hessian. Assuming the Hessian matrix \( H \) is positive definite (which is the case in this implementation of SQP), then the minimum of the function \( q(p) \) in the subspace defined by \( Z_k \) occurs when \( \nabla q(p) = 0 \), which is the solution of the system of linear equations

\[ Z_k^T H Z_k p = -Z_k^T c. \]  

(6-39)

A step is then taken of the form

\[ x_{k+1} = x_k + \alpha \hat{d}_k, \quad \text{where} \quad \hat{d}_k = Z_k^T p. \]  

(6-40)

At each iteration, because of the quadratic nature of the objective function, there are only two choices of step length \( \alpha \). A step of unity along \( \hat{d}_k \) is the exact step to the minimum of the function restricted to the null space of \( \bar{A}_k \). If such a step can be taken, without violation of the constraints, then this is the solution to QP (Equation 6-35). Otherwise, the step along \( \hat{d}_k \) to the nearest constraint is less than unity and a new constraint is included in the active set at the next iteration. The distance to the constraint boundaries in any direction \( \hat{d}_k \) is given by

\[ \alpha = \min_{i \in \{1, \ldots, m\}} \left\{ \frac{-(A_i x_k - b_i)}{A_i d_k} \right\}, \]  

(6-41)

which is defined for constraints not in the active set, and where the direction \( \hat{d}_k \) is towards the constraint boundary, i.e., \( A_i \hat{d}_k > 0, \ i = 1, \ldots, m \).

When \( n \) independent constraints are included in the active set, without location of the minimum, Lagrange multipliers, \( \lambda_k \), are calculated that satisfy the nonsingular set of linear equations

\[ \]
\[ \bar{A}_k^T \lambda_k = c. \] (6-42)

If all elements of \( \lambda_k \) are positive, \( x_k \) is the optimal solution of QP (Equation 6-35). However, if any component of \( \lambda_k \) is negative, and the component does not correspond to an equality constraint, then the corresponding element is deleted from the active set and a new iterate is sought.

Initialization

The algorithm requires a feasible point to start. If the current point from the SQP method is not feasible, then you can find a point by solving the linear programming problem

\[
\begin{align*}
\min_{\gamma \in \mathbb{R}, x \in \mathbb{R}^n} & \gamma \quad \text{such that} \\
A_i x &= b_i, \quad i = 1, \ldots, m_e \\
A_i x - \gamma &\leq b_i, \quad i = m_e + 1, \ldots, m.
\end{align*}
\] (6-43)

The notation \( A_i \) indicates the \( i \)th row of the matrix \( A \). You can find a feasible point (if one exists) to Equation 6-43 by setting \( x \) to a value that satisfies the equality constraints. You can determine this value by solving an under- or overdetermined set of linear equations formed from the set of equality constraints. If there is a solution to this problem, then the slack variable \( \gamma \) is set to the maximum inequality constraint at this point.

You can modify the preceding QP algorithm for LP problems by setting the search direction to the steepest descent direction at each iteration, where \( g_k \) is the gradient of the objective function (equal to the coefficients of the linear objective function).

\[ \hat{d}_k = -Z_k^{-1} Z_k^T g_k. \] (6-44)

If a feasible point is found using the preceding LP method, the main QP phase is entered. The search direction \( \hat{d}_k \) is initialized with a search direction \( \hat{d}_1 \) found from solving the set of linear equations.
\[ H\hat{d}_1 = -g_k, \]  

where \( g_k \) is the gradient of the objective function at the current iterate \( x_k \) (i.e., \( Hx_k + c \)).

If a feasible solution is not found for the QP problem, the direction of search for the main SQP routine \( \hat{d}_k \) is taken as one that minimizes \( \gamma \).

**Line Search and Merit Function.** The solution to the QP subproblem produces a vector \( d_k \), which is used to form a new iterate

\[ x_{k+1} = x_k + \alpha d_k. \]  

The step length parameter \( \alpha_k \) is determined in order to produce a sufficient decrease in a merit function. The merit function used by Han [22] and Powell [33] of the following form is used in this implementation.

\[ \Psi(x) = f(x) + \sum_{i=1}^{m_e} r_i \cdot g_i(x) + \sum_{i=m_e+1}^{m} r_i \cdot \max(0, g_i(x)). \]  

Powell recommends setting the penalty parameter

\[ r_i = (r_{k+1})_i = \max \left\{ \lambda_i, \frac{(r_k)_i + \lambda_i}{2} \right\}, \quad i = 1, \ldots, m. \]  

This allows positive contribution from constraints that are inactive in the QP solution but were recently active. In this implementation, the penalty parameter \( r_i \) is initially set to

\[ r_i = \frac{||\nabla f(x)||}{||\nabla g_i(x)||}, \]  

where \( || \cdot || \) represents the Euclidean norm.
This ensures larger contributions to the penalty parameter from constraints with smaller gradients, which would be the case for active constraints at the solution point.

**fmincon SQP Algorithm**

The sqp algorithm is similar to the active-set algorithm (for a description, see “fmincon Active Set Algorithm” on page 6-27). The basic sqp algorithm is described in Chapter 18 of Nocedal and Wright [31].

The most important differences between the sqp and the active-set algorithms are:

**Strict Feasibility With Respect to Bounds**

The sqp algorithm takes every iterative step in the region constrained by bounds. Furthermore, finite difference steps also respect bounds. Bounds are not strict; a step can be exactly on a boundary. This strict feasibility can be beneficial when your objective function or nonlinear constraint functions are undefined or are complex outside the region constrained by bounds.

**Robustness to Non-Double Results**

During its iterations, the sqp algorithm can attempt to take a step that fails. This means an objective function or nonlinear constraint function you supply returns a value of Inf, NaN, or a complex value. In this case, the algorithm attempts to take a smaller step.

**Refactored Linear Algebra Routines**

The sqp algorithm uses a different set of linear algebra routines to solve the quadratic programming subproblem, Equation 6-31. These routines are more efficient in both memory usage and speed than the active-set routines.

**Reformulated Feasibility Routines**

The sqp algorithm has two new approaches to the solution of Equation 6-31 when constraints are not satisfied.

- The sqp algorithm combines the objective and constraint functions into a merit function. The algorithm attempts to minimize the merit function
subject to relaxed constraints. This modified problem can lead to a feasible solution. However, this approach has more variables than the original problem, so the problem size in Equation 6-31 increases. The increased size can slow the solution of the subproblem. These routines are based on the articles by Spellucci [60] and Tone [61]. The sqp algorithm sets the penalty parameter for the merit function Equation 6-47 according to the suggestion in [41].

- Suppose nonlinear constraints are not satisfied, and an attempted step causes the constraint violation to grow. The sqp algorithm attempts to obtain feasibility using a second-order approximation to the constraints. The second-order technique can lead to a feasible solution. However, this technique can slow the solution by requiring more evaluations of the nonlinear constraint functions.

**fmincon Interior Point Algorithm**

**Barrier Function**

The interior-point approach to constrained minimization is to solve a sequence of approximate minimization problems. The original problem is

\[
\min f(x), \text{ subject to } h(x) = 0 \text{ and } g(x) \leq 0. \tag{6-50}
\]

For each \( \mu > 0 \), the approximate problem is

\[
\min_{x,s} f_{\mu}(x,s) = \min_{x,s} f(x) - \mu \sum_{i} \ln(s_i), \text{ subject to } h(x) = 0 \text{ and } g(x) + s = 0. \tag{6-51}
\]

There are as many slack variables \( s_i \) as there are inequality constraints \( g \). The \( s_i \) are restricted to be positive to keep \( \ln(s_i) \) bounded. As \( \mu \) decreases to zero, the minimum of \( f_{\mu} \) should approach the minimum of \( f \). The added logarithmic term is called a barrier function. This method is described in [40], [41], and [51].

The approximate problem Equation 6-51 is a sequence of equality constrained problems. These are easier to solve than the original inequality-constrained problem Equation 6-50.
To solve the approximate problem, the algorithm uses one of two main types of steps at each iteration:

- A *direct* step in \((x, s)\). This step attempts to solve the KKT equations, Equation 3-2 and Equation 3-3, for the approximate problem via a linear approximation. This is also called a *Newton step*.

- A *CG* (conjugate gradient) step, using a trust region.

By default, the algorithm first attempts to take a direct step. If it cannot, it attempts a CG step. One case where it does not take a direct step is when the approximate problem is not locally convex near the current iterate.

At each iteration the algorithm decreases a *merit function*, such as

\[ f_\mu(x, s) + \nu \left\| (h(x), g(x) + s) \right\|. \]

The parameter \( \nu \) may increase with iteration number in order to force the solution towards feasibility. If an attempted step does not decrease the merit function, the algorithm rejects the attempted step, and attempts a new step.

If either the objective function or a nonlinear constraint function returns a complex value, NaN, Inf, or an error at an iterate \( x_j \), the algorithm rejects \( x_j \). The rejection has the same effect as if the merit function did not decrease sufficiently: the algorithm then attempts a different, shorter step. Wrap any code that can error in `try-catch`:

```matlab
function val = userFcn(x)
try
    val = ... % code that can error
catch
    val = NaN;
end
```

The objective and constraints must yield proper (double) values at the initial point.

**Direct Step**

The following variables are used in defining the direct step:
• $H$ denotes the Hessian of the Lagrangian of $f$:

$$H = \nabla^2 f(x) + \sum_i \lambda_i \nabla^2 g_i(x) + \sum_j \lambda_j \nabla^2 h_j(x).$$

(6-52)

• $J_g$ denotes the Jacobian of the constraint function $g$.
• $J_h$ denotes the Jacobian of the constraint function $h$.
• $S = \text{diag}(s)$.
• $\lambda$ denotes the Lagrange multiplier vector associated with constraints $g$.
• $\Lambda = \text{diag}(\lambda)$.
• $y$ denotes the Lagrange multiplier vector associated with $h$.
• $e$ denote the vector of ones the same size as $g$.

Equation 6-53 defines the direct step $(\Delta x, \Delta s)$:

$$
\begin{bmatrix}
H & 0 & J_h^T & J_g^T \\
0 & S\Lambda & 0 & -S \\
J_h & 0 & I & 0 \\
J_g & -S & 0 & I
\end{bmatrix}
\begin{bmatrix}
\Delta x \\
\Delta s \\
-\Delta y \\
-\Delta \lambda
\end{bmatrix}
= -
\begin{bmatrix}
\nabla f - J_h^T y - J_g^T \lambda \\
S\lambda - \mu e \\
h \\
g + s
\end{bmatrix}.
$$

(6-53)

This equation comes directly from attempting to solve Equation 3-2 and Equation 3-3 using a linearized Lagrangian.

In order to solve this equation for $(\Delta x, \Delta s)$, the algorithm makes an LDL factorization of the matrix. (See Example 3 — The Structure of D in the MATLAB ldl function reference page.) This is the most computationally expensive step. One result of this factorization is a determination of whether the projected Hessian is positive definite or not; if not, the algorithm uses a conjugate gradient step, described in the next section.

**Conjugate Gradient Step**

The conjugate gradient approach to solving the approximate problem Equation 6-51 is similar to other conjugate gradient calculations. In this case, the algorithm adjusts both $x$ and $s$, keeping the slacks $s$ positive. The
approach is to minimize a quadratic approximation to the approximate problem in a trust region, subject to linearized constraints.

Specifically, let $R$ denote the radius of the trust region, and let other variables be defined as in “Direct Step” on page 6-39. The algorithm obtains Lagrange multipliers by approximately solving the KKT equations

$$\nabla_x L = \nabla_x f(x) + \sum_i \lambda_i \nabla g_i(x) + \sum_j y_j \nabla h_j(x) = 0,$$

in the least-squares sense, subject to $\lambda$ being positive. Then it takes a step $(\Delta x, \Delta s)$ to approximately solve

$$\min_{\Delta x, \Delta s} \nabla f^T \Delta x + \frac{1}{2} \Delta x^T \nabla^2_{xx} L \Delta x + \mu e^T S^{-1} \Delta s + \frac{1}{2} \Delta s^T S^{-1} \Delta s,$$  \hspace{1cm} (6-54)

subject to the linearized constraints

$$g(x) + J_g \Delta x + \Delta s = 0, \quad h(x) + J_h \Delta x = 0.$$  \hspace{1cm} (6-55)

To solve Equation 6-55, the algorithm tries to minimize a norm of the linearized constraints inside a region with radius scaled by $R$. Then Equation 6-54 is solved with the constraints being to match the residual from solving Equation 6-55, staying within the trust region of radius $R$, and keeping $s$ strictly positive. For details of the algorithm and the derivation, see [40], [41], and [51]. For another description of conjugate gradients, see “Preconditioned Conjugate Gradient Method” on page 6-24.

**Interior-Point Algorithm Options**

Here are the meanings and effects of several options in the interior-point algorithm.

- **AlwaysHonorConstraints** – When set to 'bounds', every iterate satisfies the bound constraints you have set. When set to 'none', the algorithm may violate bounds during intermediate iterations.
- **Hessian** – When set to:
  - 'user-supplied', pass the Hessian of the Lagrangian in a user-supplied function, whose function handle must be given in the option HessFcn.
- `'bfgs'`, `fmincon` calculates the Hessian by a dense quasi-Newton approximation.
- `'lbfgs'`, `fmincon` calculates the Hessian by a limited-memory, large-scale quasi-Newton approximation.
- `'fin-diff-grads'`, `fmincon` calculates a Hessian-times-vector product by finite differences of the gradient(s); other options need to be set appropriately.

You can also give a separate function for Hessian-times-vector. See “Hessian” on page 11-47 for more details on these options.

- `InitBarrierParam` — The starting value for \( \mu \). By default, this is 0.1.
- `ScaleProblem` — When set to `'obj-and-constr'`, the algorithm works with scaled versions of the objective function and constraints. It carefully scales them by their initial values. Disable scaling by setting `ScaleProblem` to `'none'`.
- `SubproblemAlgorithm` — Determines whether or not to attempt the direct Newton step. The default setting `'ldl-factorization'` allows this type of step to be attempted. The setting `'cg'` allows only conjugate gradient steps.

For a complete list of options see “Interior-Point Algorithm” on page 11-58.

**fminbnd Algorithm**

`fminbnd` is a solver available in any MATLAB installation. It solves for a local minimum in one dimension within a bounded interval. It is not based on derivatives. Instead, it uses golden-section search and parabolic interpolation.

**fseminf Problem Formulation and Algorithm**

**fseminf Problem Formulation**

`fseminf` addresses optimization problems with additional types of constraints compared to those addressed by `fmincon`. The formulation of `fmincon` is

\[
\min_x f(x)
\]
such that \( c(x) \leq 0, \ ceq(x) = 0, \ A x \leq b, \ Aeq x = beq, \) and \( l \leq x \leq u. \)

`fseminf` adds the following set of semi-infinite constraints to those already given. For \( w_j \) in a one- or two-dimensional bounded interval or rectangle \( I_j \), for a vector of continuous functions \( K(x, w) \), the constraints are

\[
K_j(x, w_j) \leq 0 \text{ for all } w_j I_j.
\]

The term “dimension” of an `fseminf` problem means the maximal dimension of the constraint set \( I \): 1 if all \( I_j \) are intervals, and 2 if at least one \( I_j \) is a rectangle.

The size of the vector of \( K \) does not enter into this concept of dimension.

The reason this is called semi-infinite programming is that there are a finite number of variables \((x\) and \(w_j\)), but an infinite number of constraints. This is because the constraints on \(x\) are over a set of continuous intervals or rectangles \(I_j\), which contains an infinite number of points, so there are an infinite number of constraints: \(K_j(x, w_j) \leq 0\) for an infinite number of points \(w_j\).

You might think a problem with an infinite number of constraints is impossible to solve. `fseminf` addresses this by reformulating the problem to an equivalent one that has two stages: a maximization and a minimization. The semi-infinite constraints are reformulated as

\[
\max_{w_j \in I_j} K_j(x, w_j) \leq 0 \text{ for all } j = 1, ..., |K|,
\]

where \(|K|\) is the number of components of the vector \(K\); i.e., the number of semi-infinite constraint functions. For fixed \(x\), this is an ordinary maximization over bounded intervals or rectangles.

`fseminf` further simplifies the problem by making piecewise quadratic or cubic approximations \(\kappa_j(x, w_j)\) to the functions \(K_j(x, w_j)\), for each \(x\) that the solver visits. `fseminf` considers only the maxima of the interpolation function \(\kappa_j(x, w_j)\), instead of \(K_j(x, w_j)\), in Equation 6-56. This reduces the original problem, minimizing a semi-infinitely constrained function, to a problem with a finite number of constraints.

**Sampling Points.** Your semi-infinite constraint function must provide a set of sampling points, points used in making the quadratic or cubic approximations. To accomplish this, it should contain:
The initial spacing $s$ between sampling points $w$

A way of generating the set of sampling points $w$ from $s$

The initial spacing $s$ is a $|K|$-by-2 matrix. The $j$th row of $s$ represents the spacing for neighboring sampling points for the constraint function $K_j$. If $K_j$ depends on a one-dimensional $w_j$, set $s(j,2) = 0$. `fseminf` updates the matrix $s$ in subsequent iterations.

`fseminf` uses the matrix $s$ to generate the sampling points $w$, which it then uses to create the approximation $\kappa_j(x, w_j)$. Your procedure for generating $w$ from $s$ should keep the same intervals or rectangles $I_j$ during the optimization.

**Example of Creating Sampling Points.** Consider a problem with two semi-infinite constraints, $K_1$ and $K_2$. $K_1$ has one-dimensional $w_1$, and $K_2$ has two-dimensional $w_2$. The following code generates a sampling set from $w_1 = 2$ to 12:

```matlab
% Initial sampling interval
if isnan(s(1,1))
    s(1,1) = .2;
    s(1,2) = 0;
end

% Sampling set
w1 = 2:s(1,1):12;
```

`fseminf` specifies $s$ as NaN when it first calls your constraint function. Checking for this allows you to set the initial sampling interval.

The following code generates a sampling set from $w_2$ in a square, with each component going from 1 to 100, initially sampled more often in the first component than the second:

```matlab
% Initial sampling interval
if isnan(s(1,1))
    s(2,1) = 0.2;
    s(2,2) = 0.5;
end

% Sampling set
w2x = 1:s(2,1):100;
w2y = 1:s(2,2):100;
[wx,wy] = meshgrid(w2x,w2y);

The preceding code snippets can be simplified as follows:

```matlab
% Initial sampling interval
if isnan(s(1,1))
    s = [0.2 0;0.2 0.5];
end

% Sampling set
w1 = 2:s(1,1):12;
w2x = 1:s(2,1):100;
w2y = 1:s(2,2):100;
[wx,wy] = meshgrid(w2x,w2y);
```

**fseminf Algorithm**

*fseminf* essentially reduces the problem of semi-infinite programming to a problem addressed by *fmincon*. *fseminf* takes the following steps to solve semi-infinite programming problems:

1. At the current value of \( x \), *fseminf* identifies all the \( w_{j,i} \) such that the interpolation \( \kappa_j(x, w_{j,i}) \) is a local maximum. (The maximum refers to varying \( w \) for fixed \( x \).)

2. *fseminf* takes one iteration step in the solution of the *fmincon* problem:

   \[
   \min_x f(x)
   \]

   such that \( c(x) \leq 0\), \( ceq(x) = 0\), \( A x \leq b\), \( Aeq x = beq\), and \( l \leq x \leq u\), where \( c(x) \) is augmented with all the maxima of \( \kappa_j(x, w_j) \) taken over all \( w_j I_j \), which is equal to the maxima over \( j \) and \( i \) of \( \kappa_j(x, w_{j,i}) \).

3. *fseminf* checks if any stopping criterion is met at the new point \( x \) (to halt the iterations); if not, it continues to step 4.
4 \textbf{fseminf} checks if the discretization of the semi-infinite constraints needs updating, and updates the sampling points appropriately. This provides an updated approximation $\kappa_j(x, w)$. Then it continues at step 1.
Constrained Nonlinear Optimization Examples

In this section...

“Example: Nonlinear Inequality Constraints” on page 6-47
“Example: Bound Constraints” on page 6-49
“Example: Constraints With Gradients” on page 6-50
“Example: Constrained Minimization Using fmincon’s Interior-Point Algorithm with Analytic Hessian” on page 6-53
“Example: Equality and Inequality Constraints” on page 6-61
“Example: Nonlinear Minimization with Bound Constraints and Banded Preconditioner” on page 6-62
“Example: Nonlinear Minimization with Equality Constraints” on page 6-66
“Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68
“Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians” on page 6-72
“Example: One-Dimensional Semi-Infinite Constraints” on page 6-87
“Example: Two-Dimensional Semi-Infinite Constraint” on page 6-90

Example: Nonlinear Inequality Constraints

If inequality constraints are added to Equation 6-16, the resulting problem can be solved by the fmincon function. For example, find $x$ that solves

$$
\min_x f(x) = e^{x_1} \left( 4x_1^2 + 2x_2^2 + 4x_1x_2 + 2x_2 + 1 \right).
$$

subject to the constraints

$$
x_1x_2 - x_1 - x_2 \leq -1.5,
$$

$$
x_1x_2 \geq -10.
$$

Because neither of the constraints is linear, you cannot pass the constraints to fmincon at the command line. Instead you can create a second file, confun.m,
that returns the value at both constraints at the current \( x \) in a vector \( c \). The constrained optimizer, \texttt{fmincon}, is then invoked. Because \texttt{fmincon} expects the constraints to be written in the form \( c(x) \leq 0 \), you must rewrite your constraints in the form

\[
\begin{align*}
&x_1 x_2 - x_1 - x_2 + 1.5 \leq 0, \\
&-x_1 x_2 - 10 \leq 0.
\end{align*}
\] (6-58)

**Step 1: Write a file \texttt{objfun.m} for the objective function.**

```matlab
function f = objfun(x)
f = exp(x(1))*(4*x(1)^2 + 2*x(2)^2 + 4*x(1)*x(2) + 2*x(2) + 1);
```

**Step 2: Write a file \texttt{confun.m} for the constraints.**

```matlab
function [c, ceq] = confun(x)
% Nonlinear inequality constraints
c = [1.5 + x(1)*x(2) - x(1) - x(2);
    -x(1)*x(2) - 10];
% Nonlinear equality constraints
ceq = [];
```

**Step 3: Invoke constrained optimization routine.**

```matlab
x0 = [-1,1]; % Make a starting guess at the solution
options = optimset('Algorithm','active-set');
[x,fval] = ...
fmincon(@objfun,x0,[],[],[],[],[],[],@confun,options);
```

\texttt{fmincon} produces the solution \( x \) with function value \( fval \):

```
x, fval
x =
   -9.5474  1.0474
fval =
   0.0236
```

You can evaluate the constraints at the solution by entering
\[ [c, ceq] = \text{confun}(x) \]

This returns numbers close to zero, such as

\[
c = \\
1.0e-007 * \\
-0.9032 \\
0.9032
\]

\[
ceq = \\
[]
\]

Note that both constraint values are, to within a small tolerance, less than or equal to 0; that is, \( x \) satisfies \( c(x) \leq 0 \).

**Example: Bound Constraints**

The variables in \( x \) can be restricted to certain limits by specifying simple bound constraints to the constrained optimizer function. For \text{fmincon}, the command

\[
x = \text{fmincon}(@\text{objfun}, x0, [], [], [], [], lb, ub, @\text{confun}, \text{options});
\]

limits \( x \) to be within the range \( lb \leq x \leq ub \).

To restrict \( x \) in Equation 6-57 to be greater than 0 (i.e., \( x_1 \geq 0, x_1 \geq 0 \)), use the commands

\[
x0 = [-1,1]; \quad % \text{Make a starting guess at the solution}
\]
\[
1b = [0,0]; \quad % \text{Set lower bounds}
\]
\[
ub = []; \quad % \text{No upper bounds}
\]
\[
options = \text{optimset('Algorithm','active-set');}
\]
\[
[x, fval] = ... \\
\text{fmincon}(@\text{objfun}, x0, [], [], [], [], lb, ub, @\text{confun}, \text{options});
\]

Note that to pass in the lower bounds as the seventh argument to \text{fmincon}, you must specify values for the third through sixth arguments. In this example, we specified \( [] \) for these arguments since there are no linear inequalities or linear equalities.

\text{fmincon} produces the following results:
When \( lb \) or \( ub \) contains fewer elements than \( x \), only the first corresponding elements in \( x \) are bounded. Alternatively, if only some of the variables are bounded, then use \(-\infty\) in \( lb \) for unbounded below variables and \( \infty \) in \( ub \) for unbounded above variables. For example,

\[
\begin{align*}
\mathbf{lb} &= [-\infty \ 0]; \\
\mathbf{ub} &= [10 \ \infty];
\end{align*}
\]

bounds \( x_1 \leq 10, \ x_2 \geq 0 \). \( x_1 \) has no lower bound, and \( x_2 \) has no upper bound. Using \( \infty \) and \( -\infty \) give better numerical results than using a very large positive number or a very large negative number to imply lack of bounds.

Note that the number of function evaluations to find the solution is reduced because we further restricted the search space. Fewer function evaluations are usually taken when a problem has more constraints and bound limitations because the optimization makes better decisions regarding step size and regions of feasibility than in the unconstrained case. It is, therefore, good practice to bound and constrain problems, where possible, to promote fast convergence to a solution.

**Example: Constraints With Gradients**

Ordinarily the medium-scale minimization routines use numerical gradients calculated by finite-difference approximation. This procedure systematically perturbs each of the variables in order to calculate function and constraint partial derivatives. Alternatively, you can provide a function to compute partial derivatives analytically. Typically, the problem is solved more accurately and efficiently if such a function is provided.

To solve Equation 6-57 using analytically determined gradients, do the following.
**Step 1: Write a file for the objective function and gradient.**

```
function [f,G] = objfungrad(x)
f = exp(x(1))*(4*x(1)^2+2*x(2)^2+4*x(1)*x(2)+2*x(2)+1);
% Gradient of the objective function
if nargout > 1
    G = [ f + exp(x(1)) * (8*x(1) + 4*x(2)),
         exp(x(1))*(4*x(1)+4*x(2)+2)];
end
```

**Step 2: Write a file for the nonlinear constraints and the gradients of the nonlinear constraints.**

```
function [c,ceq,DC,DCeq] = confungrad(x)
c(1) = 1.5 + x(1) * x(2) - x(1) - x(2); % Inequality constraints
if nargout > 2
    DC = [x(2)-1, -x(2);
          x(1)-1, -x(1)];
    DCeq = [];
else
    c(2) = -x(1) * x(2)-10;
end
```

\[ \nabla f = \begin{bmatrix} e^{x_1} \left( 4x_1^2 + 2x_2^2 + 4x_1x_2 + 2x_2 + 1 \right) + e^{x_1} \left( 8x_1 + 4x_2 \right) \\
                  e^{x_1} \left( 4x_1 + 4x_2 + 2 \right) \end{bmatrix} \]  \hspace{1cm} (6-59)

The columns of DC contain the partial derivatives for each respective constraint (i.e., the \(i\)th column of DC is the partial derivative of the \(i\)th constraint with respect to \(x\)). So in the above example, DC is
Since you are providing the gradient of the objective in `objfungrad.m` and the gradient of the constraints in `confungrad.m`, you must tell `fmincon` that these files contain this additional information. Use `optimset` to turn the options `GradObj` and `GradConstr` to 'on' in the example's existing options structure:

```matlab
options = optimset(options,'GradObj','on','GradConstr','on');
```

If you do not set these options to 'on' in the options structure, `fmincon` does not use the analytic gradients.

The arguments `lb` and `ub` place lower and upper bounds on the independent variables in `x`. In this example, there are no bound constraints and so they are both set to `[]`.

Step 3: Invoke the constrained optimization routine.

```matlab
x0 = [-1,1]; % Starting guess
options = optimset('Algorithm','active-set');
options = optimset(options,'GradObj','on','GradConstr','on');
lb = []; ub = []; % No upper or lower bounds
[x,fval] = fmincon(@objfungrad,x0,[],[],[],[],lb,ub,...
    @confungrad,options);
```

The results:

```matlab
x, fval
x =
   -9.5474   1.0474
fval =
   0.0236
```

```matlab
[c,ceq] = confungrad(x) % Check the constraint values at x
```

```matlab
c =
   1.0e-007 *
```
Example: Constrained Minimization Using fmincon’s Interior-Point Algorithm with Analytic Hessian

The fmincon interior-point algorithm can accept a Hessian function as an input. When you supply a Hessian, you may obtain a faster, more accurate solution to a constrained minimization problem.

The constraint set for this example is the intersection of the interior of two cones—one pointing up, and one pointing down. The constraint function $c$ is a two-component vector, one component for each cone. Since this is a three-dimensional example, the gradient of the constraint $c$ is a 3-by-2 matrix.

```matlab
function [c ceq gradc gradceq] = twocone(x)
% This constraint is two cones, z > -10 + r
% and z < 3 - r
ceq = [];
r = sqrt(x(1)^2 + x(2)^2);
c = [-10+r-x(3);
     x(3)-3+r];
if nargout > 2
    gradceq = [];
    gradc = [x(1)/r,x(1)/r;
             x(2)/r,x(2)/r;
             -1,1];
end
```

The objective function grows rapidly negative as the $x(1)$ coordinate becomes negative. Its gradient is a three-element vector.

```matlab
function [f gradf] = bigtoleft(x)
% This is a simple function that grows rapidly negative
% as x(1) gets negative
```
\%  
\texttt{f=10*x(1)^3+x(1)*x(2)^2+x(3)*(x(1)^2+x(2)^2);  

if nargout > 1  
  
  \texttt{gradf=[30*x(1)^2+x(2)^2+2*x(3)*x(1);  
                 2*x(1)*x(2)+2*x(3)*x(2);  
                 (x(1)^2+x(2)^2)];  

end  

Here is a plot of the problem. The shading represents the value of the  
objective function. You can see that the objective function is minimized near  
\texttt{x = [-6.5,0,-3.5]};}
The Hessian of the Lagrangian is given by the equation:

$$\nabla_{xx}^2 L(x, \lambda) = \nabla^2 f(x) + \sum \lambda_i \nabla^2 c_i(x) + \sum \lambda_i \nabla^2 ceq_i(x).$$

The following function computes the Hessian at a point $x$ with Lagrange multiplier structure $\lambda$:

```matlab
function h = hessinterior(x,lambda)
```

6-55
h = [60*x(1)+2*x(3),2*x(2),2*x(1); 2*x(2),2*(x(1)+x(3)),2*x(2); 2*x(1),2*x(2),0];% Hessian of f
r = sqrt(x(1)^2+x(2)^2);% radius
rinv3 = 1/r^3;
hessc = [(x(2))^2*rinv3,-x(1)*x(2)*rinv3,0; -x(1)*x(2)*rinv3,x(1)^2*rinv3,0; 0,0,0];% Hessian of both c(1) and c(2)
h = h + lambda.ineqnonlin(1)*hessc + lambda.ineqnonlin(2)*hessc;

Run this problem using the interior-point algorithm in \texttt{fmincon}. To do this using the Optimization Tool:

1. Set the problem as in the following figure.

![Optimization Tool Figure](example.png)

2. For iterative output, scroll to the bottom of the \texttt{Options} pane and select \texttt{Level of display}, \texttt{iterative}.
3 In the **Options** pane, give the analytic Hessian function handle.

4 Under **Run solver and view results**, click **Start**.
To perform the minimization at the command line:

1 Set options as follows:

   options = optimset('Algorithm','interior-point',...
       'Display','iter','GradObj','on','GradConstr','on',...
       'Hessian','user-supplied','HessFcn',@hessinterior);

2 Run fmincon with starting point \([-1,-1,-1]\), using the options structure:

   [x fval mflag output]=fmincon(@bigtoleft,[-1,-1,-1],...
       [],[],[],[],[],[],@twocone,options)

The output is:

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Feasibility</th>
<th>optimality</th>
<th>Norm of step</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>-1.300000e+01</td>
<td>0.000e+000</td>
<td>3.067e+001</td>
<td></td>
</tr>
</tbody>
</table>
Constrained Nonlinear Optimization Examples

1  2  -2.011543e+002  0.000e+000  1.739e+002  1.677e+000
2  3  -1.270471e+003  9.844e-002  3.378e+002  2.410e+000
3  4  -2.881667e+003  1.937e-002  1.079e+002  2.206e+000
4  5  -2.931003e+003  2.798e-002  5.813e+000  6.006e-001
5  6  -2.894085e+003  0.000e+000  2.352e-002  2.800e-002
6  7  -2.894125e+003  0.000e+000  5.981e-005  3.048e-005

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

x =
   -6.5000   -0.0000   -3.5000

fval =
   -2.8941e+003

mflag =
   1

output =
   iterations: 6
   funcCount: 7
   constrviolation: 0
   stepsize: 3.0479e-005
   algorithm: 'interior-point'
   firstorderopt: 5.9812e-005
   cgiterations: 3
   message: [1x782 char]

If you do not use a Hessian function, `fmincon` takes 9 iterations to converge, instead of 6:

options = optimset('Algorithm','interior-point',... 
                 'Display','iter','GradObj','on','GradConstr','on');
[x fval mflag output]=fmincon(@bigtoleft,[-1,-1,-1],... 
    [],[],[],[],[],[],@twocone,options)

First-order Norm of
Optimization Algorithms and Examples

<table>
<thead>
<tr>
<th>Iter</th>
<th>F-count</th>
<th>f(x)</th>
<th>Feasibility</th>
<th>optimality</th>
<th>step</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>-1.3000000e+001</td>
<td>0.000e+000</td>
<td>3.067e+001</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>-7.259551e+003</td>
<td>2.495e+000</td>
<td>2.414e+003</td>
<td>8.344e+000</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-7.361301e+003</td>
<td>2.529e+000</td>
<td>2.767e+001</td>
<td>5.253e-002</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-2.978165e+003</td>
<td>9.392e-002</td>
<td>1.069e+003</td>
<td>2.462e+000</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>-3.033486e+003</td>
<td>1.050e-001</td>
<td>8.282e+002</td>
<td>6.749e-001</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>-2.893740e+003</td>
<td>0.000e+000</td>
<td>4.186e+001</td>
<td>1.053e-001</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>-2.894074e+003</td>
<td>0.000e+000</td>
<td>2.637e-001</td>
<td>3.565e-004</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>-2.894124e+003</td>
<td>0.000e+000</td>
<td>2.340e-001</td>
<td>1.680e-004</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>-2.894125e+003</td>
<td>2.830e-008</td>
<td>1.180e-001</td>
<td>6.374e-004</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>-2.894125e+003</td>
<td>2.939e-008</td>
<td>1.423e-004</td>
<td>6.484e-004</td>
</tr>
</tbody>
</table>

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

x =
-6.5000  -0.0000  -3.5000

fval =
-2.8941e+003

mflag =
1

output =
iterations: 9
funcCount: 13
constrviolation: 2.9391e-008
stepsize: 6.4842e-004
algorithm: 'interior-point'
firstorderopt: 1.4235e-004
cgiterations: 0
message: [1x782 char]

Both runs lead to similar solutions, but the F-count and number of iterations are lower when using an analytic Hessian.
Example: Equality and Inequality Constraints

For routines that permit equality constraints, nonlinear equality constraints must be computed with the nonlinear inequality constraints. For linear equalities, the coefficients of the equalities are passed in through the matrix $A_{eq}$ and the right-hand-side vector $b_{eq}$.

For example, if you have the nonlinear equality constraint $x_1^2 + x_2 = 1$ and the nonlinear inequality constraint $x_1 x_2 \geq -10$, rewrite them as

$$
\begin{align*}
  x_1^2 + x_2 - 1 &= 0, \\
  -x_1 x_2 - 10 &\leq 0,
\end{align*}
$$

and then solve the problem using the following steps.

Step 1: Write a file objfun.m.

```matlab
function f = objfun(x)
    f = exp(x(1))*(4*x(1)^2+2*x(2)^2+4*x(1)*x(2)+2*x(2)+1);
end
```

Step 2: Write a file confuneq.m for the nonlinear constraints.

```matlab
function [c, ceq] = confuneq(x)
    % Nonlinear inequality constraints
    c = -x(1)*x(2) - 10;
    % Nonlinear equality constraints
    ceq = x(1)^2 + x(2) - 1;
end
```

Step 3: Invoke constrained optimization routine.

```matlab
x0 = [-1,1]; % Make a starting guess at the solution
options = optimset('Algorithm','active-set');
[x,fval] = fmincon(@objfun,x0,[],[],[],[],[],[],...
    @confuneq,options);
```

After 21 function evaluations, the solution produced is
x, fval
x =
-0.7529  0.4332
fval =
1.5093

[c, ceq] = confuneq(x) % Check the constraint values at x

c =
-9.6739
ceq =
6.3038e-009

Note that ceq is equal to 0 within the default tolerance on the constraints of 1.0e-006 and that c is less than or equal to 0 as desired.

**Example: Nonlinear Minimization with Bound Constraints and Banded Preconditioner**

The goal in this problem is to minimize the nonlinear function

\[
f(x) = 1 + \sum_{i=1}^{n} \left| (3 - 2x_i) x_i - x_{i-1} - x_{i+1} + 1 \right|^p + \sum_{i=1}^{n/2} \left| x_i + x_{i+n/2} \right|^p,
\]

such that -10.0 ≤ x_i ≤ 10.0, where n is 800 (n should be a multiple of 4), p = 7/3, and \(x_0 = x_{n+1} = 0\).

**Step 1: Write a file tbroyfg.m that computes the objective function and the gradient of the objective**

The tbroyfg.m file computes the function value and gradient. This file is long and is not included here. You can see the code for this function using the command

```
type tbroyfg
```

The sparsity pattern of the Hessian matrix has been predetermined and stored in the file tbroyhstr.mat. The sparsity structure for the Hessian of this problem is banded, as you can see in the following spy plot.
In this plot, the center stripe is itself a five-banded matrix. The following plot shows the matrix more clearly:

```matlab
spy(Hstr(1:20,1:20))
```
Use `optimset` to set the `HessPattern` parameter to `Hstr`. When a problem as large as this has obvious sparsity structure, not setting the `HessPattern` parameter requires a huge amount of unnecessary memory and computation. This is because `fmincon` attempts to use finite differencing on a full Hessian matrix of 640,000 nonzero entries.

You must also set the `GradObj` parameter to 'on' using `optimset`, since the gradient is computed in `tbroyfg.m`. Then execute `fmincon` as shown in Step 2.

**Step 2: Call a nonlinear minimization routine with a starting point `xstart`.**

```matlab
fun = @tbroyfg;
load tbroyhstr % Get Hstr, structure of the Hessian
n = 800;
xstart = -ones(n,1); xstart(2:2:n) = 1;
lb = -10*ones(n,1); ub = -lb;
options = optimset('GradObj','on','HessPattern',Hstr);

[x,fval,exitflag,output] = ...  
    fmincon(fun,xstart,[],[],[],[],lb,ub,[],options);
```
After seven iterations, the exitflag, fval, and output values are

```matlab
exitflag =
  3
fval =
  270.4790
output =
  iterations: 7
  funcCount: 8
  cgiterations: 18
  firstorderopt: 0.0163
  algorithm: 'trust-region-reflective'
  message: [1x472 char]
  constrviolation: 0
```

For bound constrained problems, the first-order optimality is the infinity norm of \(v^*g\), where \(v\) is defined as in “Box Constraints” on page 6-25, and \(g\) is the gradient.

Because of the five-banded center stripe, you can improve the solution by using a five-banded preconditioner instead of the default diagonal preconditioner. Using the `optimset` function, reset the `PrecondBandWidth` parameter to 2 and solve the problem again. (The bandwidth is the number of upper (or lower) diagonals, not counting the main diagonal.)

```matlab
fun = @tbroyfg;
load tbroyhstr % Get Hstr, structure of the Hessian
n = 800;
xstart = -ones(n,1); xstart(2:2:n,1) = 1;
lb = -10*ones(n,1); ub = -lb;
options = optimset('GradObj','on','HessPattern',Hstr, ... 
  'PrecondBandWidth',2);
[x,fval,exitflag,output] = ...
  fmincon(fun,xstart,[],[],[],[],lb,ub,[],options);
```

The number of iterations actually goes up by two; however the total number of CG iterations drops from 18 to 15. The first-order optimality measure is reduced by a factor of \(10^{-3}\):
Optimization Algorithms and Examples

exitflag =
    3

fval =
    270.4790

output =
    iterations: 9
    funcCount: 10
    cgiterations: 15
    firstorderopt: 7.5340e-005
    algorithm: 'trust-region-reflective'
    message: [1x472 char]
    constrviolation: 0

Example: Nonlinear Minimization with Equality Constraints

The trust-region reflective method for fmincon can handle equality constraints if no other constraints exist. Suppose you want to minimize the same objective as in Equation 6-17, which is coded in the function brownfgh.m, where \( n = 1000 \), such that \( Aeq \cdot x = beq \) for \( Aeq \) that has 100 equations (so \( Aeq \) is a 100-by-1000 matrix).

Step 1: Write a file brownfgh.m that computes the objective function, the gradient of the objective, and the sparse tridiagonal Hessian matrix.

The file is lengthy so is not included here. View the code with the command

type brownfgh

Because brownfgh computes the gradient and Hessian values as well as the objective function, you need to use optimset to indicate that this information is available in brownfgh, using the GradObj and Hessian options.

The sparse matrix \( Aeq \) and vector \( beq \) are available in the file browneq.mat:

load browneq
The linear constraint system is 100-by-1000, has unstructured sparsity (use \texttt{spy(Aeq)} to view the sparsity structure), and is not too badly ill-conditioned:

\begin{verbatim}
condest(Aeq*Aeq')
ans =
  2.9310e+006
\end{verbatim}

**Step 2: Call a nonlinear minimization routine with a starting point \texttt{xstart}.

\begin{verbatim}
fun = @brownfgh;
load browneq % Get Aeq and beq, the linear equalities
n = 1000;
xstart = -ones(n,1); xstart(2:2:n) = 1;
options = optimset('GradObj','on','Hessian','on');
[x,fval,exitflag,output] = ...
    fmincon(fun,xstart,[],[],Aeq,beq,[],[],[],options);
\end{verbatim}

\texttt{fmincon} prints the following exit message:

\begin{verbatim}
Local minimum possible.
\end{verbatim}

\texttt{fmincon} stopped because the final change in function value relative to its initial value is less than the default value of the function tolerance.

The \texttt{exitflag} value of 3 also indicates that the algorithm terminated because the change in the objective function value was less than the tolerance \texttt{TolFun}. The final function value is given by \texttt{fval}.

\begin{verbatim}
exitflag,fval,output
\end{verbatim}

\texttt{exitflag} =

\begin{verbatim}
3
\end{verbatim}

\texttt{fval} =

\begin{verbatim}
205.9313
\end{verbatim}

\texttt{output} =

\begin{verbatim}
    iterations: 22
    funcCount: 23
    cgiterations: 30
\end{verbatim}
Optimization Algorithms and Examples

The firstorderopt: 0.0027
algorithm: 'trust-region-reflective'
message: [1x472 char]
constrviolation: 2.2249e-013

The linear equalities are satisfied at x.

\[
\text{norm}(Aeq \times x - beq)
\]

\[
\text{ans} = \\
1.1957\text{e-012}
\]

**Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints**

The `fmincon` interior-point and trust-region reflective algorithms, and the `fminunc` large-scale algorithm can solve problems where the Hessian is dense but structured. For these problems, `fmincon` and `fminunc` do not compute \( H \times Y \) with the Hessian \( H \) directly, because forming \( H \) would be memory-intensive. Instead, you must provide `fmincon` or `fminunc` with a function that, given a matrix \( Y \) and information about \( H \), computes \( W = H \times Y \).

In this example, the objective function is nonlinear and linear equalities exist so `fmincon` is used. The description applies to the trust-region reflective algorithm; the `fminunc` large-scale algorithm is similar. For the interior-point algorithm, see the 'HessMult' option in “Hessian” on page 11-47. The objective function has the structure

\[
f(x) = \hat{f}(x) - \frac{1}{2} x^T V V^T x,
\]

where \( V \) is a 1000-by-2 matrix. The Hessian of \( f \) is dense, but the Hessian of \( \hat{f} \) is sparse. If the Hessian of \( \hat{f} \) is \( \hat{H} \), then \( H \), the Hessian of \( f \), is

\[
H = \hat{H} - V V^T.
\]

To avoid excessive memory usage that could happen by working with \( H \) directly, the example provides a Hessian multiply function, `hmfleq1`. This
function, when passed a matrix \( Y \), uses sparse matrices \( H_{info} \), which corresponds to \( \hat{H} \), and \( V \) to compute the Hessian matrix product

\[
W = H*Y = (H_{info} - V*V')*Y
\]

In this example, the Hessian multiply function needs \( \hat{H} \) and \( V \) to compute the Hessian matrix product. \( V \) is a constant, so you can capture \( V \) in a function handle to an anonymous function.

However, \( \hat{H} \) is not a constant and must be computed at the current \( x \). You can do this by computing \( \hat{H} \) in the objective function and returning \( \hat{H} \) as \( H_{info} \) in the third output argument. By using \texttt{optimset} to set the 'Hessian' options to 'on', \texttt{fmincon} knows to get the \( H_{info} \) value from the objective function and pass it to the Hessian multiply function \texttt{hmfleq1}.

**Step 1: Write a file brownvv.m that computes the objective function, the gradient, and the sparse part of the Hessian.**

The example passes \texttt{brownvv} to \texttt{fmincon} as the objective function. The \texttt{brownvv.m} file is long and is not included here. You can view the code with the command

```
type brownvv
```

Because \texttt{brownvv} computes the gradient and part of the Hessian as well as the objective function, the example (Step 3) uses \texttt{optimset} to set the \texttt{GradObj} and Hessian options to 'on'.

**Step 2: Write a function to compute Hessian-matrix products for \( H \) given a matrix \( Y \).**

Now, define a function \texttt{hmfleq1} that uses \( H_{info} \), which is computed in \texttt{brownvv}, and \( V \), which you can capture in a function handle to an anonymous function, to compute the Hessian matrix product \( W \) where

\[
W = H*Y = (H_{info} - V*V')*Y.
\]

This function must have the form

```
W = hmfleq1(Hinfo,Y)
```
The first argument must be the same as the third argument returned by the objective function `brownvv`. The second argument to the Hessian multiply function is the matrix \( Y \) (of \( W = H*Y \)).

Because `fmincon` expects the second argument \( Y \) to be used to form the Hessian matrix product, \( Y \) is always a matrix with \( n \) rows where \( n \) is the number of dimensions in the problem. The number of columns in \( Y \) can vary. Finally, you can use a function handle to an anonymous function to capture \( V \), so \( V \) can be the third argument to `hmfleq1`.

```matlab
function W = hmfleq1(Hinfo,Y,V);
%HMFLQ1 Hessian-matrix product function for BROWNVV objective.
% W = hmfleq1(Hinfo,Y,V) computes W = (Hinfo-V*V')*Y
% where Hinfo is a sparse matrix computed by BROWNVV
% and V is a 2 column matrix.
W = Hinfo*Y - V*(V'*Y);
```

**Note** The function `hmfleq1` is available in the `optimdemos` folder as `hmfleq1.m`.

---

**Step 3: Call a nonlinear minimization routine with a starting point and linear equality constraints.**

Load the problem parameter, \( V \), and the sparse equality constraint matrices, \( Aeq \) and \( beq \), from `fleq1.mat`, which is available in the `optimdemos` folder. Use `optimset` to set the `GradObj` and `Hessian` options to `'on'` and to set the `HessMult` option to a function handle that points to `hmfleq1`. Call `fmincon` with objective function `brownvv` and with \( V \) as an additional parameter:

```matlab
function [fval, exitflag, output, x] = runfleq1
% RUNFLEQ1 demonstrates 'HessMult' option for
% FMINCON with linear equalities.

% Copyright 1984-2006 The MathWorks, Inc.
% $Revision: 1.1.6.26 $ $Date: 2011/05/16 22:11:38 $

problem = load('fleq1'); % Get V, Aeq, beq
V = problem.V; Aeq = problem.Aeq; beq = problem.beq;
n = 1000; % problem dimension
```
xstart = -ones(n,1); xstart(2:2:n,1) = ones(length(2:2:n),1); % starting point
options = optimset('GradObj','on','Hessian','on','HessMult',... @(Hinfo,Y)hmflc1(Hinfo,Y,V), 'Display','iter','TolFun',1e-9);
[x,fval,exitflag,output] = fmincon(@(x)brownvv(x,V),...
xstart,[],[],Aeq,beq,[],[],[],options);

To run the preceding code, enter

[fval,exitflag,output,x] = runflc1;

Because the iterative display was set using optimset, this command generates the following iterative display:

<table>
<thead>
<tr>
<th>Iteration</th>
<th>f(x)</th>
<th>Norm of first-order step</th>
<th>Norm of optimality</th>
<th>CG-iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1997.07</td>
<td>916</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1072.57</td>
<td>6.31716</td>
<td>465</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>480.247</td>
<td>8.19711</td>
<td>201</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>136.982</td>
<td>10.3039</td>
<td>78.1</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>44.416</td>
<td>9.04685</td>
<td>16.7</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>44.416</td>
<td>100</td>
<td>16.7</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>44.416</td>
<td>25</td>
<td>16.7</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>-9.05631</td>
<td>6.25</td>
<td>52.9</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>-317.437</td>
<td>12.5</td>
<td>91.7</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>-405.381</td>
<td>12.5</td>
<td>1.11e+003</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>-451.161</td>
<td>3.125</td>
<td>327</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>-482.688</td>
<td>0.78125</td>
<td>303</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>-547.427</td>
<td>1.5625</td>
<td>187</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>-610.42</td>
<td>1.5625</td>
<td>251</td>
<td>7</td>
</tr>
<tr>
<td>14</td>
<td>-711.522</td>
<td>1.5625</td>
<td>143</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>-802.98</td>
<td>3.125</td>
<td>165</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>-820.431</td>
<td>1.13329</td>
<td>32.9</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>-822.996</td>
<td>0.492813</td>
<td>7.61</td>
<td>2</td>
</tr>
<tr>
<td>18</td>
<td>-823.236</td>
<td>0.223154</td>
<td>1.68</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>-823.245</td>
<td>0.056205</td>
<td>0.529</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>-823.246</td>
<td>0.0150139</td>
<td>0.0342</td>
<td>5</td>
</tr>
<tr>
<td>21</td>
<td>-823.246</td>
<td>0.00479085</td>
<td>0.0152</td>
<td>7</td>
</tr>
<tr>
<td>22</td>
<td>-823.246</td>
<td>0.00353697</td>
<td>0.00828</td>
<td>9</td>
</tr>
<tr>
<td>23</td>
<td>-823.246</td>
<td>0.000884424</td>
<td>0.005</td>
<td>9</td>
</tr>
<tr>
<td>24</td>
<td>-823.246</td>
<td>0.0012715</td>
<td>0.00125</td>
<td>9</td>
</tr>
</tbody>
</table>
Local minimum possible.

fmincon stopped because the final change in function value relative to its initial value is less than the selected value of the function tolerance.

Convergence is rapid for a problem of this size with the PCG iteration cost increasing modestly as the optimization progresses. Feasibility of the equality constraints is maintained at the solution.

```matlab
problem = load('fleq1'); % Get V, Aeq, beq
V = problem.V; Aeq = problem.Aeq; beq = problem.beq;

norm(Aeq*x-beq,inf)
```

```
ans =
    2.4869e-014
```

**Preconditioning**

In this example, `fmincon` cannot use $H$ to compute a preconditioner because $H$ only exists implicitly. Instead of $H$, `fmincon` uses $Hinfo$, the third argument returned by `brownvv`, to compute a preconditioner. $Hinfo$ is a good choice because it is the same size as $H$ and approximates $H$ to some degree. If $Hinfo$ were not the same size as $H$, `fmincon` would compute a preconditioner based on some diagonal scaling matrices determined from the algorithm. Typically, this would not perform as well.

**Example: Using Symbolic Math Toolbox Functions to Calculate Gradients and Hessians**

If you have a license for Symbolic Math Toolbox functions, you can use these functions to calculate analytic gradients and Hessians for objective and constraint functions. There are two relevant Symbolic Math Toolbox functions:

- `jacobian` generates the gradient of a scalar function, and generates a matrix of the partial derivatives of a vector function. So, for example, you can obtain the Hessian matrix, the second derivatives of the objective function, by applying `jacobian` to the gradient. Part of this example shows
how to use \texttt{jacobian} to generate symbolic gradients and Hessians of objective and constraint functions.

- \texttt{matlabFunction} generates either an anonymous function or a file that calculates the values of a symbolic expression. This example shows how to use \texttt{matlabFunction} to generate files that evaluate the objective and constraint function and their derivatives at arbitrary points.

Consider the electrostatics problem of placing 10 electrons in a conducting body. The electrons will arrange themselves so as to minimize their total potential energy, subject to the constraint of lying inside the body. It is well known that all the electrons will be on the boundary of the body at a minimum. The electrons are indistinguishable, so there is no unique minimum for this problem (permuting the electrons in one solution gives another valid solution). This example was inspired by Dolan, Moré, and Munson [58].

This example is a conducting body defined by the following inequalities:

\begin{align}
  z & \leq -|x| - |y| \\
  x^2 + y^2 + (z + 1)^2 & \leq 1.
\end{align}

This body looks like a pyramid on a sphere.
There is a slight gap between the upper and lower surfaces of the figure. This is an artifact of the general plotting routine used to create the figure. This routine erases any rectangular patch on one surface that touches the other surface.

The syntax and structures of the two sets of toolbox functions differ. In particular, symbolic variables are real or complex scalars, but Optimization Toolbox functions pass vector arguments. So there are several steps to take to generate symbolically the objective function, constraints, and all their requisite derivatives, in a form suitable for the interior-point algorithm of fmincon:
To see the efficiency in using gradients and Hessians, see “Compare to Optimization Without Gradients and Hessians” on page 6-85.

Create the Variables

Generate a symbolic vector \( x \) as a 30-by-1 vector composed of real symbolic variables \( x_{ij} \), \( i \) between 1 and 10, and \( j \) between 1 and 3. These variables represent the three coordinates of electron \( i \): \( x_{i1} \) corresponds to the \( x \) coordinate, \( x_{i2} \) corresponds to the \( y \) coordinate, and \( x_{i3} \) corresponds to the \( z \) coordinate.

\[
x = \text{cell}(3, 10);
\text{for } i = 1:10
   \text{for } j = 1:3
      x{[j,i]} = \text{sprintf}('x%d%d',i,j);
   \text{end}
\text{end}
x = \text{x(:); % now } x \text{ is a 30-by-1 vector}
x = \text{sym}(x, 'real');
\]

The vector \( x \) is:

\[
x
\]
Include the Linear Constraints

Write the linear constraints in Equation 6-61,

\[ z \leq -|x| - |y|, \]

as a set of four linear inequalities for each electron:
\[\begin{align*}
\xi_3 - \xi_1 - \xi_2 &\leq 0 \\
\xi_3 - \xi_1 + \xi_2 &\leq 0 \\
\xi_3 + \xi_1 - \xi_2 &\leq 0 \\
\xi_3 + \xi_1 + \xi_2 &\leq 0
\end{align*}\]

Therefore there are a total of 40 linear inequalities for this problem.

Write the inequalities in a structured way:

\[
B = \begin{bmatrix} 1,1,1; -1,1,1; 1,-1,1; -1,-1,1 \end{bmatrix};
\]

\[
A = \text{zeros}(40,30);
\]

\[
\text{for } i=1:10
\]
\[
A(4*i-3:4*i,3*i-2:3*i) = B;
\]
\[
\text{end}
\]

\[
b = \text{zeros}(40,1);
\]

You can see that \(A*x \quad b\) represents the inequalities:

\[
A*x
\]

\[
\text{ans} =
\]
\[
\begin{align*}
x_{11} &+ x_{12} + x_{13} \\
x_{12} &- x_{11} + x_{13} \\
x_{11} &- x_{12} + x_{13} \\
x_{13} &- x_{12} - x_{11} \\
x_{21} &+ x_{22} + x_{23} \\
x_{22} &- x_{21} + x_{23} \\
x_{21} &- x_{22} + x_{23} \\
x_{23} &- x_{22} - x_{21} \\
x_{31} &+ x_{32} + x_{33} \\
x_{32} &- x_{31} + x_{33} \\
x_{31} &- x_{32} + x_{33} \\
x_{33} &- x_{32} - x_{31} \\
x_{41} &+ x_{42} + x_{43} \\
x_{42} &- x_{41} + x_{43} \\
x_{41} &- x_{42} + x_{43} \\
x_{43} &- x_{42} - x_{41} \\
x_{51} &+ x_{52} + x_{53} \\
x_{52} &- x_{51} + x_{53}
\end{align*}
\]
Create the Nonlinear Constraints, Their Gradients and Hessians

The nonlinear constraints in Equation 6-62,

\[ x^2 + y^2 + (z+1)^2 \leq 1, \]

are also structured. Generate the constraints, their gradients, and Hessians as follows:

\[
c = \text{sym(zeros}(1,10));
\]

\[
i = 1:10;
\]

\[
c = (x(3*i-2).^2 + x(3*i-1).^2 + (x(3*i)+1).^2 - 1).';
\]

\[
\text{gradc = jacobian(c,x).'}; \% .' performs transpose
\]

\[
\text{hessc = cell}(1, 10);
\]

\[
\text{for } i = 1:10
\]
The constraint vector \( \mathbf{c} \) is a row vector, and the gradient of \( \mathbf{c}(i) \) is represented in the \( i \)th column of the matrix \( \mathbf{gradc} \). This is the correct form, as described in “Nonlinear Constraints” on page 2-33.

The Hessian matrices, \( \mathbf{hessc}(1) \ldots \mathbf{hessc}(10) \), are square and symmetric. It is better to store them in a cell array, as is done here, than in separate variables such as \( \mathbf{hessc1}, \ldots, \mathbf{hessc10} \).

Use the \( .' \) syntax to transpose. The \( .' \) syntax means conjugate transpose, which has different symbolic derivatives.

**Create the Objective Function, Its Gradient and Hessian**

The objective function, potential energy, is the sum of the inverses of the distances between each electron pair:

\[
\text{energy} = \sum_{i<j} \frac{1}{|x_i - x_j|}
\]

The distance is the square root of the sum of the squares of the differences in the components of the vectors.

Calculate the energy, its gradient, and its Hessian as follows:

```matlab
energy = sym(0);
for i = 1:3:25
    for j = i+3:3:28
        dist = x(i:i+2) - x(j:j+2);
        energy = energy + 1/sqrt(dist.'*dist);
    end
end

gradenergy = jacobian(energy,x).';

hessenergy = jacobian(gradenergy,x);
```
Create the Objective Function File

The objective function should have two outputs, energy and gradenergy. Put both functions in one vector when calling matlabFunction to reduce the number of subexpressions that matlabFunction generates, and to return the gradient only when the calling function (fmincon in this case) requests both outputs. This example shows placing the resulting files in your current folder. Of course, you can place them anywhere you like, as long as the folder is on the MATLAB path.

```matlab
currdir = [pwd filesep]; % You may need to use currdir = pwd
filename = [currdir,'demoenergy.m'];
matlabFunction(energy,gradenergy,'file',filename,'vars',{x});
```

This syntax causes matlabFunction to return energy as the first output, and gradenergy as the second. It also takes a single input vector \{x\} instead of a list of inputs \(x_{11}, ..., x_{103}\).

The resulting file `demoenergy.m` contains, in part, the following lines or similar ones:

```matlab
function [energy,gradenergy] = demoenergy(in1)
%DEMOENERGY
% [ENERGY,GRADENERGY] = DEMOENERGY(IN1)
...
x101 = in1(28,:);
...
energy = 1./t140.^(1./2) + ...;
if nargout > 1
...
    gradenergy = [(t174.*(t185 - 2.*x11))./2 - ...];
end
```

This function has the correct form for an objective function with a gradient; see “Writing Scalar Objective Functions” on page 2-17.

Create the Constraint Function File

Generate the nonlinear constraint function, and put it in the correct format.

```matlab
filename = [currdir,'democonstr.m'];
matlabFunction(c,[],gradc,[],'file',filename,'vars',{x},...
'outputs', {'c', 'ceq', 'gradc', 'gradceq'});

The resulting file democonstr.m contains, in part, the following lines or similar ones:

```matlab
function [c,ceq,gradc,gradceq] = democonstr(in1)
    %DEMOCONSTR
    % [C,CEQ,GRADC,GRADCEQ] = DEMOCONSTR(IN1)
    ... x101 = in1(28,:);
    ... c = [t417.^2 + ...];
    if nargout > 1
        ceq = [];
    end
    if nargout > 2
        gradc = [2.*x11,...];
    end
    if nargout > 3
        gradceq = [];
    end
```

This function has the correct form for a constraint function with a gradient; see “Nonlinear Constraints” on page 2-33.

**Generate the Hessian Files**

To generate the Hessian of the Lagrangian for the problem, first generate files for the energy Hessian and for the constraint Hessians.

The Hessian of the objective function, hessenergy, is a very large symbolic expression, containing over 150,000 symbols, as evaluating `size(char(hessenergy))` shows. So it takes a substantial amount of time to run `matlabFunction(hessenergy)`.

To generate a file hessenergy.m, run the following two lines:

```matlab
filename = [currdir,'hessenergy.m'];
matlabFunction(hessenergy,'file',filename,'vars',{x});
```
In contrast, the Hessians of the constraint functions are small, and fast to compute:

```matlab
for i = 1:10
    ii = num2str(i);
    thane = ['hessc',ii];
    filename = [currdir,thename,'.m'];
    matlabFunction(hessc{i},'file',filename,'vars',{x});
end
```

After generating all the files for the objective and constraints, put them together with the appropriate Lagrange multipliers in a file `hessfinal.m` as follows:

```matlab
function H = hessfinal(X,lambda)

% Call the function hessenergy to start
H = hessenergy(X);

% Add the Lagrange multipliers * the constraint Hessians
H = H + hessc1(X) * lambda.ineqnonlin(1);
H = H + hessc2(X) * lambda.ineqnonlin(2);
H = H + hessc3(X) * lambda.ineqnonlin(3);
H = H + hessc4(X) * lambda.ineqnonlin(4);
H = H + hessc5(X) * lambda.ineqnonlin(5);
H = H + hessc6(X) * lambda.ineqnonlin(6);
H = H + hessc7(X) * lambda.ineqnonlin(7);
H = H + hessc8(X) * lambda.ineqnonlin(8);
H = H + hessc9(X) * lambda.ineqnonlin(9);
H = H + hessc10(X) * lambda.ineqnonlin(10);
```

**Run the Optimization**

Start the optimization with the electrons distributed randomly on a sphere of radius 1/2 centered at $[0,0,-1]$:

```matlab
rng('default'); % for reproducibility
Xinitial = randn(3,10); % columns are normal 3-D vectors
for j=1:10
    Xinitial(:,j) = Xinitial(:,j)/norm(Xinitial(:,j))/2;
    % this normalizes to a 1/2-sphere
```
end
Xinitial(3,:) = Xinitial(3,:) - 1; % center at [0,0,-1]
Xinitial = Xinitial(:); % Convert to a column vector

Set the options to use the interior-point algorithm, and to use gradients and the Hessian:

options = optimset('Algorithm','interior-point','GradObj','on',
                   'GradConstr','on','Hessian','user-supplied',
                   'HessFcn',@hessfinal,'Display','final');

Call fmincon:

[xfinal fval exitflag output] = fmincon(@demoenergy,Xinitial,...
                                    A,b,[],[],[],[],[],@democonstr,options)

The output is as follows:

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

xfinal =
  -0.0317
   0.0317
  -1.9990
   0.6356
   0.6356
  -1.4381
   0.0000
   0.0000
   0.0000
  -1.0000
   1.0000
  -0.0000
-1.0000
-1.0000
-0.0000
-1.0000
0.6689
0.6644
-1.3333
-0.6667
0.6667
-1.3333
0.6667
-1.3333
0.0000
1.0000
-1.0000
-0.6644
-0.6689
-1.3333

fval =
34.1365

exitflag =
1

output =
  iterations: 19
  funcCount: 28
  constrviolation: 0
  stepsizes: 4.0372e-005
  algorithm: 'interior-point'
  firstorderopt: 4.0015e-007
  cgiterations: 55
  message: [1x781 char]

Even though the initial positions of the electrons were random, the final positions are nearly symmetric:
Comparing to Optimization Without Gradients and Hessians

The use of gradients and Hessians makes the optimization run faster and more accurately. To compare with the same optimization using no gradient or Hessian information, set the options not to use gradients and Hessians:

```matlab
options = optimset('Algorithm','interior-point',...
                     'Display','final');
[xfinal2 fval2 exitflag2 output2] = fmincon(@demoenergy,Xinitial,...
                                          A,b,[],[],[],[],@democonstr,options)
```

The output shows that `fmincon` found an equivalent minimum, but took more iterations and many more function evaluations to do so:
Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

\[
\text{xfinal12 =} \\
\begin{array}{cccccccc}
0.0000 & 1.0000 & -1.0000 & 0.6689 & -0.6644 & -1.3334 & -0.6644 & 0.6689 \\
-1.3334 & 0.0000 & -1.0000 & -1.0000 & 0.6357 & 0.6357 & -1.4380 & -0.0317 \\
-0.0317 & -1.9990 & 1.0000 & 0.0000 & -1.0000 & -1.0000 & 0.0000 & -1.0000 \\
-1.0000 & -1.0000 & 0.0000 & 0.0000 & -0.0000 & -0.0000 & 0.0000 & 0.0000 \\
-0.6667 & -0.6667 & -1.3334 & 0.0000 & -1.0000 & -1.0000 & 0.0000 & -0.6667 \\
-0.6667 & -1.3334 & 0.0000 & -1.0000 & -0.6667 & -1.3334 & 0.0000 & -1.0000 \\
\end{array}
\]

\[
\text{fval12 =} \\
34.1365
\]
exitflag2 =
    1

output2 =
    iterations: 75
    funcCount: 2371
    constrviolation: 0
    stepsize: 9.4859e-007
    algorithm: 'interior-point'
    firstorderopt: 2.6305e-006
    cgiterations: 0
    message: [1x781 char]

In this run the number of function evaluations (in output2.funcCount) is 2371, compared to 28 (in output.funcCount) when using gradients and Hessian.

**Clear the Symbolic Variable Assumptions**
The symbolic variables in this example have the assumption, in the symbolic engine workspace, that they are real. To clear this assumption from the symbolic engine workspace, it is not sufficient to delete the variables. You must clear the variables using the syntax

```
syms x11 x12 x13 clear
```

or reset the symbolic engine using the command

```
reset(symengine)
```

After resetting the symbolic engine you should clear all symbolic variables from the MATLAB workspace with the clear command, or clear variable_list.

**Example: One-Dimensional Semi-Infinite Constraints**
Find values of \( x \) that minimize

\[
f(x) = (x_1 - 0.5)^2 + (x_2 - 0.5)^2 + (x_3 - 0.5)^2
\]
where

\[
K_1(x, w_1) = \sin(w_1 x_1) \cos(w_1 x_2) - \frac{1}{1000} (w_1 - 50)^2 - \sin(w_1 x_3) - x_3 \leq 1, \\
K_2(x, w_2) = \sin(w_2 x_2) \cos(w_2 x_1) - \frac{1}{1000} (w_2 - 50)^2 - \sin(w_2 x_3) - x_3 \leq 1, 
\]

for all values of \(w_1\) and \(w_2\) over the ranges

\[
1 \leq w_1 \leq 100, \\
1 \leq w_2 \leq 100. 
\]

Note that the semi-infinite constraints are one-dimensional, that is, vectors. Because the constraints must be in the form \(K_i(x, w_i) \leq 0\), you need to compute the constraints as

\[
K_1(x, w_1) = \sin(w_1 x_1) \cos(w_1 x_2) - \frac{1}{1000} (w_1 - 50)^2 - \sin(w_1 x_3) - x_3 - 1 \leq 0, \\
K_2(x, w_2) = \sin(w_2 x_2) \cos(w_2 x_1) - \frac{1}{1000} (w_2 - 50)^2 - \sin(w_2 x_3) - x_3 - 1 \leq 0. 
\]

First, write a file that computes the objective function.

```matlab
function f = myfun(x,s) 
% Objective function 
f = sum((x-0.5).^2); 
```

Second, write a file `mycon.m` that computes the nonlinear equality and inequality constraints and the semi-infinite constraints.

```matlab
function [c,ceq,K1,K2,s] = mycon(X,s) 
% Initial sampling interval 
if isnan(s(1,1)), 
    s = [0.2 0; 0.2 0]; 
end 
% Sample set 
w1 = 1:s(1,1):100; 
w2 = 1:s(2,1):100; 

% Semi-infinite constraints 
```
K1 = sin(w1*X(1)).*cos(w1*X(2)) - 1/1000*(w1-50).^2 -...
   sin(w1*X(3))-X(3)-1;
K2 = sin(w2*X(2)).*cos(w2*X(1)) - 1/1000*(w2-50).^2 -...
   sin(w2*X(3))-X(3)-1;

% No finite nonlinear constraints
C = []; ceq=[];

% Plot a graph of semi-infinite constraints
plot(w1,K1,'-',w2,K2,':
   title('Semi-infinite constraints')
   drawnow

Then, invoke an optimization routine.

x0 = [0.5; 0.2; 0.3]; % Starting guess
[x,fval] = fseminf(@myfun,x0,2,@mycon);

After eight iterations, the solution is

x
x =
   0.6675
   0.3012
   0.4022

The function value and the maximum values of the semi-infinite constraints
at the solution x are

fval
fval =
   0.0771

[c,ceq,K1,K2] = mycon(x,NaN); % Initial sampling interval
max(K1)
ans =
   -0.0077
max(K2)
ans =
   -0.0812
A plot of the semi-infinite constraints is produced.

This plot shows how peaks in both constraints are on the constraint boundary.

The plot command inside mycon.m slows down the computation. Remove this line to improve the speed.

**Example: Two-Dimensional Semi-Infinite Constraint**

Find values of $x$ that minimize

$$f(x) = (x_1 - 0.2)^2 + (x_2 - 0.2)^2 + (x_3 - 0.2)^2,$$

where

$$K_1(x,w) = \sin(w_1x_1)\cos(w_2x_2) - \frac{1}{1000}(w_1 - 50)^2 - \sin(w_1x_3) - x_3 + \ldots$$

$$\sin(w_2x_2)\cos(w_1x_1) - \frac{1}{1000}(w_2 - 50)^2 - \sin(w_2x_3) - x_3 \leq 1.5,$$

for all values of $w_1$ and $w_2$ over the ranges
\[ 1 \leq w_1 \leq 100, \]
\[ 1 \leq w_2 \leq 100, \]

starting at the point \( x = [0.25, 0.25, 0.25] \).

Note that the semi-infinite constraint is two-dimensional, that is, a matrix.

First, write a file that computes the objective function.

```matlab
function f = myfun(x,s)
    % Objective function
    f = sum((x-0.2).^2);
end
```

Second, write a file for the constraints, called `mycon.m`. Include code to draw the surface plot of the semi-infinite constraint each time `mycon` is called. This enables you to see how the constraint changes as \( X \) is being minimized.

```matlab
function [c,ceq,K1,s] = mycon(X,s)
    % Initial sampling interval
    if isnan(s(1,1)),
        s = [2 2];
    end

    % Sampling set
    w1x = 1:s(1,1):100;
    w1y = 1:s(1,2):100;
    [wx,wy] = meshgrid(w1x,w1y);

    % Semi-infinite constraint
    K1 = sin(wx*X(1)).*cos(wx*X(2))-1/1000*(wx-50).^2 - ...
        sin(wx*X(3))-X(3)+sin(wy*X(2)).*cos(wx*X(1))-...
        1/1000*(wy-50).^2-sin(wy*X(3))-X(3)-1.5;

    % No finite nonlinear constraints
    c = []; ceq=[];

    % Mesh plot
    m = surf(wx,wy,K1,'edgecolor','none','facecolor','interp');
    camlight headlight
    title('Semi-infinite constraint')
drawnow
```
Next, invoke an optimization routine.

\[
x_0 = [0.25, 0.25, 0.25]; \quad \% \text{Starting guess}
\]

\[
[x,fval] = \text{fseminf}(@myfun,x0,1,@mycon)
\]

After nine iterations, the solution is

\[
x
\]

\[
x =
\]

\[
\begin{array}{ccc}
0.2522 & 0.1714 & 0.1936 \\
\end{array}
\]

and the function value at the solution is

\[
fval
\]

\[
fval =
\]

\[
0.0036
\]

The goal was to minimize the objective \( f(x) \) such that the semi-infinite constraint satisfied \( K_1(x,w) \leq 1.5 \). Evaluating \( \text{mycon} \) at the solution \( x \) and looking at the maximum element of the matrix \( K_1 \) shows the constraint is easily satisfied.

\[
[c,ceq,K1] = \text{mycon}(x,[0.5,0.5]); \quad \% \text{Sampling interval 0.5}
\]

\[
\text{max(max(K1))}
\]

\[
\text{ans} =
\]

\[
-0.0333
\]

This call to \( \text{mycon} \) produces the following surf plot, which shows the semi-infinite constraint at \( x \).
Linear Programming Algorithms

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**Definition**
Linear programming is the problem of finding a vector \( x \) that minimizes a linear function \( f^T x \) subject to linear constraints:

\[
\min_x f^T x
\]

such that one or more of the following hold: \( A x \leq b \), \( A_{eq} x = b_{eq} \), \( l \leq x \leq u \).

**Large Scale Linear Programming**

**Introduction**
The default large-scale method is based on LIPSOL ([52]), which is a variant of Mehrotra's predictor-corrector algorithm ([47]), a primal-dual interior-point method.

**Main Algorithm**
The algorithm begins by applying a series of preprocessing steps (see “Preprocessing” on page 6-97). After preprocessing, the problem has the form

\[
\min_x f^T x \text{ such that } \begin{cases} A x = b \\ 0 \leq x \leq u. \end{cases}
\]  

(6-63)

The upper bounds constraints are implicitly included in the constraint matrix \( A \). With the addition of primal slack variables \( s \), Equation 6-63 becomes
\[ \min f^T x \text{ such that } \begin{cases} A \cdot x = b \\ x + s = u \\ x \geq 0, \ s \geq 0. \end{cases} \quad (6-64) \]

which is referred to as the **primal** problem: \( x \) consists of the primal variables and \( s \) consists of the primal slack variables. The **dual** problem is

\[ \max b^T y - u^T w \text{ such that } \begin{cases} A^T \cdot y - w + z = f \\ z \geq 0, \ w \geq 0, \end{cases} \quad (6-65) \]

where \( y \) and \( w \) consist of the dual variables and \( z \) consists of the dual slacks. The optimality conditions for this linear program, i.e., the primal Equation 6-64 and the dual Equation 6-65, are

\[
F(x, y, z, s, w) = \begin{pmatrix} A \cdot x - b \\ x + s - u \\ x_i z_i \\ s_i w_i \end{pmatrix} = 0, \\
x \geq 0, \ z \geq 0, \ s \geq 0, \ w \geq 0, \quad (6-66)
\]

where \( x_i z_i \) and \( s_i w_i \) denote component-wise multiplication.

The quadratic equations \( x_i z_i = 0 \) and \( s_i w_i = 0 \) are called the **complementarity** conditions for the linear program; the other (linear) equations are called the **feasibility** conditions. The quantity

\[ x^T z + s^T w \]

is the **duality gap**, which measures the residual of the complementarity portion of \( F \) when \((x,z,s,w) \geq 0\).

The algorithm is a **primal-dual algorithm**, meaning that both the primal and the dual programs are solved simultaneously. It can be considered a Newton-like method, applied to the linear-quadratic system \( F(x,y,z,s,w) = 0 \) in Equation 6-66, while at the same time keeping the iterates \( x, z, w, \) and \( s \)
positive, thus the name interior-point method. (The iterates are in the strictly interior region represented by the inequality constraints in Equation 6-64.)

The algorithm is a variant of the predictor-corrector algorithm proposed by Mehrotra. Consider an iterate \( v = [x;y;z;s;w] \), where \([x;z;s;w] > 0\) First compute the so-called prediction direction

\[
\Delta v_p = -\left(F^T(v)\right)^{-1} F(v),
\]

which is the Newton direction; then the so-called corrector direction

\[
\Delta v_c = -\left(F^T(v)\right)^{-1} F(v + \Delta v_p) - \mu \hat{e},
\]

where \( \mu > 0 \) is called the centering parameter and must be chosen carefully. \( \hat{e} \) is a zero-one vector with the ones corresponding to the quadratic equations in \( F(v) \), i.e., the perturbations are only applied to the complementarity conditions, which are all quadratic, but not to the feasibility conditions, which are all linear. The two directions are combined with a step length parameter \( \alpha > 0 \) and update \( v \) to obtain the new iterate \( v^+ \):

\[
v^+ = v + \alpha (\Delta v_p + \Delta v_c),
\]

where the step length parameter \( \alpha \) is chosen so that

\[
v^+ = [x^+;y^+;z^+;s^+;w^+]
\]

satisfies

\([x^+;z^+;s^+;w^+] > 0\).

In solving for the preceding predictor/corrector directions, the algorithm computes a (sparse) direct factorization on a modification of the Cholesky factors of \( A \cdot A^T \). If \( A \) has dense columns, it instead uses the Sherman-Morrison formula. If that solution is not adequate (the residual is too large), it performs an LDL factorization of an augmented system form of the step equations to
find a solution. (See Example 4 — The Structure of D in the MATLAB ldl function reference page.)

The algorithm then loops until the iterates converge. The main stopping criteria is a standard one:

\[
\frac{\|r_b\|}{\max(1,\|b\|)} + \frac{\|r_f\|}{\max(1,\|f\|)} + \frac{\|r_u\|}{\max(1,\|u\|)} + \frac{|f^Tx - b^Ty + u^Tw|}{\max(1,|f^Tx|,|b^Ty - u^Tw|)} \leq tol,
\]

where

- \(r_b = Ax - b\)
- \(r_f = A^Ty - w + z - f\)
- \(r_u = x + s - u\)

are the primal residual, dual residual, and upper-bound feasibility respectively, and

\[f^Tx - b^Ty + u^Tw\]

is the difference between the primal and dual objective values, and \(tol\) is some tolerance. The sum in the stopping criteria measures the total relative errors in the optimality conditions in Equation 6-66.

**Preprocessing**

A number of preprocessing steps occur before the actual iterative algorithm begins. The resulting transformed problem is one where

- All variables are bounded below by zero.
- All constraints are equalities.
- Fixed variables, those with equal upper and lower bounds, are removed.
- Rows of all zeros in the constraint matrix are removed.
- The constraint matrix has full structural rank.
• Columns of all zeros in the constraint matrix are removed.
• When a significant number of singleton rows exist in the constraint matrix, the associated variables are solved for and the rows removed.

While these preprocessing steps can do much to speed up the iterative part of the algorithm, if the Lagrange multipliers are required, the preprocessing steps must be undone since the multipliers calculated during the algorithm are for the transformed problem, and not the original. Thus, if the multipliers are not requested, this transformation back is not computed, and might save some time computationally.

Active-Set Medium-Scale linprog Algorithm

The medium-scale active-set linear programming algorithm is a variant of the sequential quadratic programming algorithm used by fmincon (“Sequential Quadratic Programming (SQP)” on page 6-28). The difference is that the quadratic term is set to zero.

At each major iteration of the SQP method, a QP problem of the following form is solved, where $A_i$ refers to the $i$th row of the $m$-by-$n$ matrix $A$.

\[
\min_{d \in \mathbb{R}^n} q(d) = c^T d, \\
A_i d = b_i, \quad i = 1,...,m_e \\
A_i d \leq b_i, \quad i = m_e + 1,...,m.
\]

The method used in Optimization Toolbox functions is an active set strategy (also known as a projection method) similar to that of Gill et al., described in [18] and [17]. It has been modified for both Linear Programming (LP) and Quadratic Programming (QP) problems.

The solution procedure involves two phases. The first phase involves the calculation of a feasible point (if one exists). The second phase involves the generation of an iterative sequence of feasible points that converge to the solution. In this method an active set, $A_k$, is maintained that is an estimate of the active constraints (i.e., those that are on the constraint boundaries) at the solution point. Virtually all QP algorithms are active set methods. This
point is emphasized because there exist many different methods that are very
similar in structure but that are described in widely different terms.

\( \bar{A}_k \) is updated at each iteration \( k \), and this is used to form a basis for a search
direction \( \hat{d}_k \). Equality constraints always remain in the active set \( \bar{A}_k \). The
notation for the variable \( \hat{d}_k \) is used here to distinguish it from \( d_k \) in the major
iterations of the SQP method. The search direction \( \hat{d}_k \) is calculated and
minimizes the objective function while remaining on any active constraint
boundaries. The feasible subspace for \( \hat{d}_k \) is formed from a basis \( Z_k \) whose
columns are orthogonal to the estimate of the active set \( \bar{A}_k \) (i.e., \( \bar{A}_k Z_k = 0 \)).
Thus a search direction, which is formed from a linear summation of any
combination of the columns of \( Z_k \), is guaranteed to remain on the boundaries
of the active constraints.

The matrix \( Z_k \) is formed from the last \( m - l \) columns of the QR decomposition
of the matrix \( \bar{A}_k^T \), where \( l \) is the number of active constraints and \( l < m \).
That is, \( Z_k \) is given by

\[
Z_k = Q[:, l+1 : m],
\]

(6-67)

where

\[
Q^T \bar{A}_k^T = \begin{bmatrix} R \\ 0 \end{bmatrix}.
\]

Once \( Z_k \) is found, a new search direction \( \hat{d}_k \) is sought that minimizes \( q(d) \)
where \( \hat{d}_k \) is in the null space of the active constraints. That is, \( \hat{d}_k \) is a linear
combination of the columns of \( Z_k \): \( \hat{d}_k = Z_k p \) for some vector \( p \).

Then if you view the quadratic as a function of \( p \), by substituting for \( \hat{d}_k \),
you have
\[ q(p) = \frac{1}{2} p^T Z_k^T H Z_k p + c^T Z_k p. \]  

(6-68)

Differentiating this with respect to \( p \) yields

\[ \nabla q(p) = Z_k^T H Z_k p + Z_k^T c. \]  

(6-69)

\( \nabla q(p) \) is referred to as the projected gradient of the quadratic function because it is the gradient projected in the subspace defined by \( Z_k \). The term \( Z_k^T H Z_k \) is called the projected Hessian. Assuming the Hessian matrix \( H \) is positive definite (which is the case in this implementation of SQP), then the minimum of the function \( q(p) \) in the subspace defined by \( Z_k \) occurs when \( \nabla q(p) = 0 \), which is the solution of the system of linear equations

\[ Z_k^T H Z_k p = -Z_k^T c. \]  

(6-70)

A step is then taken of the form

\[ x_{k+1} = x_k + \alpha \hat{d}_k, \text{ where } \hat{d}_k = Z_k^T p. \]  

(6-71)

At each iteration, because of the quadratic nature of the objective function, there are only two choices of step length \( \alpha \). A step of unity along \( \hat{d}_k \) is the exact step to the minimum of the function restricted to the null space of \( \bar{A}_k \). If such a step can be taken, without violation of the constraints, then this is the solution to QP (Equation 6-68). Otherwise, the step along \( \hat{d}_k \) to the nearest constraint is less than unity and a new constraint is included in the active set at the next iteration. The distance to the constraint boundaries in any direction \( \hat{d}_k \) is given by

\[ \alpha = \min_{i \in \{1, \ldots, m\}} \left\{ \frac{-(A_i x_k - b_i)}{A_i \hat{d}_k} \right\}, \]  

(6-72)

which is defined for constraints not in the active set, and where the direction \( \hat{d}_k \) is towards the constraint boundary, i.e., \( A_i \hat{d}_k > 0, i = 1, \ldots, m \).
When \( n \) independent constraints are included in the active set, without location of the minimum, Lagrange multipliers, \( \lambda_k \), are calculated that satisfy the nonsingular set of linear equations
\[
\bar{A}_k^T \lambda_k = c. \tag{6-73}
\]

If all elements of \( \lambda_k \) are positive, \( x_k \) is the optimal solution of QP (Equation 6-68). However, if any component of \( \lambda_k \) is negative, and the component does not correspond to an equality constraint, then the corresponding element is deleted from the active set and a new iterate is sought.

**Initialization**

The algorithm requires a feasible point to start. If the current point from the SQP method is not feasible, then you can find a point by solving the linear programming problem
\[
\begin{align*}
\min_{\gamma \in \mathbb{R}, \ x \in \mathbb{R}^n} & \quad \gamma \quad \text{such that} \\
A_i x &= b_i, \quad i = 1, \ldots, m_e \\
A_i x - \gamma &\leq b_i, \quad i = m_e + 1, \ldots, m. \tag{6-74}
\end{align*}
\]

The notation \( A_i \) indicates the \( i \)th row of the matrix \( A \). You can find a feasible point (if one exists) to Equation 6-74 by setting \( x \) to a value that satisfies the equality constraints. You can determine this value by solving an under- or overdetermined set of linear equations formed from the set of equality constraints. If there is a solution to this problem, then the slack variable \( \gamma \) is set to the maximum inequality constraint at this point.

You can modify the preceding QP algorithm for LP problems by setting the search direction to the steepest descent direction at each iteration, where \( g_k \) is the gradient of the objective function (equal to the coefficients of the linear objective function).
\[
\hat{d}_k = -Z_k Z_k^T g_k. \tag{6-75}
\]

If a feasible point is found using the preceding LP method, the main QP phase is entered. The search direction \( \hat{d}_k \) is initialized with a search direction \( \hat{d}_1 \) found from solving the set of linear equations.
\[ H \hat{d}_k = -g_k, \]  

where \( g_k \) is the gradient of the objective function at the current iterate \( x_k \) (i.e., \( Hx_k + c \)).

If a feasible solution is not found for the QP problem, the direction of search for the main SQP routine \( \hat{d}_k \) is taken as one that minimizes \( \gamma \).

**Medium-Scale linprog Simplex Algorithm**

The simplex algorithm, invented by George Dantzig in 1947, is one of the earliest and best known optimization algorithms. The algorithm solves the linear programming problem

\[
\begin{align*}
\min_{x} & \quad f^T x \\
\text{such that} & \quad A \cdot x \leq b, \\
& \quad Aeq \cdot x = beq, \\
& \quad lb \leq x \leq ub.
\end{align*}
\]

The algorithm moves along the edges of the polyhedron defined by the constraints, from one vertex to another, while decreasing the value of the objective function, \( f^T x \), at each step. This section describes an improved version of the original simplex algorithm that returns a vertex optimal solution.

This section covers the following topics:

- “Main Algorithm” on page 6-102
- “Preprocessing” on page 6-104
- “Using the Simplex Algorithm” on page 6-105
- “Basic and Nonbasic Variables” on page 6-105

**Main Algorithm**

The simplex algorithm has two phases:

- Phase 1 — Compute an initial basic feasible point.
• Phase 2 — Compute the optimal solution to the original problem.

**Note** You cannot supply an initial point \( x_0 \) for `linprog` with the simplex algorithm. If you pass in \( x_0 \) as an input argument, `linprog` ignores \( x_0 \) and computes its own initial point for the algorithm.

**Phase 1.** In phase 1, the algorithm finds an initial basic feasible solution (see “Basic and Nonbasic Variables” on page 6-105 for a definition) by solving an auxiliary piecewise linear programming problem. The objective function of the auxiliary problem is the linear penalty function

\[ P = \sum_j P_j(x_j), \]

where \( P_j(x_j) \) is defined by

\[
P_j(x_j) = \begin{cases} 
  x_j - u_j & \text{if } x_j > u_j \\
  0 & \text{if } l_j \leq x_j \leq u_j \\
  l_j - x_j & \text{if } l_j > x_j.
\end{cases}
\]

\( P(x) \) measures how much a point \( x \) violates the lower and upper bound conditions. The auxiliary problem is

\[
\min_x \sum_j P_j \quad \text{subject to } \begin{cases} 
  A \cdot x \leq b \\
  A_{eq} \cdot x = beq.
\end{cases}
\]

The original problem has a feasible basis point if and only if the auxiliary problem has minimum value 0.

The algorithm finds an initial point for the auxiliary problem by a heuristic method that adds slack and artificial variables as necessary. The algorithm then uses this initial point together with the simplex algorithm to solve the auxiliary problem. The solution is the initial point for phase 2 of the main algorithm.
Phase 2. In phase 2, the algorithm applies the simplex algorithm, starting at the initial point from phase 1, to solve the original problem. At each iteration, the algorithm tests the optimality condition and stops if the current solution is optimal. If the current solution is not optimal, the algorithm

1. Chooses one variable, called the entering variable, from the nonbasic variables and adds the corresponding column of the nonbasis to the basis (see “Basic and Nonbasic Variables” on page 6-105 for definitions).

2. Chooses a variable, called the leaving variable, from the basic variables and removes the corresponding column from the basis.

3. Updates the current solution and the current objective value.

The algorithm chooses the entering and the leaving variables by solving two linear systems while maintaining the feasibility of the solution.

The algorithm detects when there is no progress in the Phase 2 solution process. It attempts to continue by performing bound perturbation. For an explanation of this part of the algorithm, see Applegate, Bixby, Chvatal, and Cook [59].

Preprocessing
The simplex algorithm uses the same preprocessing steps as the large-scale linear programming solver, which are described in “Preprocessing” on page 6-97. In addition, the algorithm uses two other steps:

1. Eliminates columns that have only one nonzero element and eliminates their corresponding rows.

2. For each constraint equation $a \mathbf{x} = b$, where $a$ is a row of $A_{eq}$, the algorithm computes the lower and upper bounds of the linear combination $a \mathbf{x}$ as $r_{lb}$ and $r_{ub}$ if the lower and upper bounds are finite. If either $r_{lb}$ or $r_{ub}$ equals $b$, the constraint is called a forcing constraint. The algorithm sets each variable corresponding to a nonzero coefficient of $a \mathbf{x}$ equal to its upper or lower bound, depending on the forcing constraint. The algorithm then deletes the columns corresponding to these variables and deletes the rows corresponding to the forcing constraints.
Using the Simplex Algorithm

To use the simplex method, set 'LargeScale' to 'off' and 'Simplex' to 'on' in options.

\[
\text{options} = \text{optimset('LargeScale','off','Simplex','on')}
\]

Then call the function \texttt{linprog} with the options input argument. See the reference page for \texttt{linprog} for more information.

\texttt{linprog} returns empty output arguments for \texttt{x} and \texttt{fval} if it detects infeasibility or unboundedness in the preprocessing procedure. \texttt{linprog} returns the current point when it

- Exceeds the maximum number of iterations
- Detects that the problem is infeasible or unbounded in phases 1 or 2

When the problem is unbounded, \texttt{linprog} returns \texttt{x} and \texttt{fval} in the unbounded direction.

Basic and Nonbasic Variables

This section defines the terms \textit{basis}, \textit{nonbasis}, and \textit{basic feasible solutions} for a linear programming problem. The definition assumes that the problem is given in the following standard form:

\[
\begin{array}{ll}
\text{min } f^T x & \text{such that } \\
& A \cdot x = b, \\
& lb \leq x \leq ub.
\end{array}
\]

(Nota:te that \(A\) and \(b\) are not the matrix and vector defining the inequalities in the original problem.) Assume that \(A\) is an \(m\)-by-\(n\) matrix, of rank \(m < n\),

whose columns are \(\{a_1, a_2, ..., a_n\}\). Suppose that \(\{a_{i_1}, a_{i_2}, ..., a_{i_m}\}\) is a basis for the column space of \(A\), with index set \(B = \{i_1, i_2, ..., i_m\}\), and that \(N = \{1, 2, ..., n\} \setminus B\) is the complement of \(B\). The submatrix \(A_B\) is called a \textit{basis} and the complementary submatrix \(A_N\) is called a \textit{nonbasis}. The vector of \textit{basic variables} is \(x_B\) and the vector of \textit{nonbasic variables} is \(x_N\). At each iteration in phase 2, the algorithm replaces one column of the current basis with a column of the nonbasis and updates the variables \(x_B\) and \(x_N\) accordingly.
If $x$ is a solution to $A \cdot x = b$ and all the nonbasic variables in $x_N$ are equal to either their lower or upper bounds, $x$ is called a basic solution. If, in addition, the basic variables in $x_B$ satisfy their lower and upper bounds, so that $x$ is a feasible point, $x$ is called a basic feasible solution.
Example: Linear Programming with Equalities and Inequalities

The problem is

\[
\min_{x} f^T x \quad \text{such that} \quad \begin{cases}
A \cdot x \leq b, \\
A_{eq} \cdot x = b_{eq}, \\
x \geq 0.
\end{cases}
\]

You can load the matrices and vectors \(A, A_{eq}, b, b_{eq}, f\), and the lower bounds \(lb\) into the MATLAB workspace with

```matlab
load sc50b
```

This problem in \(sc50b.mat\) has 48 variables, 30 inequalities, and 20 equalities.

You can use `linprog` to solve the problem:

```matlab
[x,fval,exitflag,output] = ... 
linprog(f,A,b,Aeq,beq,lb,[],[],optimset('Display','iter'));
```

Because the iterative display was set using `optimset`, the results displayed are

<table>
<thead>
<tr>
<th>Residuals:</th>
<th>Primal</th>
<th>Dual</th>
<th>Duality</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeas</td>
<td>Infeas</td>
<td>Gap</td>
<td>Rel</td>
<td></td>
</tr>
<tr>
<td>A\cdot x - b</td>
<td>A\cdot y + z - f</td>
<td>x\cdot z</td>
<td>Error</td>
<td></td>
</tr>
<tr>
<td>Iter 0:</td>
<td>1.50e+003</td>
<td>2.19e+001</td>
<td>1.91e+004</td>
<td>1.00e+002</td>
</tr>
<tr>
<td>Iter 1:</td>
<td>1.15e+002</td>
<td>2.37e-015</td>
<td>3.62e+003</td>
<td>9.90e-001</td>
</tr>
</tbody>
</table>
Optimization Algorithms and Examples

Iter 2: 1.61e-012 2.62e-015 4.32e+002 9.48e-001
Iter 3: 3.11e-012 4.26e-015 7.78e+001 6.88e-001
Iter 4: 4.75e-011 6.01e-016 2.38e+001 2.69e-001
Iter 5: 3.65e-010 4.97e-016 5.05e+000 6.89e-002
Iter 6: 3.09e-011 2.18e-016 1.64e-001 2.34e-003
Iter 7: 1.77e-012 1.56e-016 1.09e-005 1.55e-007
Iter 8: 1.30e-012 1.50e-016 1.09e-011 1.55e-013

Optimization terminated.

For this problem, the large-scale linear programming algorithm quickly reduces the scaled residuals below the default tolerance of 1e-08.

The exitflag value is positive, telling you linprog converged. You can also get the final function value in fval and the number of iterations in output.iterations:

exitflag =
   1
fval =
   -70.0000
output =
    iterations: 8
    algorithm: 'large-scale: interior point'
    cgiterations: 0
    message: 'Optimization terminated.'
    constrviolation: 6.8212e-013
    firstorderopt: 2.7908e-013

Example: Linear Programming with Dense Columns in the Equalities

The problem is

\[ \min_{x} f^T x \quad \text{such that} \quad \begin{cases} Aeq \cdot x = beq, \\ lb \leq x \leq ub. \end{cases} \]

You can load the matrices and vectors Aeq, beq, f, lb, and ub into the MATLAB workspace with

load densecolumns
The problem in `densecolumns.mat` has 1677 variables and 627 equalities with lower bounds on all the variables, and upper bounds on 399 of the variables. The equality matrix \( A_{eq} \) has dense columns among its first 25 columns, which is easy to see with a `spy` plot:

\[
\text{spy}(A_{eq})
\]

You can use `linprog` to solve the problem:

\[
[x, fval, exitflag, output] = ...
\]

\[
\text{linprog}(f,[],[],A_{eq},beq,lb,ub,[],\text{optimset}('Display','iter'));
\]

Because the iterative display was set using `optimset`, the results displayed are

<table>
<thead>
<tr>
<th>Residuals:</th>
<th>Primal</th>
<th>Dual</th>
<th>Upper</th>
<th>Duality</th>
<th>Total</th>
<th>Rel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Infeas</td>
<td>Infeas</td>
<td>Bounds</td>
<td>Gap</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( A^x - b )</td>
<td>( A'y + z - w - f )</td>
<td>( {x} + s - ub )</td>
<td>( x'z + s'w )</td>
<td>Error</td>
<td></td>
</tr>
<tr>
<td>Iter 0:</td>
<td>1.67e+003</td>
<td>8.11e+002</td>
<td>1.35e+003</td>
<td>5.30e+006</td>
<td>2.92e+001</td>
<td></td>
</tr>
<tr>
<td>Iter 1:</td>
<td>1.37e+002</td>
<td>1.33e+002</td>
<td>1.11e+002</td>
<td>1.27e+006</td>
<td>2.48e+000</td>
<td></td>
</tr>
<tr>
<td>Iter 2:</td>
<td>3.56e+001</td>
<td>2.38e+001</td>
<td>2.89e+001</td>
<td>3.42e+005</td>
<td>1.99e+000</td>
<td></td>
</tr>
<tr>
<td>Iter 3:</td>
<td>4.86e+000</td>
<td>8.88e+000</td>
<td>3.94e+000</td>
<td>1.40e+005</td>
<td>1.89e+000</td>
<td></td>
</tr>
<tr>
<td>Iter 4:</td>
<td>4.24e-001</td>
<td>5.89e-001</td>
<td>3.44e-001</td>
<td>1.91e+004</td>
<td>8.41e-001</td>
<td></td>
</tr>
<tr>
<td>Iter 5:</td>
<td>1.23e-001</td>
<td>2.02e-001</td>
<td>9.97e-002</td>
<td>8.41e+003</td>
<td>5.79e-001</td>
<td></td>
</tr>
<tr>
<td>Iter 6:</td>
<td>3.98e-002</td>
<td>7.91e-002</td>
<td>3.23e-002</td>
<td>4.05e+003</td>
<td>3.52e-001</td>
<td></td>
</tr>
</tbody>
</table>
Optimization Algorithms and Examples

Iter 7: 7.25e-003 3.83e-002 5.88e-003 1.85e+003 1.85e-001
Iter 8: 1.47e-003 1.34e-002 1.19e-003 8.12e+002 8.52e-002
Iter 9: 2.52e-004 3.39e-003 2.04e-004 2.78e+002 2.99e-002
Iter 10: 3.46e-005 1.08e-003 2.81e-005 1.09e+002 1.18e-002
Iter 11: 6.96e-007 3.00e-12 5.64e-007 1.48e+001 1.62e-003
Iter 12: 7.00e-007 2.44e-012 3.18e-008 8.32e-001 9.09e-005
Iter 13: 8.50e-008 1.07e-012 3.86e-009 7.26e-002 7.94e-006
Iter 14: 1.44e-010 1.25e-012 6.53e-012 1.11e-003 1.21e-007
Iter 15: 7.59e-014 2.50e-012 3.72e-013 8.62e-008 9.42e-012
Optimization terminated.

You can see the returned values of exitflag, fval, and output:

exitflag,fval,output

exitflag =
1

fval =
9.1464e+003

output =
iteration: 15
algorithm: 'large-scale: interior point'
cgiterations: 0
message: 'Optimization terminated.'
constrviolation: 4.4587e-013
firstorderopt: 5.0368e-009

This time the algorithm detects dense columns in Aeq. Therefore, instead of using a sparse Cholesky factorization, linprog tries to use the Sherman-Morrison formula to solve a linear system involving Aeq*Aeq'. If the Sherman-Morrison formula does not give a satisfactory residual, the algorithm uses a solution process based on LDL factorization. See “Main Algorithm” on page 6-94.
Quadratic Programming Algorithms

In this section...

“Definition” on page 6-111
“interior-point-convex quadprog Algorithm” on page 6-111
“trust-region-reflective quadprog Algorithm” on page 6-115
“active-set quadprog Algorithm” on page 6-120

Definition
Quadratic programming is the problem of finding a vector $x$ that minimizes a quadratic function, possibly subject to linear constraints:

$$\min_{x} \frac{1}{2} x^T H x + c^T x$$

such that $A x \leq b$, $Aeq x = beq$, $l \leq x \leq u$.

interior-point-convex quadprog Algorithm
The interior-point-convex algorithm performs the following steps:

1 “Presolve/Postsolve” on page 6-111
2 “Generate Initial Point” on page 6-112
3 “Predictor-Corrector” on page 6-112
4 “Multiple Corrections” on page 6-115

Presolve/Postsolve
The algorithm begins by attempting to simplify the problem by removing redundancies and simplifying constraints. In particular, the presolve portion performs the following tasks, among others:

- Check if any variables have equal upper and lower bounds. If so, check for feasibility, then fix and remove the variables.
• Check if any linear inequality constraints involve just one variable. If so, check for feasibility, and change the linear constraint to a bound.

• Check if any linear equality constraints involve just one variable. If so, check for feasibility, then fix and remove the variable.

• Check if any linear constraint matrix has zero rows. If so, check for feasibility, and delete the rows.

• Check if the bounds and linear constraints are consistent.

• Check if any variables appear only as linear terms in the objective function and do not appear in any linear constraint. If so, check for feasibility and boundedness, and fix the variables at their appropriate bounds.

In the presolve step the algorithm might detect an infeasible or unbounded problem. If so, the algorithm halts and issues an appropriate exit message.

If the algorithm does not detect an infeasible or unbounded problem in the presolve step, it continues with the other steps. At the end, it reconstructs the original problem, undoing any presolve transformations. This final step is the postsolve step.

For details, see Gould and Toint [63].

**Generate Initial Point**

The initial point $x_0$ for the algorithm is:

1. Initialize $x_0$ to $\text{ones}(n,1)$, where $n$ is the number of rows in $H$.

2. For components that have both an upper bound $ub$ and a lower bound $lb$, if a component of $x_0$ is not strictly inside the bounds, the component is set to $(\text{ub} + \text{lb})/2$.

3. For components that have only one bound, modify the component if necessary to lie strictly inside the bound.

**Predictor-Corrector**

Similar to the `fmincon` interior-point algorithm, the `interior-point-convex` algorithm tries to find a point where the Karush-Kuhn-Tucker (KKT)
conditions hold. For the quadratic programming problem described in “Definition” on page 6-111, these conditions are:

\[
\begin{align*}
Hx + c - A_{eq}^T y - \bar{A}^T z &= 0 \\
\bar{A}x - \bar{b} - s &= 0 \\
A_{eq}x - b_{eq} &= 0
\end{align*}
\]

\[
s_i z_i = 0, \ i = 1, 2, ..., m \\
s \geq 0 \\
z \geq 0.
\]

Here

- $\bar{A}$ is the extended linear inequality matrix that includes bounds written as linear inequalities. $\bar{b}$ is the corresponding linear inequality vector, including bounds.
- $s$ is the vector of slacks that convert inequality constraints to equalities. $s$ has length $m$, the number of linear inequalities and bounds.
- $z$ is the vector of Lagrange multipliers corresponding to $s$.
- $y$ is the vector of Lagrange multipliers associated with the equality constraints.

The algorithm first predicts a step from the Newton-Raphson formula, then computes a corrector step. The corrector attempts to better enforce the nonlinear constraint $s_i z_i = 0$.

Definitions for the predictor step:

- $r_d$, the dual residual:

\[
r_d = Hx + c - A_{eq}^t y - \bar{A}^T z.
\]

- $r_{eq}$, the primal equality constraint residual:

\[
r_{eq} = A_{eq}x - b_{eq}.
\]
• $r_{ineq}$, the primal inequality constraint residual, which includes bounds and slacks:

$$r_{ineq} = \bar{A}x - \bar{b} - s.$$  

• $r_{sz}$, the complementarity residual:

$$r_{sz} = Sz.$$  

$S$ is the diagonal matrix of slack terms, $z$ is the column matrix of Lagrange multipliers.

• $r_c$, the average complementarity:

$$r_c = \frac{s^T z}{m}.$$  

In a Newton step, the changes in $x$, $s$, $y$, and $z$, are given by:

$$
\begin{pmatrix}
H & 0 & -A_{eq}^T & -\bar{A}^T \\
A_{eq} & 0 & 0 & 0 \\
\bar{A} & -I & 0 & 0 \\
0 & Z & 0 & S
\end{pmatrix}
\begin{pmatrix}
\Delta x \\
\Delta s \\
\Delta y \\
\Delta z
\end{pmatrix} =
\begin{pmatrix}
r_d \\
r_{eq} \\
r_{ineq} \\
r_{sz}
\end{pmatrix}.
$$

However, a full Newton step might be infeasible, because of the positivity constraints on $s$ and $z$. Therefore, quadprog shortens the step, if necessary, to maintain positivity.

Additionally, to maintain a “centered” position in the interior, instead of trying to solve $s_i z_i = 0$, the algorithm takes a positive parameter $\sigma$, and tries to solve

$$s_i z_i = \sigma r_c.$$  

quadprog replaces $r_{sz}$ in the Newton step equation with $r_{sz} + \Delta s \Delta z - \sigma r^c \cdot 1$, where $1$ is the vector of ones. Also, quadprog reorders the Newton equations to obtain a symmetric, more numerically stable system for the predictor step calculation.
For details, see Mehrotra [47].

**Multiple Corrections**

After calculating the corrected Newton step, quadprog can perform more calculations to get both a longer current step, and to prepare for better subsequent steps. These multiple correction calculations can improve both performance and robustness. For details, see Gondzio [62].

**trust-region-reflective quadprog Algorithm**

Many of the methods used in Optimization Toolbox solvers are based on trust regions, a simple yet powerful concept in optimization.

To understand the trust-region approach to optimization, consider the unconstrained minimization problem, minimize \( f(x) \), where the function takes vector arguments and returns scalars. Suppose you are at a point \( x \) in \( n \)-space and you want to improve, i.e., move to a point with a lower function value.

The basic idea is to approximate \( f \) with a simpler function \( q \), which reasonably reflects the behavior of function \( f \) in a neighborhood \( N \) around the point \( x \). This neighborhood is the trust region. A trial step \( s \) is computed by minimizing (or approximately minimizing) over \( N \). This is the trust-region subproblem,

\[
\min_s \{ q(s), \ s \in N \}.
\]  

The current point is updated to be \( x + s \) if \( f(x + s) < f(x) \); otherwise, the current point remains unchanged and \( N \), the region of trust, is shrunk and the trial step computation is repeated.

The key questions in defining a specific trust-region approach to minimizing \( f(x) \) are how to choose and compute the approximation \( q \) (defined at the current point \( x \)), how to choose and modify the trust region \( N \), and how accurately to solve the trust-region subproblem. This section focuses on the unconstrained problem. Later sections discuss additional complications due to the presence of constraints on the variables.

In the standard trust-region method ([48]), the quadratic approximation \( q \) is defined by the first two terms of the Taylor approximation to \( F \) at \( x \); the
neighborhood $N$ is usually spherical or ellipsoidal in shape. Mathematically
the trust-region subproblem is typically stated

$$\min \left\{ \frac{1}{2} s^T H s + s^T g \text{ such that } \|Ds\| \leq \Delta \right\},$$

(6-78)

where $g$ is the gradient of $f$ at the current point $x$, $H$ is the Hessian matrix
(the symmetric matrix of second derivatives), $D$ is a diagonal scaling matrix, $\Delta$
is a positive scalar, and $\| . \|$ is the 2-norm. Good algorithms exist for solving
Equation 6-78 (see [48]); such algorithms typically involve the computation of
a full eigensystem and a Newton process applied to the secular equation

$$\frac{1}{\Delta} - \frac{1}{\|s\|} = 0.$$

Such algorithms provide an accurate solution to Equation 6-78. However,
they require time proportional to several factorizations of $H$. Therefore, for
large-scale problems a different approach is needed. Several approximation
and heuristic strategies, based on Equation 6-78, have been proposed in
the literature ([42] and [50]). The approximation approach followed in
Optimization Toolbox solvers is to restrict the trust-region subproblem
to a two-dimensional subspace $S$ ([39] and [42]). Once the subspace $S$
has been computed, the work to solve Equation 6-78 is trivial even if full
eigenvalue/eigenvector information is needed (since in the subspace, the
problem is only two-dimensional). The dominant work has now shifted to
the determination of the subspace.

The two-dimensional subspace $S$ is determined with the aid of a
preconditioned conjugate gradient process described below. The solver defines
$S$ as the linear space spanned by $s_1$ and $s_2$, where $s_1$ is in the direction of the
gradient $g$, and $s_2$ is either an approximate Newton direction, i.e., a solution to

$$H \cdot s_2 = -g,$$

(6-79)

or a direction of negative curvature,
The philosophy behind this choice of $S$ is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence (via the Newton step, when it exists).

A sketch of unconstrained minimization using trust-region ideas is now easy to give:

1. Formulate the two-dimensional trust-region subproblem.
2. Solve Equation 6-78 to determine the trial step $s$.
3. If $f(x + s) < f(x)$, then $x = x + s$.
4. Adjust $\Delta$.

These four steps are repeated until convergence. The trust-region dimension $\Delta$ is adjusted according to standard rules. In particular, it is decreased if the trial step is not accepted, i.e., $f(x + s) \geq f(x)$. See [46] and [49] for a discussion of this aspect.

Optimization Toolbox solvers treat a few important special cases of $f$ with specialized functions: nonlinear least-squares, quadratic functions, and linear least-squares. However, the underlying algorithmic ideas are the same as for the general case. These special cases are discussed in later sections.

The subspace trust-region method is used to determine a search direction. However, instead of restricting the step to (possibly) one reflection step, as in the nonlinear minimization case, a piecewise reflective line search is conducted at each iteration. See [45] for details of the line search.

**Preconditioned Conjugate Gradient Method**

A popular way to solve large symmetric positive definite systems of linear equations $Hp = -g$ is the method of Preconditioned Conjugate Gradients (PCG). This iterative approach requires the ability to calculate matrix-vector products of the form $Hv$ where $v$ is an arbitrary vector. The symmetric positive definite matrix $M$ is a preconditioner for $H$. That is, $M = C^2$, where $C^{-1}HC^{-1}$ is a well-conditioned matrix or a matrix with clustered eigenvalues.
In a minimization context, you can assume that the Hessian matrix $H$ is symmetric. However, $H$ is guaranteed to be positive definite only in the neighborhood of a strong minimizer. Algorithm PCG exits when a direction of negative (or zero) curvature is encountered, i.e., $d^T H d \leq 0$. The PCG output direction, $p$, is either a direction of negative curvature or an approximate ($tol$ controls how approximate) solution to the Newton system $Hp = -g$. In either case $p$ is used to help define the two-dimensional subspace used in the trust-region approach discussed in “Trust-Region Methods for Nonlinear Minimization” on page 6-3.

**Linear Equality Constraints**

Linear constraints complicate the situation described for unconstrained minimization. However, the underlying ideas described previously can be carried through in a clean and efficient way. The large-scale methods in Optimization Toolbox solvers generate strictly feasible iterates.

The general linear equality constrained minimization problem can be written

$$\min \{ f(x) \text{ such that } Ax = b \}, \quad (6-81)$$

where $A$ is an $m$-by-$n$ matrix ($m \leq n$). Some Optimization Toolbox solvers preprocess $A$ to remove strict linear dependencies using a technique based on the LU factorization of $A^T$ [46]. Here $A$ is assumed to be of rank $m$.

The method used to solve Equation 6-81 differs from the unconstrained approach in two significant ways. First, an initial feasible point $x_0$ is computed, using a sparse least-squares step, so that $Ax_0 = b$. Second, Algorithm PCG is replaced with Reduced Preconditioned Conjugate Gradients (RPCG), see [46], in order to compute an approximate reduced Newton step (or a direction of negative curvature in the null space of $A$). The key linear algebra step involves solving systems of the form

$$\begin{bmatrix} C & A^T \\ A & 0 \end{bmatrix} \begin{bmatrix} s \\ t \end{bmatrix} = \begin{bmatrix} r \\ 0 \end{bmatrix}, \quad (6-82)$$

where $\tilde{A}$ approximates $A$ (small nonzeros of $A$ are set to zero provided rank is not lost) and $C$ is a sparse symmetric positive-definite approximation to $H$, i.e., $C = H$. See [46] for more details.
Box Constraints
The box constrained problem is of the form

\[ \min \{ f(x) \text{ such that } l \leq x \leq u \}, \tag{6-83} \]

where \( l \) is a vector of lower bounds, and \( u \) is a vector of upper bounds. Some (or all) of the components of \( l \) can be equal to \(-\infty\) and some (or all) of the components of \( u \) can be equal to \( \infty \). The method generates a sequence of strictly feasible points. Two techniques are used to maintain feasibility while achieving robust convergence behavior. First, a scaled modified Newton step replaces the unconstrained Newton step (to define the two-dimensional subspace \( S \)). Second, reflections are used to increase the step size.

The scaled modified Newton step arises from examining the Kuhn-Tucker necessary conditions for Equation 6-83,

\[ (D(x))^{-2} g = 0, \tag{6-84} \]

where

\[ D(x) = \text{diag} \left( \left| v_k \right|^{-1/2} \right), \]

and the vector \( v(x) \) is defined below, for each \( 1 \leq i \leq n \):

- If \( g_i < 0 \) and \( u_i < \infty \) then \( v_i = x_i - u_i \)
- If \( g_i \geq 0 \) and \( l_i > -\infty \) then \( v_i = x_i - l_i \)
- If \( g_i < 0 \) and \( u_i = \infty \) then \( v_i = -1 \)
- If \( g_i \geq 0 \) and \( l_i = -\infty \) then \( v_i = 1 \)

The nonlinear system Equation 6-84 is not differentiable everywhere. Nondifferentiability occurs when \( v_i = 0 \). You can avoid such points by maintaining strict feasibility, i.e., restricting \( l < x < u \).

The scaled modified Newton step \( s_k \) for the nonlinear system of equations given by Equation 6-84 is defined as the solution to the linear system
\[ \hat{M}D^N_s = -\hat{g} \]  
\text{at the } k\text{th iteration, where}

\[ \hat{g} = D^{-1}g = \text{diag}\left(\left|v\right|^{1/2}\right)g, \]  
\text{and}

\[ \hat{M} = D^{-1}HD^{-1} + \text{diag}(g)J^v. \]

Here \( J^v \) plays the role of the Jacobian of \( |v| \). Each diagonal component of the diagonal matrix \( J^v \) equals 0, –1, or 1. If all the components of \( l \) and \( u \) are finite, \( J^v = \text{diag}(\text{sign}(g)) \). At a point where \( g_i = 0, v_i \) might not be differentiable.

\( J^v_{ii} = 0 \) is defined at such a point. Nondifferentiability of this type is not a cause for concern because, for such a component, it is not significant which value \( v_i \) takes. Further, \( |v_i| \) will still be discontinuous at this point, but the function \( |v_i| g_i \) is continuous.

Second, reflections are used to increase the step size. A (single) reflection step is defined as follows. Given a step \( p \) that intersects a bound constraint, consider the first bound constraint crossed by \( p \); assume it is the \( i \)th bound constraint (either the \( i \)th upper or \( i \)th lower bound). Then the reflection step \( p^R = p \) except in the \( i \)th component, where \( p^R_i = -p_i \).

**active-set quadprog Algorithm**

Recall the problem quadprog addresses:

\[ \min_x \frac{1}{2}x^THx + c^Tx \]  
\text{such that } A x \leq b, Aeq x = beq, \text{ and } l \leq x \leq u. \ m \text{ is the total number of linear constraints, the sum of number of rows of } A \text{ and of } Aeq.

The medium-scale quadprog algorithm is an active-set strategy (also known as a projection method) similar to that of Gill et al., described in [18] and [17]. It has been modified for both Linear Programming (LP) and Quadratic Programming (QP) problems.
The solution procedure involves two phases. The first phase involves the calculation of a feasible point (if one exists). The second phase involves the generation of an iterative sequence of feasible points that converge to the solution.

**Active Set Iterations**

In this method an active set matrix, $S_k$, is maintained that is an estimate of the active constraints (i.e., those that are on the constraint boundaries) at the solution point. Specifically, the active set $S_k$ consists of the rows of $A_{eq}$, and a subset of the rows of $A$. $S_k$ is updated at each iteration $k$, and is used to form a basis for a search direction $d_k$. Equality constraints always remain in the active set $S_k$. The search direction $d_k$ is calculated and minimizes the objective function while remaining on active constraint boundaries. The feasible subspace for $d_k$ is formed from a basis $Z_k$ whose columns are orthogonal to the estimate of the active set $S_k$ (i.e., $S_kZ_k = 0$). Thus a search direction, which is formed from a linear summation of any combination of the columns of $Z_k$, is guaranteed to remain on the boundaries of the active constraints.

The matrix $Z_k$ is formed from the last $m - l$ columns of the QR decomposition of the matrix $S_k^T$, where $l$ is the number of active constraints and $l < m$.

That is, $Z_k$ is given by

$$Z_k = Q[:, l + 1 : m],$$

(6-89)

where

$$Q^T S_k^T = \begin{bmatrix} R \\ 0 \end{bmatrix}.$$  

Once $Z_k$ is found, a search direction $d_k$ is sought that minimizes the objective function at $d_k$, where $d_k$ is in the null space of the active constraints. That is, $d_k$ is a linear combination of the columns of $Z_k$: $d_k = Z_kp$ for some vector $p$.

Then if you view the quadratic objective function as a function of $p$, by substituting for $d_k$, the result is
\[ q(p) = \frac{1}{2} p^T Z_k^T H Z_k p + c^T Z_k p. \]  
\[ (6-90) \]

Differentiating this with respect to \( p \) yields

\[ \nabla q(p) = Z_k^T H Z_k p + Z_k^T c. \]  
\[ (6-91) \]

\( \nabla q(p) \) is referred to as the projected gradient of the quadratic function because it is the gradient projected in the subspace defined by \( Z_k \). The term \( Z_k^T H Z_k \) is called the projected Hessian. Assuming the Hessian matrix \( H \) is positive definite, the minimum of the function \( q(p) \) in the subspace defined by \( Z_k \) occurs when \( \nabla q(p) = 0 \), which is the solution of the system of linear equations

\[ Z_k^T H Z_k p = -Z_k^T c. \]  
\[ (6-92) \]

The next step is

\[ x_{k+1} = x_k + \alpha d_k, \quad \text{where} \quad d_k = Z_k^T p. \]  
\[ (6-93) \]

At each iteration, because of the quadratic nature of the objective function, there are only two choices of step length \( \alpha \). A step of unity along \( d_k \) is the exact step to the minimum of the function restricted to the null space of \( S_k \). If such a step can be taken, without violation of the constraints, then this is the solution to QP (Equation 6-88). Otherwise, the step along \( d_k \) to the nearest constraint is less than unity and a new constraint is included in the active set at the next iteration. The distance to the constraint boundaries in any direction \( d_k \) is given by

\[ \alpha = \min_{i \in \{1,...,m\}} \left\{ \frac{-\left( A_i x_k - b_i \right)}{A_i d_k} \right\}, \]  
\[ (6-94) \]

which is defined for constraints not in the active set, and where the direction \( d_k \) is towards the constraint boundary, i.e., \( A_i d_k > 0, \ i = 1,...,m \).

Lagrange multipliers, \( \lambda_k \), are calculated that satisfy the nonsingular set of linear equations
\[ S_k^T \lambda_k = c. \] (6-95)

If all elements of \( \lambda_k \) are positive, \( x_k \) is the optimal solution of QP (Equation 6-88). However, if any component of \( \lambda_k \) is negative, and the component does not correspond to an equality constraint, then the corresponding element is deleted from the active set and a new iterate is sought.

**Initialization**

The algorithm requires a feasible point to start. If the initial point is not feasible, then you can find a feasible point by solving the linear programming problem

\[
\begin{align*}
\min_{\gamma \in \mathbb{R}, x \in \mathbb{R}^n} & \gamma \\
\text{such that} & A_i x = b_i, \quad i = 1, \ldots, m_e \quad \text{(the rows of Aeq)} \\
& A_i x - \gamma \leq b_i, \quad i = m_e + 1, \ldots, m \quad \text{(the rows of A)}.
\end{align*}
\] (6-96)

The notation \( A_i \) indicates the \( i \)th row of the matrix \( A \). You can find a feasible point (if one exists) to Equation 6-96 by setting \( x \) to a value that satisfies the equality constraints. You can determine this value by solving an under- or overdetermined set of linear equations formed from the set of equality constraints. If there is a solution to this problem, the slack variable \( \gamma \) is set to the maximum inequality constraint at this point.

You can modify the preceding QP algorithm for LP problems by setting the search direction \( d \) to the steepest descent direction at each iteration, where \( g_k \) is the gradient of the objective function (equal to the coefficients of the linear objective function):

\[ d = -Z_k Z_k^T g_k. \] (6-97)

If a feasible point is found using the preceding LP method, the main QP phase is entered. The search direction \( d_k \) is initialized with a search direction \( d_1 \) found from solving the set of linear equations.
\[ H d_1 = -g_k , \]  \hspace{1cm} (6-98)

where \( g_k \) is the gradient of the objective function at the current iterate \( x_k \) (i.e., \( H x_k + c \)).
Example: Quadratic Minimization with Bound Constraints

To minimize a large-scale quadratic with upper and lower bounds, you can use the `quadprog` function.

The problem stored in the MAT-file `qpbox1.mat` is a positive definite quadratic, and the Hessian matrix $H$ is tridiagonal, subject to upper ($ub$) and lower ($lb$) bounds.

**Step 1: Load the Hessian and define $f$, $lb$, and $ub$.**

```matlab
load qpbox1 % Get H
lb = zeros(400,1); lb(400) = -inf;
ub = 0.9*ones(400,1); ub(400) = inf;
f = zeros(400,1); f([1 400]) = -2;
```

**Step 2: Call a quadratic minimization routine with a starting point $xstart$.**

```matlab
xstart = 0.5*ones(400,1);
[x,fval,exitflag,output] = ... 
quadprog(H,f,[],[],[],lb,ub,xstart);
```

Looking at the resulting values of `exitflag` and `output`,

- `exitflag`, `output`
exitflag = 
  3

output = 
   algorithm: 'trust-region-reflective'
   iterations: 19
   constrviolation: 0
   firstorderopt: 1.3674e-005
   cgiterations: 1644
   message: [1x206 char]

You can see that while convergence occurred in 20 iterations, the high number of CG iterations indicates that the cost of the linear system solve is high. In light of this cost, one strategy would be to limit the number of CG iterations per optimization iteration. The default number is the dimension of the problem divided by two, 200 for this problem. Suppose you limit it to 50 using the MaxPCGIter flag in options:

options = optimset('MaxPCGIter',50);
[x,fval,exitflag,output] = ...
    quadprog(H,f,[],[],[],[],lb,ub,xstart,options);

This time convergence still occurs and the total number of CG iterations (1547) has dropped:

exitflag,output

exitflag = 
  3

output = 
   algorithm: 'trust-region-reflective'
   iterations: 36
   constrviolation: 0
   firstorderopt: 2.3821e-005
   cgiterations: 1547
   message: [1x206 char]

A second strategy would be to use a direct solver at each iteration by setting the PrecondBandWidth option to inf:
options = optimset('PrecondBandWidth',inf);
[x,fval,exitflag,output] = ...
    quadprog(H,f,[],[],[],[],lb,ub,xstart,options);

Now the number of iterations has dropped to 10:

exitflag,output

exitflag =
    3

output =
    algorithm: 'trust-region-reflective'
    iterations: 10
    constrviolation: 0
    firstorderopt: 6.0684e-009
    cgiterations: 0
    message: [1x206 char]

Using a direct solver at each iteration usually causes the number of iterations
to decrease, but often takes more time per iteration. For this problem, the
tradeoff is beneficial, as the time for quadprog to solve the problem decreases
by a factor of 10.

Example: Quadratic Minimization with a Dense but Structured Hessian

The quadprog large-scale method can also solve large problems where the
Hessian is dense but structured. For these problems, quadprog does not
compute $H*Y$ with the Hessian $H$ directly, as it does for medium-scale
problems and for large-scale problems with sparse $H$, because forming $H$
would be memory-intensive. Instead, you must provide quadprog with a
function that, given a matrix $Y$ and information about $H$, computes $W = H*Y$.

In this example, the Hessian matrix $H$ has the structure $H = B + A*A'$ where
$B$ is a sparse 512-by-512 symmetric matrix, and $A$ is a 512-by-10 sparse
matrix composed of a number of dense columns. To avoid excessive memory
usage that could happen by working with $H$ directly because $H$ is dense, the
example provides a Hessian multiply function, qpbox4mult. This function,
when passed a matrix $Y$, uses sparse matrices $A$ and $B$ to compute the Hessian matrix product $W = H*Y = (B + A*A')*Y$.

In this example, the matrices $A$ and $B$ need to be provided to the Hessian multiply function $qpbox4mult$. You can pass one matrix as the first argument to $\text{quadprog}$, which is passed to the Hessian multiply function. You can use a nested function to provide the value of the second matrix.

**Step 1: Decide what part of $H$ to pass to $\text{quadprog}$ as the first argument.**

Either $A$ or $B$ can be passed as the first argument to $\text{quadprog}$. The example chooses to pass $B$ as the first argument because this results in a better preconditioner (see “Preconditioning” on page 6-131).

\[
\text{quadprog}(B,f,[],[],[],l,u,xstart,options)
\]

**Step 2: Write a function to compute Hessian-matrix products for $H$.**

Now, define a function $\text{runqpbox4}$ that

- Contains a nested function $qpbox4mult$ that uses $A$ and $B$ to compute the Hessian matrix product $W$, where $W = H*Y = (B + A*A')*Y$. The nested function must have the form

  \[
  W = qpbox4mult(Hinfo,Y,\ldots)
  \]

  The first two arguments $Hinfo$ and $Y$ are required.
- Loads the problem parameters from $qpbox4.mat$.
- Uses $\text{optimset}$ to set the $\text{HessMult}$ option to a function handle that points to $qpbox4mult$.
- Calls $\text{quadprog}$ with $B$ as the first argument.

The first argument to the nested function $qpbox4mult$ must be the same as the first argument passed to $\text{quadprog}$, which in this case is the matrix $B$.

The second argument to $qpbox4mult$ is the matrix $Y$ (of $W = H*Y$). Because $\text{quadprog}$ expects $Y$ to be used to form the Hessian matrix product, $Y$ is always
a matrix with \( n \) rows, where \( n \) is the number of dimensions in the problem. The number of columns in \( Y \) can vary. The function \( \text{qpbox4mult} \) is nested so that the value of the matrix \( A \) comes from the outer function.

```matlab
function [fval, exitflag, output, x] = runqpbox4
    % RUNQPBOX4 demonstrates 'HessMult' option for QUADPROG with % bounds.

    problem = load('qpbox4'); % Get xstart, u, l, B, A, f
    xstart = problem.xstart; u = problem.u; l = problem.l;
    B = problem.B; A = problem.A; f = problem.f;
    mtxmpy = @qpbox4mult; % function handle to qpbox4mult nested % subfunction

    % Choose the HessMult option
    options = optimset('HessMult', mtxmpy);

    % Pass B to qpbox4mult via the Hinfo argument. Also, B will be % used in computing a preconditioner for PCG.
    [x, fval, exitflag, output] = ... \quad \text{quadprog}(B,f,[],[],[],[],l,u,xstart,options);

    function W = qpbox4mult(B,Y);
        %QPBOX4MULT Hessian matrix product with dense %structured Hessian.
        % W = qpbox4mult(B,Y) computes W = (B + A'*A)'*Y where % INPUT:
        % B - sparse square matrix (512 by 512)
        % Y - vector (or matrix) to be multiplied by % B + A'*A.
        % VARIABLES from outer function runqpbox4:
        % A - sparse matrix with 512 rows and 10 columns.
        %
        % OUTPUT:
        % W - The product (B + A'*A)'*Y.
        %
        W = B*Y + A*(A'*Y);
```

6-129
Step 3: Call a quadratic minimization routine with a starting point.
To call the quadratic minimizing routine contained in runqpbox4, enter

\[ [fval,exitflag,output] = \text{runqpbox4}; \]

to run the preceding code. Then display the values for \( fval \), \( exitflag \), and \( output \). The results are

Optimization terminated: relative function value changing by
less than sqrt(OPTIONS.TolFun), no negative curvature detected
in current trust region model and the rate of progress (change
in \( f(x) \)) is slow.

\( fval,exitflag,output \)

\( fval = \)
-1.0538e+003

\( exitflag = \)
3

\( output = \)
    algorithm: 'trust-region-reflective'
    iterations: 18
    constrviolation: 0
    firstorderopt: 0.0043
    cgiterations: 30
    message: [1x206 char]

After 18 iterations with a total of 30 PCG iterations, the function value is
reduced to

\( fval \)
\( fval = \)
-1.0538e+003
and the first-order optimality is

```matlab
output.firstorderopt
ans =
    0.0043
```

**Preconditioning**

In this example, `quadprog` cannot use \( H \) to compute a preconditioner because \( H \) only exists implicitly. Instead, `quadprog` uses \( B \), the argument passed in instead of \( H \), to compute a preconditioner. \( B \) is a good choice because it is the same size as \( H \) and approximates \( H \) to some degree. If \( B \) were not the same size as \( H \), `quadprog` would compute a preconditioner based on some diagonal scaling matrices determined from the algorithm. Typically, this would not perform as well.

Because the preconditioner is more approximate than when \( H \) is available explicitly, adjusting the `TolPCG` parameter to a somewhat smaller value might be required. This example is the same as the previous one, but reduces `TolPCG` from the default 0.1 to 0.01.

```matlab
function [fval, exitflag, output, x] = runqpbox4prec
    % RUNQPBOX4PREC demonstrates 'HessMult' option for QUADPROG
    % with bounds.
    problem = load('qpbox4'); % Get xstart, u, l, B, A, f
    xstart = problem.xstart; u = problem.u; l = problem.l;
    B = problem.B; A = problem.A; f = problem.f;
    mtxmpy = @qpbox4mult; % function handle to qpbox4mult nested subfunction

    % Choose the HessMult option
    % Override the TolPCG option
    options = optimset('HessMult',mtxmpy,'TolPCG',0.01);

    % Pass B to qpbox4mult via the H argument. Also, B will be % used in computing a preconditioner for PCG.
    % A is passed as an additional argument after 'options'
    [x, fval, exitflag, output] = quadprog(B,f,[],[],[],[],[],[],[],l,u,xstart,options);
```
function W = qpbox4mult(B,Y);
    %QPBOX4MULT Hessian matrix product with dense
    %structured Hessian.
    % W = qpbox4mult(B,Y) computes W = (B + A*A')*Y where
    % INPUT:
    %  B - sparse square matrix (512 by 512)
    %  Y - vector (or matrix) to be multiplied by B + A'*A.
    % VARIABLES from outer function runqpbox4:
    %  A - sparse matrix with 512 rows and 10 columns.
    %
    % OUTPUT:
    %  W - The product (B + A*A')*Y.

    % Order multiplies to avoid forming A*A',
    % which is large and dense
    W = B*Y + A*(A'*Y);
end
end

Now, enter

    [fval,exitflag,output] = runqpbox4prec;

to run the preceding code. After 18 iterations and 50 PCG iterations, the
function value has the same value to five significant digits

    fval
    fval =
    -1.0538e+003

but the first-order optimality is further reduced.

    output.firstorderopt
    ans =
    0.0028

**Note** Decreasing To1Pcg too much can substantially increase the number of
PCG iterations.
Example: Large Sparse Quadratic Program with Interior Point Algorithm

This example shows the value of using sparse arithmetic when you have a sparse problem. The matrix has \( n \) rows, where you choose \( n \). For some large \( n \), the active-set algorithm runs out of memory, but the interior-point-convex algorithm works fine.

The problem is to minimize \( x' \cdot H \cdot x / 2 + f' \cdot x \) subject to

\[
x(1) + x(2) + \ldots + x(n) = 0,
\]

where \( f = [-1; -2; -3; \ldots; -n] \).

1. Create the parameter \( n \) and the utility matrix \( T \). The matrix \( T \) is a sparse circulant matrix that is simply a helper for creating the sparse positive-definite quadratic matrix \( H \).

\[
n = 30000; \text{ % Adjust } n \text{ to a large value} \\
T = 
\text{spalloc}(n,n,n); \text{ % make a sparse circulant matrix} \\
r = 1:n-1; \\
\text{for } m = r \\
\quad T(m,m+1)=1; \\
\text{end} \\
T(n,1) = 1;
\]

2. Create a sparse vector \( v \). Then create the matrix \( H \) by shifted versions of \( v \cdot v' \). The matrix \( T \) creates shifts of \( v \).

\[
v(n) = 0; \quad v(1) = 1; \quad v(2) = 2; \quad v(4) = 3; \\
v = (\text{sparse}(v))'; \\
\text{% Make a banded type of matrix} \\
H = 
\text{spalloc}(n,n,7*n); \\
r = 1:n; \\
\text{for } m = r \\
\quad H = H + v\cdot v'; \\
\quad v = T\cdot v; \\
\text{end}
\]

3. Take a look at the structure of \( H \):

\[
\text{spy}(H)
\]
4 Create the problem vector $f$ and linear constraint.

$$f = -r; \quad $\text{linear term}$ \\
A = \text{ones}(1,n); \quad b = 0;$$

5 Solve the quadratic programming problem with the interior-point-convex algorithm.

```matlab
options = optimset('Algorithm','interior-point-convex'); 
[x,fval,exitflag,output,lambda] = ...
    quadprog(H,f,A,b,[],[],[],[],options);
```

Minimum found that satisfies the constraints. Optimization completed because the objective function is non-decreasing in feasible directions, to within the selected value of the function tolerance, and constraints are satisfied to within the selected value of the constraint tolerance.
6 View the solution value, output structure, and Lagrange multiplier:

fval, output, lambda

fval =
-3.1331e+010

output =
  message: [1x912 char]
  algorithm: 'interior-point-convex'
  firstorderopt: 1.3691e-004
  constrviolation: 9.1268e-009
  iterations: 5
  cgiterations: []

lambda =
  ineqlin: 1.5000e+004
  eqlin: [0x1 double]
  lower: [30000x1 double]
  upper: [30000x1 double]

Since there are no lower bounds or upper bounds, all the values in lambda.lower and lambda.upper are 0. The inequality constraint is active, since lambda.ineqlin is nonzero.

7 Notice that quadprog with the active-set algorithm fails with an out-of-memory error:

options = optimset('Algorithm','active-set');
[x fval] = quadprog(H,f,A,b,[],[],[],[],[],options);

Warning: Cannot use sparse matrices with active-set algorithm:
  converting to full.
> In quadprog at 377
Error using eye
Out of memory. Type HELP MEMORY for your options.

Error in qpsub at 224
  Q = eye(numberOfVariables,numberOfVariables);

Error in quadprog at 429
[X, lambdaqp, exitflag, output, -, -, msg] = ...
Binary Integer Programming Algorithms

In this section...

“Definition” on page 6-137
“bintprog Algorithm” on page 6-137

Definition

Binary integer programming is the problem of finding a binary vector $x$ that minimizes a linear function $f^T x$ subject to linear constraints:

$$\min_{x} f^T x$$

such that $A x \leq b$, $Aeq x = beq$, $x$ binary.

bintprog Algorithm

bintprog uses a linear programming (LP)-based branch-and-bound algorithm to solve binary integer programming problems. The algorithm searches for an optimal solution to the binary integer programming problem by solving a series of LP-relaxation problems, in which the binary integer requirement on the variables is replaced by the weaker constraint $0 \leq x \leq 1$. The algorithm

- Searches for a binary integer feasible solution
- Updates the best binary integer feasible point found so far as the search tree grows
- Verifies that no better integer feasible solution is possible by solving a series of linear programming problems

The following sections describe the branch-and-bound method in greater detail.

Branching

The algorithm creates a search tree by repeatedly adding constraints to the problem, that is, "branching." At a branching step, the algorithm chooses a
variable $x_j$ whose current value is not an integer and adds the constraint $x_j = 0$ to form one branch and the constraint $x_j = 1$ to form the other branch. This process can be represented by a binary tree, in which the nodes represent the added constraints. The following picture illustrates a complete binary tree for a problem that has three variables, $x_1$, $x_2$, and $x_3$. Note that, in general, the order of the variables going down the levels in the tree is not the usual order of their subscripts

![Binary Tree Illustration]

**Deciding Whether to Branch**
At each node, the algorithm solves an LP-relaxation problem using the constraints at that node and decides whether to branch or to move to another node depending on the outcome. There are three possibilities:

- If the LP-relaxation problem at the current node is infeasible or its optimal value is greater than that of the best integer point, the algorithm removes the node from the tree, after which it does not search any branches below that node. The algorithm then moves to a new node according to the method you specify in `NodeSearchStrategy` option.

- If the algorithm finds a new feasible integer point with lower objective value than that of the best integer point, it updates the current best integer point and moves to the next node.

- If the LP-relaxation problem is optimal but not integer and the optimal objective value of the LP relaxation problem is less than the best integer point, the algorithm branches according to the method you specify in the `BranchStrategy` option.

See “Options” on page 11-5 for a description of the `NodeSearchStrategy` and `BranchStrategy` options.
Bounds
The solution to the LP-relaxation problem provides a lower bound for the binary integer programming problem. If the solution to the LP-relaxation problem is already a binary integer vector, it provides an upper bound for the binary integer programming problem.

As the search tree grows more nodes, the algorithm updates the lower and upper bounds on the objective function, using the bounds obtained in the bounding step. The bound on the objective value serves as the threshold to cut off unnecessary branches.

Limits for the Algorithm
The algorithm for bintprog could potentially search all $2^n$ binary integer vectors, where $n$ is the number of variables. As a complete search might take a very long time, you can limit the search using the following options

- **MaxNodes** — Maximum number of nodes the algorithm searches
- **MaxRLPIter** — Maximum number of iterations the LP-solver performs at any node
- **MaxTime** — Maximum amount of time in seconds the algorithm runs

See “Options” on page 11-5 for more information.
Binary Integer Programming Examples

Example: Investments with Constraints
This example uses bintprog to solve an integer programming problem that is not obviously a binary integer programming problem. This is done by representing each nonbinary integer-valued variable as an appropriate sum of binary variables, and by using linear constraints carefully. While the example is not particularly realistic, it demonstrates a variety of techniques:

- How to formulate nonbinary integer programming problems
- How to formulate an objective and constraints
- How to use indicator variables (\(y_i\) in the example)

Problem Statement
There are five investment opportunities labeled 1, 2, 3, 4, and 5. The investments have the costs and payoffs listed in the following table.

<table>
<thead>
<tr>
<th>Investment</th>
<th>Buy-In Cost</th>
<th>Cost/Unit</th>
<th>Payoff/Unit</th>
<th>Max # Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$25</td>
<td>$5</td>
<td>$15</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>$35</td>
<td>$7</td>
<td>$25</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>$28</td>
<td>$6</td>
<td>$17</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>$20</td>
<td>$4</td>
<td>$13</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>$40</td>
<td>$8</td>
<td>$18</td>
<td>3</td>
</tr>
</tbody>
</table>

- The maximum total investment is $125.
- The problem is to maximize profit, which is payoff minus cost.
- The payoff is the sum of the units bought times the payoff/unit.
- The cost per investment is the buy-in cost plus the cost/unit times the number of units if you buy at least one unit; otherwise, it is 0.
- The cost is the sum of the costs per investment.
It is convenient to formulate this problem using the indicator variables $y_i$. Define these as $y_i = 1$ when corresponding quantity variable $x_i$ is positive, and $y_i = 0$ when $x_i = 0$:

- $x_i =$ # units purchased of investment $i$
- $y_i = 1$ if $x_i > 0$, $y_i = 0$ otherwise
- $\text{cost} = \Sigma (\text{Buy-in cost})_i \cdot y_i + \Sigma (\text{cost/unit})_i \cdot x_i$
- $\text{payoff} = \Sigma (\text{payoff/unit})_i \cdot x_i$
- $\text{profit} = \text{payoff} - \text{cost}$

In addition, there are several constraints on the investments:

- You may not invest in both 2 and 5.
- You may invest in 1 only if you invest in at least one of 2 and 3.
- You must invest in at least two of 3, 4, and 5.
- You may not invest more than the listed maximum number of units in each investment.

The constraints are represented in symbols as follows:

- $y_2 + y_5 \leq 1$
- $y_1 \leq y_2 + y_3$
- $y_3 + y_4 + y_5 \geq 2$
- $x_1 \leq 5; x_2 \leq 4; x_3 \leq 5; x_4 \leq 7; x_5 \leq 3$
- $\text{cost} \leq 125$

**bintprog Formulation**

To frame this problem as a binary integer programming problem, perform the following steps:

1. Represent each integer variable $x_i$ by three binary integer variables $z_{i,j}$, $j = 1,...,3$, as follows:

   $$x_i = z_{i,1} + 2z_{i,2} + 4z_{i,3}, \quad i = 1,...,5.$$
Three $z_{ij}$ suffice to represent $x_i$, since each $x_i$ is assumed to be 7 or less. And, since $x_5 \leq 3$, $z_{5,3} = 0$.

2 Combine the variables $y$ and $z$ into a single vector $t$ as follows:

<table>
<thead>
<tr>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
<th>$t_4$</th>
<th>$t_5$</th>
<th>$t_6$</th>
<th>$t_7$</th>
<th>$t_8$</th>
<th>$t_9$</th>
<th>$t_{10}$</th>
<th>$t_{11}$</th>
<th>$t_{12}$</th>
<th>$t_{13}$</th>
<th>$t_{14}$</th>
<th>$t_{15}$</th>
<th>$t_{16}$</th>
<th>$t_{17}$</th>
<th>$t_{18}$</th>
<th>$t_{19}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_1$</td>
<td>$y_2$</td>
<td>$y_3$</td>
<td>$y_4$</td>
<td>$y_5$</td>
<td>$z_{1,1}$</td>
<td>$z_{1,2}$</td>
<td>$z_{1,3}$</td>
<td>$z_{2,1}$</td>
<td>$z_{2,2}$</td>
<td>$z_{2,3}$</td>
<td>$z_{3,1}$</td>
<td>$z_{3,2}$</td>
<td>$z_{3,3}$</td>
<td>$z_{4,1}$</td>
<td>$z_{4,2}$</td>
<td>$z_{4,3}$</td>
<td>$z_{5,1}$</td>
<td>$z_{5,2}$</td>
</tr>
</tbody>
</table>

3 Include the constraints $y_i = 0$ if and only if all the corresponding $z_{ij} = 0$ as follows:

- $y_i \leq z_{i,1} + z_{i,2} + z_{i,3}$
- $z_{i,1} + 2z_{i,2} + 4z_{i,3} \leq y_i \ast (\text{Max \# units})$

These two inequalities enforce $y_i = 0$ if and only if all the $z_{ij} = 0$, and they also enforce the maximum # units constraints.

4 As described in “Maximizing an Objective” on page 2-27, you find a maximum of an objective function by minimizing the negative of the objective function. So, to find the maximum profit, minimize the negative of the profit. The vector $f$ that gives the negative of the profit in the form $f' \ast t$ is

$$f = [25, 35, 28, 20, 40, -10, -20, -40, -18, -36, -72, -11, -22, -44, \ldots, -9, -18, -36, -10, -20]'$$

- The first five entries in $f$ represent the buy-in costs; these are incurred if the corresponding $y_i = 1$.
- The next three entries, $f(6)$, $f(7)$, and $f(8)$, represent the negative of payoff minus cost per unit for investment 1, $-(15 - 5)$, multiplied by 1, 2, and 4 respectively.
- The entries $f(9)$, $f(10)$, and $f(11)$ represent the corresponding quantities for investment 2: $-(25 - 7)$, multiplied by 1, 2, and 4.
- $f(12)$, $f(13)$, and $f(14)$ correspond to investment 3
- $f(15)$, $f(16)$, and $f(17)$ correspond to investment 4
- $f(18)$ and $f(19)$ correspond to investment 5
5 Formulate all the constraints as inequalities of the form $A \cdot t \leq b$, as required in the `bintprog` formulation “Definition” on page 6-137.

The following matrix $A$ represents the constraints, along with the vector $b$:

```matlab
A = zeros(14,19);
A(1,1:19) = [25 35 28 20 40 5 10 20 7 14 28 61 22 44 81 68 1 6];
6 12 24 4 8 16 8 16];
A(2,1) = 1; A(2,6) = -1; A(2,7) = -1; A(2,8) = -1;
A(3,2) = 1; A(3,9) = -1; A(3,10) = -1; A(3,11) = -1;
A(4,3) = 1; A(4,12) = -1; A(4,13) = -1; A(4,14) = -1;
A(5,4) = 1; A(5,15) = -1; A(5,16) = -1; A(5,17) = -1;
A(6,5) = 1; A(6,18) = -1; A(6,19) = -1;
A(7,1) = -5; A(7,6) = 1; A(7,7) = 2; A(7,8) = 4;
A(8,2) = -4; A(8,9) = 1; A(8,10) = 2; A(8,11) = 4;
A(9,3) = -5; A(9,12) = 1; A(9,13) = 2; A(9,14) = 4;
A(10,4) = -7; A(10,15) = 1; A(10,16) = 2; A(10,17) = 4;
A(11,5) = -3; A(11,18) = 1; A(11,19) = 2;
A(12,2) = 1; A(12,5) = 1;
A(13,1) = 1; A(13,2) = -1; A(13,3) = -1;
A(14,3) = -1; A(14,4) = -1; A(14,5) = -1;
b = [125 0 0 0 0 0 0 0 0 0 0 0 0 1 0 -2]';
```

- The first row of $A$ represents the cost structure; no more than $125 is available.
- Rows 2 through 6 represent $y_i \leq \sum_j z_{ij}$, $i = 1,...,5$.
- Rows 7 through 11 represent the maximum # units constraints. They also enforce $y_i = 1$ when $\sum_j z_{ij} > 0$.
- Rows 12, 13, and 14 represent the other constraints on investments.

**bintprog Solution**

*bintprog* solves the optimization problem as follows:

```
[t fval exitflag output] = bintprog(f,A,b);
Optimization terminated.
```

To examine the result, enter

```
t',fval
```
You can easily see that the only positive values of $y$ are $y_3$ and $y_4$. The values of $x$ that correspond to these, $x_3$ and $x_4$, are

\[ t(12) + 2t(13) + 4t(14) \]
\[ \text{ans} = \]
\[ 5 \]

\[ t(15) + 2t(16) + 4t(17) \]
\[ \text{ans} = \]
\[ 7 \]

In other words, to obtain the maximum profit, $70, invest in 5 units of 3 and 7 units of 4. By the way, this uses only

\[ 28 + (5*6) + 20 + (7*4) = 106 \]

of the $125 you had to invest, so there is $19 left uninvested. You can also see this by checking the first constraint, $[A\cdot t](1)$:

\[ A(1,:)\cdot t \]
\[ \text{ans} = \]
\[ 106 \]
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**Definition**

Least squares, in general, is the problem of finding a vector \( x \) that is a local minimizer to a function that is a sum of squares, possibly subject to some constraints:

\[
\min_x \|F(x)\|_2^2 = \min_x \sum_i F_i^2(x)
\]

such that \( Ax \leq b, \ Aeq x = beq, \ lb \leq x \leq ub. \)

There are several Optimization Toolbox solvers available for various types of \( F(x) \) and various types of constraints:

<table>
<thead>
<tr>
<th>Solver</th>
<th>( F(x) )</th>
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<tr>
<td>( \backslash )</td>
<td>( Cx - d )</td>
<td>None</td>
</tr>
<tr>
<td>\texttt{lsqnonneg}</td>
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<tr>
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<td>( F(x, xdata) - ydata )</td>
<td>Bound</td>
</tr>
</tbody>
</table>

There are four least-squares algorithms in Optimization Toolbox solvers, in addition to the algorithms used in \( \backslash \):

- Trust-region-reflective
- Levenberg-Marquardt
- \texttt{lsqlin} medium-scale (the large-scale algorithm is trust-region reflective)
• The algorithm used by \texttt{lsqnonneg}

The trust-region reflective algorithm, \texttt{lsqnonneg} algorithm, and Levenberg-Marquardt algorithm are large-scale; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48. The medium-scale \texttt{lsq1in} algorithm is not large-scale. For a general survey of nonlinear least-squares methods, see Dennis [8]. Specific details on the Levenberg-Marquardt method can be found in Moré [28].

**Large-Scale Least Squares**

**Large Scale Trust-Region Reflective Least Squares**

Many of the methods used in Optimization Toolbox solvers are based on trust regions, a simple yet powerful concept in optimization.

To understand the trust-region approach to optimization, consider the unconstrained minimization problem, minimize $f(x)$, where the function takes vector arguments and returns scalars. Suppose you are at a point $x$ in $n$-space and you want to improve, i.e., move to a point with a lower function value. The basic idea is to approximate $f$ with a simpler function $q$, which reasonably reflects the behavior of function $f$ in a neighborhood $N$ around the point $x$. This neighborhood is the trust region. A trial step $s$ is computed by minimizing (or approximately minimizing) over $N$. This is the trust-region subproblem,

$$\min_{s} \{q(s), s \in N\}. \quad (6-99)$$

The current point is updated to be $x + s$ if $f(x + s) < f(x)$; otherwise, the current point remains unchanged and $N$, the region of trust, is shrunk and the trial step computation is repeated.

The key questions in defining a specific trust-region approach to minimizing $f(x)$ are how to choose and compute the approximation $q$ (defined at the current point $x$), how to choose and modify the trust region $N$, and how accurately to solve the trust-region subproblem. This section focuses on the unconstrained problem. Later sections discuss additional complications due to the presence of constraints on the variables.
In the standard trust-region method ([48]), the quadratic approximation \( q \) is defined by the first two terms of the Taylor approximation to \( F \) at \( x \); the neighborhood \( N \) is usually spherical or ellipsoidal in shape. Mathematically the trust-region subproblem is typically stated

\[
\min \left\{ \frac{1}{2} s^T H s + s^T g \text{ such that } \|D s\| \leq \Delta \right\},
\]

(6-100)

where \( g \) is the gradient of \( f \) at the current point \( x \), \( H \) is the Hessian matrix (the symmetric matrix of second derivatives), \( D \) is a diagonal scaling matrix, \( \Delta \) is a positive scalar, and \( \| \cdot \| \) is the 2-norm. Good algorithms exist for solving Equation 6-100 (see [48]); such algorithms typically involve the computation of a full eigensystem and a Newton process applied to the secular equation

\[
\frac{1}{\Delta} - \frac{1}{\|s\|} = 0.
\]

Such algorithms provide an accurate solution to Equation 6-100. However, they require time proportional to several factorizations of \( H \). Therefore, for large-scale problems a different approach is needed. Several approximation and heuristic strategies, based on Equation 6-100, have been proposed in the literature ([42] and [50]). The approximation approach followed in Optimization Toolbox solvers is to restrict the trust-region subproblem to a two-dimensional subspace \( S \) ([39] and [42]). Once the subspace \( S \) has been computed, the work to solve Equation 6-100 is trivial even if full eigenvalue/eigenvector information is needed (since in the subspace, the problem is only two-dimensional). The dominant work has now shifted to the determination of the subspace.

The two-dimensional subspace \( S \) is determined with the aid of a preconditioned conjugate gradient process described below. The solver defines \( S \) as the linear space spanned by \( s_1 \) and \( s_2 \), where \( s_1 \) is in the direction of the gradient \( g \), and \( s_2 \) is either an approximate Newton direction, i.e., a solution to

\[
H \cdot s_2 = -g,
\]

(6-101)

or a direction of negative curvature,
\( s_2^T \cdot H \cdot s_2 < 0. \) \hspace{1cm} (6-102)

The philosophy behind this choice of \( S \) is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence (via the Newton step, when it exists).

A sketch of unconstrained minimization using trust-region ideas is now easy to give:

1. Formulate the two-dimensional trust-region subproblem.
2. Solve Equation 6-100 to determine the trial step \( s \).
3. If \( f(x + s) < f(x) \), then \( x = x + s \).
4. Adjust \( \Delta \).

These four steps are repeated until convergence. The trust-region dimension \( \Delta \) is adjusted according to standard rules. In particular, it is decreased if the trial step is not accepted, i.e., \( f(x + s) \geq f(x) \). See [46] and [49] for a discussion of this aspect.

Optimization Toolbox solvers treat a few important special cases of \( f \) with specialized functions: nonlinear least-squares, quadratic functions, and linear least-squares. However, the underlying algorithmic ideas are the same as for the general case. These special cases are discussed in later sections.

**Large Scale Nonlinear Least Squares**

An important special case for \( f(x) \) is the nonlinear least-squares problem

\[
\min_x \sum_i f_i^2(x) = \min_x \|F(x)\|_2^2,
\]  

(6-103)

where \( F(x) \) is a vector-valued function with component \( i \) of \( F(x) \) equal to \( f_i(x) \). The basic method used to solve this problem is the same as in the general case described in “Trust-Region Methods for Nonlinear Minimization” on page 6-3. However, the structure of the nonlinear least-squares problem is exploited to enhance efficiency. In particular, an approximate Gauss-Newton direction, i.e., a solution \( s \) to
Least Squares (Model Fitting) Algorithms

\[
\min \| Js + F \|_2^2, \tag{6-104}
\]

(where \( J \) is the Jacobian of \( F(x) \)) is used to help define the two-dimensional subspace \( S \). Second derivatives of the component function \( f_i(x) \) are not used.

In each iteration the method of preconditioned conjugate gradients is used to approximately solve the normal equations, i.e.,

\[
J^TJs = -J^TF,
\]

although the normal equations are not explicitly formed.

**Large Scale Linear Least Squares**

In this case the function \( f(x) \) to be solved is

\[
f(x) = \|Cx + d \|_2^2,
\]

possibly subject to linear constraints. The algorithm generates strictly feasible iterates converging, in the limit, to a local solution. Each iteration involves the approximate solution of a large linear system (of order \( n \), where \( n \) is the length of \( x \)). The iteration matrices have the structure of the matrix \( C \). In particular, the method of preconditioned conjugate gradients is used to approximately solve the normal equations, i.e.,

\[
C^TCx = -C^Td,
\]

although the normal equations are not explicitly formed.

The subspace trust-region method is used to determine a search direction. However, instead of restricting the step to (possibly) one reflection step, as in the nonlinear minimization case, a piecewise reflective line search is conducted at each iteration, as in the quadratic case. See [45] for details of the line search. Ultimately, the linear systems represent a Newton approach capturing the first-order optimality conditions at the solution, resulting in strong local convergence rates.
**Jacobian Multiply Function.** `lsqlin` can solve the linearly-constrained least-squares problem without using the matrix $C$ explicitly. Instead, it uses a Jacobian multiply function `jmfun`,

$$ W = \text{jmfun}(\text{Jinfo}, Y, \text{flag}) $$

that you provide. The function must calculate the following products for a matrix $Y$:

- If `flag` == 0 then $W = C'*(C*Y)$.
- If `flag` > 0 then $W = C*Y$.
- If `flag` < 0 then $W = C'*Y$.

This can be useful if $C$ is large, but contains enough structure that you can write `jmfun` without forming $C$ explicitly. For an example, see “Example: Jacobian Multiply Function with Linear Least Squares” on page 6-162.

**Levenberg-Marquardt Method**

In the least-squares problem a function $f(x)$ is minimized that is a sum of squares.

$$ \min_x f(x) = \|F(x)\|_2^2 = \sum_i F_i^2(x). \quad (6-105) $$

Problems of this type occur in a large number of practical applications, especially when fitting model functions to data, i.e., nonlinear parameter estimation. They are also prevalent in control where you want the output, $y(x,t)$, to follow some continuous model trajectory, $\varphi(t)$, for vector $x$ and scalar $t$. This problem can be expressed as

$$ \min_{x\in\mathbb{R}^n} \int_{t_1}^{t_2} (y(x,t) - \varphi(t))^2 \, dt, \quad (6-106) $$

where $y(x,t)$ and $\varphi(t)$ are scalar functions.

When the integral is discretized using a suitable quadrature formula, the above can be formulated as a least-squares problem:
Least Squares (Model Fitting) Algorithms

\[
\min_{x \in \mathbb{R}^n} f(x) = \sum_{i=1}^{m} (\bar{y}(x,t_i) - \bar{\phi}(t_i))^2 ,
\]

(6-107)

where \(\bar{y}\) and \(\bar{\phi}\) include the weights of the quadrature scheme. Note that in this problem the vector \(F(x)\) is

\[
F(x) = \begin{bmatrix}
\bar{y}(x,t_1) - \bar{\phi}(t_1) \\
\bar{y}(x,t_2) - \bar{\phi}(t_2) \\
\vdots \\
\bar{y}(x,t_m) - \bar{\phi}(t_m)
\end{bmatrix}.
\]

In problems of this kind, the residual \(|F(x)|\) is likely to be small at the optimum since it is general practice to set realistically achievable target trajectories. Although the function in LS can be minimized using a general unconstrained minimization technique, as described in “Basics of Unconstrained Optimization” on page 6-6, certain characteristics of the problem can often be exploited to improve the iterative efficiency of the solution procedure. The gradient and Hessian matrix of LS have a special structure.

Denoting the \(m\)-by-\(n\) Jacobian matrix of \(F(x)\) as \(J(x)\), the gradient vector of \(f(x)\) as \(G(x)\), the Hessian matrix of \(f(x)\) as \(H(x)\), and the Hessian matrix of each \(F_i(x)\) as \(H_i(x)\), you have

\[
G(x) = 2J(x)^T F(x)
\]

\[
H(x) = 2J(x)^T J(x) + 2Q(x),
\]

(6-108)

where

\[
Q(x) = \sum_{i=1}^{m} F_i(x) \cdot H_i(x).
\]

The matrix \(Q(x)\) has the property that when the residual \(|F(x)|\) tends to zero as \(x_k\) approaches the solution, then \(Q(x)\) also tends to zero. Thus when \(|F(x)|\) is small at the solution, a very effective method is to use the Gauss-Newton direction as a basis for an optimization procedure.
In the Gauss-Newton method, a search direction, \( d_k \), is obtained at each major iteration, \( k \), that is a solution of the linear least-squares problem:

\[
\min_{x \in \mathbb{R}} \| J(x_k) - F(x_k) \|_2^2.
\]  

(6-109)

The direction derived from this method is equivalent to the Newton direction when the terms of \( Q(x) \) can be ignored. The search direction \( d_k \) can be used as part of a line search strategy to ensure that at each iteration the function \( f(x) \) decreases.

The Gauss-Newton method often encounters problems when the second-order term \( Q(x) \) is significant. A method that overcomes this problem is the Levenberg-Marquardt method.

The Levenberg-Marquardt \([25], \text{and } [27]\) method uses a search direction that is a solution of the linear set of equations

\[
\left( J(x_k)^T J(x_k) + \lambda_k I \right) d_k = -J(x_k)^T F(x_k),
\]  

(6-110)

or, optionally, of the equations

\[
\left( J(x_k)^T J(x_k) + \lambda_k \text{diag} \left( J(x_k)^T J(x_k) \right) \right) d_k = -J(x_k)^T F(x_k),
\]  

(6-111)

where the scalar \( \lambda_k \) controls both the magnitude and direction of \( d_k \). Set option ScaleProblem to 'none' to choose Equation 6-110, and set ScaleProblem to 'Jacobian' to choose Equation 6-111.

When \( \lambda_k \) is zero, the direction \( d_k \) is identical to that of the Gauss-Newton method. As \( \lambda_k \) tends to infinity, \( d_k \) tends towards the steepest descent direction, with magnitude tending to zero. This implies that for some sufficiently large \( \lambda_k \), the term \( F(x_k + d_k) < F(x_k) \) holds true. The term \( \lambda_k \) can therefore be controlled to ensure descent even when second-order terms, which restrict the efficiency of the Gauss-Newton method, are encountered.

The Levenberg-Marquardt method therefore uses a search direction that is a cross between the Gauss-Newton direction and the steepest descent direction. This is illustrated in Figure 6-4, Levenberg-Marquardt Method on
Rosenbrock’s Function. The solution for Rosenbrock’s function converges after 90 function evaluations compared to 48 for the Gauss-Newton method. The poorer efficiency is partly because the Gauss-Newton method is generally more effective when the residual is zero at the solution. However, such information is not always available beforehand, and the increased robustness of the Levenberg-Marquardt method compensates for its occasional poorer efficiency.

Figure 6-4: Levenberg-Marquardt Method on Rosenbrock’s Function

For an animated version of this figure, enter `bandem` at the MATLAB command line.
Least Squares (Model Fitting) Examples

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| “Example: Nonlinear Least-Squares with Full Jacobian Sparsity Pattern” on page 6-159 |
| “Example: Linear Least-Squares with Bound Constraints” on page 6-161 |
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| “Example: Nonlinear Curve Fitting with lsqcurvefit” on page 6-167 |

Example: Using lsqnonlin With a Simulink Model

Suppose that you want to optimize the control parameters in the Simulink model `optsim.mdl`. (This model can be found in the `optim/optimdemos` folder. Note that Simulink must be installed on your system to load this model.) The model includes a nonlinear process plant modeled as a Simulink block diagram.

Plant with Actuator Saturation

The plant is an under-damped third-order model with actuator limits. The actuator limits are a saturation limit and a slew rate limit. The actuator saturation limit cuts off input values greater than 2 units or less than -2 units. The slew rate limit of the actuator is 0.8 units/sec. The closed-loop response of the system to a step input is shown in Closed-Loop Response on page 6-155. You can see this response by opening the model (type `optsim` at the command line or click the model name), and selecting Start from the Simulation menu. The response plots to the scope.
Closed-Loop Response

The problem is to design a feedback control loop that tracks a unit step input to the system. The closed-loop plant is entered in terms of the blocks where the plant and actuator have been placed in a hierarchical Subsystem block. A Scope block displays output trajectories during the design process.

Closed-Loop Model
One way to solve this problem is to minimize the error between the output and the input signal. The variables are the parameters of the Proportional Integral Derivative (PID) controller. If you only need to minimize the error at one time unit, it would be a single objective function. But the goal is to minimize the error for all time steps from 0 to 100, thus producing a multiobjective function (one function for each time step).

The routine `lsqnonlin` is used to perform a least-squares fit on the tracking of the output. The tracking is performed via the function `tracklsq`, which returns the error signal `yout`, the output computed by calling `sim`, minus the input signal 1. The code for `tracklsq` is contained in the file `runtracklsq.m`, shown below.

The function `runtracklsq` sets up all the needed values and then calls `lsqnonlin` with the objective function `tracklsq`, which is nested inside `runtracklsq`. The variable `options` passed to `lsqnonlin` defines the criteria and display characteristics. In this case you ask for output, use the medium-scale algorithm, and give termination tolerances for the step and objective function on the order of 0.001.

To run the simulation in the model `optsim`, the variables `Kp`, `Ki`, `Kd`, `a1`, and `a2` (`a1` and `a2` are variables in the Plant block) must all be defined. `Kp`, `Ki`, and `Kd` are the variables to be optimized. The function `tracklsq` is nested inside `runtracklsq` so that the variables `a1` and `a2` are shared between the two functions. The variables `a1` and `a2` are initialized in `runtracklsq`.

The objective function `tracklsq` runs the simulation. The simulation can be run either in the base workspace or the current workspace, that is, the workspace of the function calling `sim`, which in this case is the workspace of `tracklsq`. In this example, the `SrcWorkspace` option is set to `'Current'` to tell `sim` to run the simulation in the current workspace. The simulation is performed to 100 seconds.

When the simulation is completed, the `myobj` object is created in the current workspace (that is, the workspace of `tracklsq`). The Outport block in the block diagram model puts the `yout` field of the object into the current workspace at the end of the simulation.

The following is the code for `runtracklsq`:
function [Kp,Ki,Kd] = runtracklsq
% RUNTRACKLSQ demonstrates using LSQNONLIN with Simulink.

optsim % Load the model
pid0 = [0.63 0.0504 1.9688]; % Set initial values
a1 = 3; a2 = 43; % Initialize model plant variables
options = optimset('Algorithm','levenberg-marquardt',... 
    'Display','off','TolX',0.001,'TolFun',0.001);

pid = lsqnonlin(@tracklsq, pid0, [], [], options);
Kp = pid(1); Ki = pid(2); Kd = pid(3);

function F = tracklsq(pid)
% Track the output of optsim to a signal of 1

% Variables a1 and a2 are needed by the model optsim. 
% They are shared with RUNTRACKLSQ so do not need to be 
% redefined here.
Kp = pid(1);
Ki = pid(2);
Kd = pid(3);

% Set sim options and compute function value
myobj = sim('optsim','SrcWorkspace','Current', ... 
    'StopTime','100');
F = myobj.get('yout') - 1;
end
end

Copy the code for runtracklsq to a file named runtracklsq.m, placed in a folder on your MATLAB path.

When you run runtracklsq, the optimization gives the solution for the proportional, integral, and derivative (Kp, Ki, Kd) gains of the controller:

[Kp, Ki, Kd] = runtracklsq

Done initializing optsim.

Kp = 
    2.9633
Ki =
0.1436

Kd =
13.1386

Here is the resulting closed-loop step response.
Note The call to `sim` results in a call to one of the Simulink ordinary differential equation (ODE) solvers. A choice must be made about the type of solver to use. From the optimization point of view, a fixed-step solver is the best choice if that is sufficient to solve the ODE. However, in the case of a stiff system, a variable-step method might be required to solve the ODE.

The numerical solution produced by a variable-step solver, however, is not a smooth function of parameters, because of step-size control mechanisms. This lack of smoothness can prevent the optimization routine from converging. The lack of smoothness is not introduced when a fixed-step solver is used. (For a further explanation, see [53].)

Simulink® Design Optimization™ software is recommended for solving multiobjective optimization problems in conjunction with Simulink variable-step solvers. It provides a special numeric gradient computation that works with Simulink and avoids introducing a problem of lack of smoothness.

Example: Nonlinear Least-Squares with Full Jacobian Sparsity Pattern

The trust-region reflective algorithm in `lsqnonlin`, `lsqcurvefit`, and `fsolve` can be used with small- to medium-scale problems without computing the Jacobian in `fun` or providing the Jacobian sparsity pattern. (This example also applies to the case of using `fmincon` or `fminunc` without computing the Hessian or supplying the Hessian sparsity pattern.) How small is small- to medium-scale? No absolute answer is available, as it depends on the amount of virtual memory available in your computer system configuration.

Suppose your problem has $m$ equations and $n$ unknowns. If the command $J = \text{sparse}(\text{ones}(m,n))$ causes an `Out of memory` error on your machine, then this is certainly too large a problem. If it does not result in an error, the problem might still be too large, but you can only find out by running it and seeing if MATLAB is able to run within the amount of virtual memory available on your system.

Let’s say you have a small problem with 10 equations and 2 unknowns, such as finding $x$ that minimizes

$$6-159$$
\[
\sum_{k=1}^{10} \left( 2 + 2k - e^{kx_1} - e^{kx_2} \right)^2,
\]

starting at the point \( x = [0.3, 0.4] \).

Because \texttt{lsqnonlin} assumes that the sum of squares is not explicitly formed in the user function, the function passed to \texttt{lsqnonlin} should instead compute the vector valued function

\[
F_k(x) = 2 + 2k - e^{kx_1} - e^{kx_2},
\]

for \( k = 1 \) to 10 (that is, \( F \) should have 10 components).

**Step 1: Write a file \texttt{myfun.m} that computes the objective function values.**

```matlab
function F = myfun(x)
k = 1:10;
F = 2 + 2*k-exp(k*x(1))-exp(k*x(2));
```

**Step 2: Call the nonlinear least-squares routine.**

```matlab
x0 = [0.3 0.4] % Starting guess
[x,resnorm] = lsqnonlin(@myfun,x0); % Invoke optimizer
```

Because the Jacobian is not computed in \texttt{myfun.m}, and no Jacobian sparsity pattern is provided by the JacobPattern option in options, \texttt{lsqnonlin} calls the trust-region reflective algorithm with JacobPattern set to 

\( Jstr =\text{sparse(ones(10,2))} \). This is the default for \texttt{lsqnonlin}. Note that the Jacobian option in options is set to 'off' by default.

When the finite-differencing routine is called the first time, it detects that \( Jstr \) is actually a dense matrix, i.e., that no speed benefit is derived from storing it as a sparse matrix. From then on the finite-differencing routine uses \( Jstr =\text{ones(10,2)} \) (a full matrix) for the optimization computations.

After about 24 function evaluations, this example gives the solution
Most computer systems can handle much larger full problems, say into the hundreds of equations and variables. But if there is some sparsity structure in the Jacobian (or Hessian) that can be taken advantage of, the large-scale methods will always run faster if this information is provided.

**Example: Linear Least-Squares with Bound Constraints**

Many situations give rise to sparse linear least-squares problems, often with bounds on the variables. The next problem requires that the variables be nonnegative. This problem comes from fitting a function approximation to a piecewise linear spline. Specifically, particles are scattered on the unit square. The function to be approximated is evaluated at these points, and a piecewise linear spline approximation is constructed under the condition that (linear) coefficients are not negative. There are 2000 equations to fit on 400 variables:

```matlab
load particle % Get C, d
lb = zeros(400,1);
[x,resnorm,residual,exitflag,output] = ...
    lsqlin(C,d,[],[],[],lb);
```

The default diagonal preconditioning works fairly well:

```matlab
exitflag,resnorm,output
```

```matlab
exitflag =
    3
resnorm =
    22.5794
output =
```
iterations: 10
algorithm: 'large-scale: trust-region reflective Newton'
firstorderopt: 2.7870e-005
cgiterations: 42
message: [1x123 char]

For bound constrained problems, the first-order optimality is the infinity norm of $v^*g$, where $v$ is defined as in “Box Constraints” on page 6-25, and $g$ is the gradient.

You can improve (decrease) the first-order optimality measure by using a sparse QR factorization in each iteration. To do this, set PrecondBandWidth to inf:

```matlab
options = optimset('PrecondBandWidth',inf);
[x,resnorm,residual,exitflag,output] = ...
    lsqlin(C,d,[],[],[],lb,[],[],options);
```

The first-order optimality measure decreases:

```matlab
exitflag,resnorm,output
```

```matlab
exitflag =
1
resnorm =
22.5794
output =
    iterations: 12
    algorithm: 'large-scale: trust-region reflective Newton'
    firstorderopt: 5.5907e-015
cgiterations: 0
    message: [1x104 char]
```

**Example: Jacobian Multiply Function with Linear Least Squares**

You can solve a least-squares problem of the form
Least Squares (Model Fitting) Examples

\[
\min_x \frac{1}{2} \|C \cdot x - d\|_2^2
\]

such that \( A \cdot x \leq b, \ A_{eq} \cdot x = b_{eq}, \ lb \leq x \leq ub \), for problems where \( C \) is very large, perhaps too large to be stored, by using a Jacobian multiply function.

For example, consider the case where \( C \) is a \( 2n \)-by-\( n \) matrix based on a circulant matrix. This means the rows of \( C \) are shifts of a row vector \( v \). This example has the row vector \( v \) with elements of the form \((-1)^{k+1}/k\):

\[
v = [1, -1/2, 1/3, -1/4, \ldots, -1/n],
\]

cyclically shifted:

\[
C = \begin{bmatrix}
1 & -1/2 & 1/3 & \cdots & -1/n \\
-1/n & 1 & -1/2 & \cdots & 1/(n-1) \\
1/(n-1) & -1/n & 1 & \cdots & -1/(n-2) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
-1/2 & 1/3 & -1/4 & \cdots & 1 \\
1 & -1/2 & 1/3 & \cdots & -1/n \\
-1/n & 1 & -1/2 & \cdots & 1/(n-1) \\
1/(n-1) & -1/n & 1 & \cdots & -1/(n-2) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
-1/2 & 1/3 & -1/4 & \cdots & 1
\end{bmatrix}.
\]

This least-squares example considers the problem where

\[
d = [n-1; n-2; \ldots; -n],
\]

and the constraints are \(-5 \leq x(i) \leq 5\) for \( i = 1, \ldots, n \).

For large enough \( n \), the dense matrix \( C \) does not fit into computer memory. (\( n = 10,000 \) is too large on one tested system.)

A Jacobian multiply function has the following syntax:

\[
w = jmfcn(Jinfo,Y,flag)
\]
Jinfo is a matrix the same size as C, used as a preconditioner. If C is too large to fit into memory, Jinfo should be sparse. Y is a vector or matrix sized so that C*Y or C'*Y makes sense. flag tells jmfcn which product to form:

- flag > 0 ⇒ w = C*Y
- flag < 0 ⇒ w = C'*Y
- flag = 0 ⇒ w = C'*C*Y

Since C is such a simply structured matrix, it is easy to write a Jacobian multiply function in terms of the vector v; i.e., without forming C. Each row of C*Y is the product of a shifted version of v times Y. The following matrix performs one step of the shift: v shifts to v*T, where

\[
T = \begin{bmatrix}
0 & 1 & 0 & \ldots & 0 \\
0 & 0 & 1 & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \ldots & 1 \\
1 & 0 & 0 & \ldots & 0
\end{bmatrix}
\]

To compute C*Y, compute v*Y to find the first row, then shift v and compute the second row, and so on.

To compute C'*Y, perform the same computation, but use a shifted version of temp, the vector formed from the first row of C':

\[
\text{temp} = [\text{fliplr}(v)*T, \text{fliplr}(v)*T];
\]

To compute C'*C*Y, simply compute C*Y using shifts of v, and then compute C' times the result using shifts of fliplr(v).

The dolsqJac function in the following code sets up the vector v and matrix T, and calls the solver lsqlin:

```matlab
function [x,resnorm,residual,exitflag,output] = dolsqJac(n)
    r = 1:n-1; % index for making vectors
    T = spalloc(n,n,n); % making a sparse circulant matrix
```

6-164
for m = r
    T(m,m+1)=1;
end
T(n,1) = 1;

v(n) = (-1)^(n+1)/n; % allocating the vector v
v(r) =( -1).^(r+1)./r;

% Now C should be a 2n-by-n circulant matrix based on v, % but that might be too large to fit into memory.

r = 1:2*n;
d(r) = n-r;

Jinfo = [speye(n);speye(n)]; % sparse matrix for preconditioning
% This matrix is a required input for the solver;
% preconditioning is not really being used in this example

% Pass the matrix T and vector v so they don't need to be
% computed in the Jacobian multiply function
options = optimset('JacobMult', ... 
    @(Jinfo,Y,flag)lsqcirculant(Jinfo,Y,flag,T,v));

lb = -5*ones(1,n);
ub = 5*ones(1,n);

[x,resnorm,residual,exitflag,output] = ... 
    lsqlin(Jinfo,d,[],[],[],[],lb,ub,[],options);

The Jacobian multiply function lsqcirculant is as follows:

function w = lsqcirculant(Jinfo,Y,flag,T,v)
% This function computes the Jacobian multiply functions
% for a 2n-by-n circulant matrix example

if flag > 0
    w = Jpositive(Y);
elseif flag < 0
    w = Jnegative(Y);
else

\[ w = J_{\text{negative}}(J_{\text{positive}}(Y)); \]

function \( a = J_{\text{positive}}(q) \)
% Calculate \( C^\prime q \)
\[
\text{temp} = v;
\]
\[
a = \text{zeros(size}(q)); \quad \text{% allocating the matrix} \ a
\]
\[
a = [a;a]; \quad \text{% the result is twice as tall as the input}
\]
\[
\text{for } r = 1:\text{size}(a,1)
\]
\[
a(r,:) = \text{temp}^\prime q; \quad \text{% compute the rth row}
\]
\[
\text{temp} = \text{temp}^\prime T; \quad \text{% shift the circulant}
\]
end
end

function \( a = J_{\text{negative}}(q) \)
% Calculate \( C^\prime q \)
\[
\text{temp} = \text{fliplr}(v)^\prime T; \quad \text{% the circulant for} \ C^\prime
\]
\[
\text{len} = \text{size}(q,1)/2; \quad \text{% the returned vector is half as long}
\]
% as the input vector
\[
a = \text{zeros(len,size}(q,2)); \quad \text{% allocating the matrix} \ a
\]
\[
\text{for } r = 1:len
\]
\[
a(r,:) = [\text{temp},\text{temp}]^\prime q; \quad \text{% compute the rth row}
\]
\[
\text{temp} = \text{temp}^\prime T; \quad \text{% shift the circulant}
\]
end
end

When \( n = 3000 \), \( C \) is an 18,000,000-element dense matrix. Here are the results of the \texttt{dolsqJac} function for \( n = 3000 \) at selected values of \( x \), and the output structure:

\[
[x, \text{resnorm}, \text{residual}, \text{exitflag}, \text{output}] = \text{dolsqJac}(3000);
\]

Optimization terminated: relative function value changing by less than \texttt{OPTIONS.TolFun}.
Least Squares (Model Fitting) Examples

x(1)
anst =
  5.0000

x(1500)
anst =
  -0.5201

x(3000)
anst =
  -5.0000

output
output =
  iterations: 16
  algorithm: 'large-scale: trust-region reflective Newton'
  firstorderopt: 5.9351e-005
  cgiterations: 36
  message: [1x87 char]

Example: Nonlinear Curve Fitting with lsqcurvefit

`lsqcurvefit` enables you to fit parameterized nonlinear functions to data easily. You can use `lsqnonlin` as well; `lsqcurvefit` is simply a convenient way to call `lsqnonlin` for curve fitting.

In this example, the vector `xdata` represents 100 data points, and the vector `ydata` represents the associated measurements. Generate the data using the following script:

```
rng(5489,'twister') % reproducible
xdata = -2*log(rand(100,1));
ydata = (ones(100,1) + .1*randn(100,1)) + (3*ones(100,1)+...
  0.5*randn(100,1)).*exp((-2*ones(100,1)+...
  .5*randn(100,1))).*xdata);
```

The modeled relationship between `xdata` and `ydata` is
\[
ydata_i = a_1 + a_2 \exp(-a_3 xdata_i) + \varepsilon_i.\quad (6-112)
\]

The script generates \(xdata\) from 100 independent samples from an exponential distribution with mean 2. It generates \(ydata\) from Equation 6-112 using \(a = [1;3;2]\), perturbed by adding normal deviates with standard deviations \([0.1;0.5;0.5]\).

The goal is to find parameters \(\hat{a}_i, i = 1, 2, 3\), for the model that best fit the data.

In order to fit the parameters to the data using \texttt{lsqcurvefit}, you need to define a fitting function. Define the fitting function \texttt{predicted} as an anonymous function:

\[
\texttt{predicted} = @(a,xdata) a(1) \cdot \text{ones}(100,1) + a(2) \cdot \exp(-a(3) \cdot xdata); 
\]

To fit the model to the data, \texttt{lsqcurvefit} needs an initial estimate \(a0\) of the parameters. Enter

\[
\texttt{a0} = [2;2;2]; 
\]

Run the solver \texttt{lsqcurvefit} as follows:

\[
\texttt{[ahat,resnorm,residual,exitflag,output,lambda,jacobian]} = \ldots 
\texttt{lsqcurvefit(predicted,a0,xdata,ydata);} 
\]

Local minimum possible.

\texttt{lsqcurvefit} stopped because the final change in the sum of squares relative to its initial value is less than the default value of the function tolerance.

To see the resulting least-squares estimate of \(\hat{a}\), enter:

\[
\texttt{ahat} 
\]

\[
\texttt{ahat} = 
\begin{array}{c}
1.0169 \\
3.1444 \\
2.1596 
\end{array} 
\]
The fitted values $a_{\hat{}}$ are within 8% of $a = [1;3;2]$.

If you have Statistics Toolbox™ software, use the `nlparsci` function to generate confidence intervals for the $a_{\hat{}}$ estimate.
Multiobjective Optimization Algorithms

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Definition

There are two Optimization Toolbox multiobjective solvers: \texttt{fgoalattain} and \texttt{fminimax}.

- \texttt{fgoalattain} addresses the problem of reducing a set of nonlinear functions \( F_i(x) \) below a set of goals \( F^*_i \). Since there are several functions \( F_i(x) \), it is not always clear what it means to solve this problem, especially when you cannot achieve all the goals simultaneously. Therefore, the problem is reformulated to one that is always well-defined.

The unscaled goal attainment problem is to minimize the maximum of \( F_i(x) - F^*_i \).

There is a useful generalization of the unscaled problem. Given a set of positive weights \( w_i \), the goal attainment problem tries to find \( x \) to minimize the maximum of

\[
\frac{F_i(x) - F^*_i}{w_i}.
\]  

(6-113)

This minimization is supposed to be accomplished while satisfying all types of constraints: \( c(x) \leq 0, \ ceq(x) = 0, \ A x \leq b, \ Aeq x = beq, \) and \( l \leq x \leq u \).

If you set all weights equal to 1 (or any other positive constant), the goal attainment problem is the same as the unscaled goal attainment problem. If the \( F^*_i \) are positive, and you set all weights as \( w_i = F^*_i \), the goal attainment problem becomes minimizing the relative difference between the functions \( F_i(x) \) and the goals \( F^*_i \).

In other words, the goal attainment problem is to minimize a slack variable \( \gamma \), defined as the maximum over \( i \) of the expressions in Equation 6-113. This implies the expression that is the formal statement of the goal attainment problem:
\[
\min_{\gamma} \gamma
\]

such that \( F(x) - w \gamma \leq F^* \), \( c(x) \leq 0 \), \( ceq(x) = 0 \), \( A \leq x \leq b \), \( Aeq x = beq \), and \( l \leq x \leq u \).

- \( \text{fminimax} \) addresses the problem of minimizing the maximum of a set of nonlinear functions, subject to all types of constraints:

\[
\min \max_{x \in x_i} F_i(x)
\]

such that \( c(x) \leq 0 \), \( ceq(x) = 0 \), \( A \leq x \leq b \), \( Aeq x = beq \), and \( l \leq x \leq u \).

Clearly, this problem is a special case of the unscaled goal attainment problem, with \( F^*_i = 0 \) and \( w_i = 1 \).

### Algorithms

#### Goal Attainment Method

This section describes the goal attainment method of Gembicki [16]. This method uses a set of design goals, \( F^* = \{F_1^*, F_2^*, \ldots, F_m^*\} \), associated with a set of objectives, \( F(x) = \{F_1(x), F_2(x), \ldots, F_m(x)\} \). The problem formulation allows the objectives to be under- or overachieved, enabling the designer to be relatively imprecise about the initial design goals. The relative degree of under- or overachievement of the goals is controlled by a vector of weighting coefficients, \( w = \{w_1, w_2, \ldots, w_m\} \), and is expressed as a standard optimization problem using the formulation

\[
\text{minimize } \gamma \in \mathbb{R}, x \in \Omega
\]

such that \( F_i(x) - w_i \gamma \leq F_i^* \), \( i = 1, \ldots, m \).

The term \( w_i \gamma \) introduces an element of slackness into the problem, which otherwise imposes that the goals be rigidly met. The weighting vector, \( w \), enables the designer to express a measure of the relative tradeoffs between the objectives. For instance, setting the weighting vector \( w \) equal to the initial goals indicates that the same percentage under- or overachievement of the goals, \( F^* \), is achieved. You can incorporate hard constraints into the
design by setting a particular weighting factor to zero (i.e., $w_i = 0$). The goal attainment method provides a convenient intuitive interpretation of the design problem, which is solvable using standard optimization procedures. Illustrative examples of the use of the goal attainment method in control system design can be found in Fleming ([10] and [11]).

The goal attainment method is represented geometrically in the figure below in two dimensions.

$$\begin{align*}
\text{minimize } & \gamma, x \in \Omega \\
\text{subject to } & F_1(x) - w_1 \gamma \leq F_1^* \\
& F_2(x) - w_2 \gamma \leq F_2^*
\end{align*}$$

Figure 6-5: Geometrical Representation of the Goal Attainment Method

Specification of the goals, $\{F_1^*, F_2^*\}$, defines the goal point, $P$. The weighting vector defines the direction of search from $P$ to the feasible function space, $\Lambda(\gamma)$. During the optimization $\gamma$ is varied, which changes the size of the feasible region. The constraint boundaries converge to the unique solution point $F_1^s, F_2^s$.

Algorithm Improvements for the Goal Attainment Method

The goal attainment method has the advantage that it can be posed as a nonlinear programming problem. Characteristics of the problem can also be exploited in a nonlinear programming algorithm. In sequential quadratic programming (SQP), the choice of merit function for the line search is not easy because, in many cases, it is difficult to “define” the relative importance between improving the objective function and reducing constraint violations.
This has resulted in a number of different schemes for constructing the merit function (see, for example, Schittkowski [36]). In goal attainment programming there might be a more appropriate merit function, which you can achieve by posing Equation 6-114 as the minimax problem

$$\min_{x \in \mathbb{R}^n} \max_i \{ \Lambda_i \},$$  

(6-115)

where $\Lambda_i = \frac{F_i(x) - F^*_i}{w_i}, \ i = 1, ..., m.$

Following the argument of Brayton et al. [2] for minimax optimization using SQP, using the merit function of Equation 6-47 for the goal attainment problem of Equation 6-115 gives

$$\psi(x, \gamma) = \gamma + \sum_{i=1}^{m} r_i \cdot \max \{ 0, F_i(x) - w_i \gamma - F^*_i \}. \tag{6-116}$$

When the merit function of Equation 6-116 is used as the basis of a line search procedure, then, although $\psi(x, \gamma)$ might decrease for a step in a given search direction, the function $\max \Lambda_i$ might paradoxically increase. This is accepting a degradation in the worst case objective. Since the worst case objective is responsible for the value of the objective function $\gamma$, this is accepting a step that ultimately increases the objective function to be minimized. Conversely, $\psi(x, \gamma)$ might increase when $\max \Lambda_i$ decreases, implying a rejection of a step that improves the worst case objective.

Following the lines of Brayton et al. [2], a solution is therefore to set $\psi(x)$ equal to the worst case objective, i.e.,

$$\psi(x) = \max_i \Lambda_i. \tag{6-117}$$

A problem in the goal attainment method is that it is common to use a weighting coefficient equal to 0 to incorporate hard constraints. The merit function of Equation 6-117 then becomes infinite for arbitrary violations of the constraints.
To overcome this problem while still retaining the features of Equation 6-117, the merit function is combined with that of Equation 6-48, giving the following:

\[ \psi(x) = \sum_{i=1}^{m} \begin{cases} r_i \cdot \max \left\{ 0, F_i(x) - w_i \gamma - F_i^* \right\} & \text{if } w_i = 0 \\ \max \Lambda_i, i = 1, \ldots, m & \text{otherwise.} \end{cases} \]  

(6-118)

Another feature that can be exploited in SQP is the objective function \( \gamma \). From the KKT equations it can be shown that the approximation to the Hessian of the Lagrangian, \( H \), should have zeros in the rows and columns associated with the variable \( \gamma \). However, this property does not appear if \( H \) is initialized as the identity matrix. \( H \) is therefore initialized and maintained to have zeros in the rows and columns associated with \( \gamma \).

These changes make the Hessian, \( H \), indefinite. Therefore \( H \) is set to have zeros in the rows and columns associated with \( \gamma \), except for the diagonal element, which is set to a small positive number (e.g., \( 1e-10 \)). This allows use of the fast converging positive definite QP method described in “Quadratic Programming Solution” on page 6-32.

The preceding modifications have been implemented in \texttt{fgoalattain} and have been found to make the method more robust. However, because of the rapid convergence of the SQP method, the requirement that the merit function strictly decrease sometimes requires more function evaluations than an implementation of SQP using the merit function of Equation 6-47.

**Minimizing the Maximum Objective**

\texttt{fminimax} uses a goal attainment method. It takes goals of 0, and weights of 1. With this formulation, the goal attainment problem becomes

\[ \min_{x} \max_{i} \left( \frac{f_i(x) - \text{goal}_i}{\text{weight}_i} \right) = \min_{x} \max_{i} f_i(x), \]

which is the minimax problem.

Parenthetically, you might expect \texttt{fminimax} to turn the multiobjective function into a single objective. The function
Multiobjective Optimization Algorithms

\[
f(x) = \max(F_1(x), \ldots, F_j(x))
\]

is a single objective function to minimize. However, it is not differentiable, and Optimization Toolbox objectives are required to be smooth. Therefore the minimax problem is formulated as a smooth goal attainment problem.
Multiobjective Optimization Examples

In this section...

“Example: Using fminimax with a Simulink Model” on page 6-176
“Example: Signal Processing Using fgoalattain” on page 6-179

Example: Using fminimax with a Simulink Model

Another approach to optimizing the control parameters in the Simulink model shown in Plant with Actuator Saturation on page 6-154 is to use the fminimax function. In this case, rather than minimizing the error between the output and the input signal, you minimize the maximum value of the output at any time t between 0 and 100.

The code for this example, shown below, is contained in the function runtrackmm, in which the objective function is simply the output yout returned by the sim command. But minimizing the maximum output at all time steps might force the output to be far below unity for some time steps. To keep the output above 0.95 after the first 20 seconds, the constraint function trackmmcon contains the constraint yout >= 0.95 from t=20 to t=100. Because constraints must be in the form g <= 0, the constraint in the function is g = -yout(20:100)+.95.

Both trackmmobj and trackmmcon use the result yout from sim, calculated from the current PID values. To avoid calling the simulation twice, runtrackmm has nested functions so that the value of yout is shared between the objective and constraint functions. The simulation is called only when the current point changes.

The following is the code for runtrackmm:

```matlab
function [Kp, Ki, Kd] = runtrackmm

optsim % initialize Simulink(R)
pid0 = [0.63 0.0504 1.9688];
% a1, a2, yout are shared with TRACKMMOBJ and TRACKMMCON
a1 = 3; a2 = 43; % Initialize plant variables in model
yout = []; % Give yout an initial value
```
pold = []; % tracks last pid
options = optimset('Display','iter',...
    'TolX',0.001,'TolFun',0.001);
pid = fminimax(@trackmmobj,pid0,[],[],[],[],[],...
    @trackmmcon,options);
Kp = pid(1); Ki = pid(2); Kd = pid(3);

function F = trackmmobj(pid)
    % Track the output of optsim to a signal of 1.
    % Variables a1 and a2 are shared with RUNTRACKMM.
    % Variable yout is shared with RUNTRACKMM and
    % RUNTRACKMMCON.
    updateIfNeeded(pid)

    F = yout;
end

function [c,ceq] = trackmmcon(pid)
    % Track the output of optsim to a signal of 1.
    % Variable yout is shared with RUNTRACKMM and
    % TRACKMMOBJ
    updateIfNeeded(pid)

    c = -yout(20:100)+.95;
    ceq=[];
end

function updateIfNeeded(pid)
    if ~isequal(pid,pold) % compute only if needed

        Kp = pid(1);
        Ki = pid(2);
        Kd = pid(3);

        myobj = sim('optsim','SrcWorkspace','Current');
        yout = myobj.get('yout');

        pold = pid;
    end
end
Copy the code for runtrackmm to a file named runtrackmm.m, placed in a folder on your MATLAB path.

When you run the code, it returns the following results:

```
[Kp,Ki,Kd] = runtrackmm
```

```
6-178
end
```

The last value in the Objective value column of the output shows that the maximum value for all the time steps is 0.9997. The closed loop response with this result is shown in the figure Closed-Loop Response Using fminimax on page 6-179.
This solution differs from the solution obtained in “Example: Using lsqnonlin With a Simulink Model” on page 6-154 because you are solving different problem formulations.

**Closed-Loop Response Using fminimax**

**Example: Signal Processing Using fgoalattain**

Consider designing a linear-phase Finite Impulse Response (FIR) filter. The problem is to design a lowpass filter with magnitude one at all frequencies between 0 and 0.1 Hz and magnitude zero between 0.15 and 0.5 Hz.

The frequency response $H(f)$ for such a filter is defined by
where $A(f)$ is the magnitude of the frequency response. One solution is to apply a goal attainment method to the magnitude of the frequency response. Given a function that computes the magnitude, \texttt{fgoalattain} will attempt to vary the magnitude coefficients $a(n)$ until the magnitude response matches the desired response within some tolerance. The function that computes the magnitude response is given in \texttt{filtmin.m}. This function uses $a$, the magnitude function coefficients, and $w$, the discretization of the frequency domain of interest.

To set up a goal attainment problem, you must specify the goal and weights for the problem. For frequencies between 0 and 0.1, the goal is one. For frequencies between 0.15 and 0.5, the goal is zero. Frequencies between 0.1 and 0.15 are not specified, so no goals or weights are needed in this range.

This information is stored in the variable \texttt{goal} passed to \texttt{fgoalattain}. The length of \texttt{goal} is the same as the length returned by the function \texttt{filtmin}. So that the goals are equally satisfied, usually \texttt{weight} would be set to \texttt{abs(goal)}. However, since some of the goals are zero, the effect of using \texttt{weight=abs(goal)} will force the objectives with \texttt{weight 0} to be satisfied as hard constraints, and the objectives with \texttt{weight 1} possibly to be underattained (see “Goal Attainment Method” on page 6-171). Because all the goals are close in magnitude, using a \texttt{weight} of unity for all goals will give them equal priority. (Using \texttt{abs(goal)} for the weights is more important when the magnitude of \texttt{goal} differs more significantly.) Also, setting

\begin{verbatim}
options = optimset('GoalsExactAchieve',length(goal));
\end{verbatim}

specifies that each objective should be as near as possible to its goal value (neither greater nor less than).

**Step 1: Write a file filtmin.m**

```matlab
function y = filtmin(a,w)
```

\begin{equation}
H(f) = \sum_{n=0}^{2M} h(n)e^{-j2\pi fn} = A(f)e^{-j2\pi fM},
A(f) = \sum_{n=0}^{M-1} a(n)\cos(2\pi fn),
\end{equation}

(6-119)
n = length(a);
y = cos(w'*(0:n-1)*2*pi)*a ;

**Step 2: Invoke optimization routine**

```matlab
% Plot with initial coefficients
a0 = ones(15,1);
incr = 50;
w = linspace(0,0.5,incr);

y0 = filtmin(a0,w);
clf, plot(w,y0,'-.b');
drawnow;

% Set up the goal attainment problem
w1 = linspace(0,0.1,incr) ;
w2 = linspace(0.15,0.5,incr);
w0 = [w1 w2];
goal = [1.0*ones(1,length(w1)) zeros(1,length(w2))];
weight = ones(size(goal));

% Call fgoalattain
options = optimset('GoalsExactAchieve',length(goal));
[a,fval,attainfactor,exitflag]=fgoalattain(@(x)filtmin(x,w0),...
a0,goal,weight,[],[],[],[],[],[],options);

% Plot with the optimized (final) coefficients
y = filtmin(a,w);
hold on, plot(w,y,'r')
axis([0 0.5 -3 3])
xlabel('Frequency (Hz)')
ylabel('Magnitude Response (dB)')
legend('initial', 'final')
grid on
```

Compare the magnitude response computed with the initial coefficients and the final coefficients (Magnitude Response with Initial and Final Magnitude Coefficients on page 6-182). Note that you could use the `firpm` function in Signal Processing Toolbox™ software to design this filter.
Magnitude Response with Initial and Final Magnitude Coefficients
Equation Solving Algorithms

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<tr>
<td>“Levenberg-Marquardt Method” on page 6-189</td>
</tr>
<tr>
<td>“\ Algorithm” on page 6-189</td>
</tr>
<tr>
<td>“fzero Algorithm” on page 6-189</td>
</tr>
</tbody>
</table>

Definition

Given a set of $n$ nonlinear functions $F_i(x)$, where $n$ is the number of components of the vector $x$, the goal of equation solving is to find a vector $x$ that makes all $F_i(x) = 0$.

The `fsolve` function has three algorithms for solving systems of nonlinear multidimensional equations:

- Trust-region dogleg
- Trust-region-reflective
- Levenberg-Marquardt

All algorithms are large-scale; see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48.

The `fzero` function solves a single one-dimensional equation.

The `\` function solves systems of linear equations.

Trust-Region Dogleg Method

Another approach is to solve a linear system of equations to find the search direction, namely, Newton’s method says to solve for the search direction $d_{k+1}$ such that
\[ J(x_k)d_k = -F(x_k) \]

\[ x_{k+1} = x_k + d_k, \]

where \( J(x_k) \) is the \( n \)-by-\( n \) Jacobian

\[
J(x_k) = \begin{bmatrix}
\nabla F_1(x_k)^T \\
\n\nabla F_2(x_k)^T \\
\vdots \\
\n\nabla F_n(x_k)^T 
\end{bmatrix}.
\]

Newton’s method can run into difficulties. \( J(x_k) \) may be singular, and so the Newton step \( d_k \) is not even defined. Also, the exact Newton step \( d_k \) may be expensive to compute. In addition, Newton’s method may not converge if the starting point is far from the solution.

Using trust-region techniques (introduced in “Trust-Region Methods for Nonlinear Minimization” on page 6-3) improves robustness when starting far from the solution and handles the case when \( J(x_k) \) is singular. To use a trust-region strategy, a merit function is needed to decide if \( x_{k+1} \) is better or worse than \( x_k \). A possible choice is

\[
\min_d f(d) = \frac{1}{2} F(x_k + d)^T F(x_k + d).
\]

But a minimum of \( f(d) \) is not necessarily a root of \( F(x) \).

The Newton step \( d_k \) is a root of

\[
M(x_k + d) = F(x_k) + J(x_k)d,
\]

and so it is also a minimum of \( m(d) \), where
\[
\min_{d} m(d) = \frac{1}{2} \left\| M(x_k + d) \right\|_2^2 = \frac{1}{2} \left\| F(x_k) + J(x_k)d \right\|_2^2 = \frac{1}{2} F(x_k)^T F(x_k) + d^T J(x_k)^T F(x_k) + \frac{1}{2} d^T J(x_k)^T J(x_k) d
\]

Then \( m(d) \) is a better choice of merit function than \( f(d) \), and so the trust-region subproblem is

\[
\min_{d} \left[ \frac{1}{2} F(x_k)^T F(x_k) + d^T J(x_k)^T F(x_k) + \frac{1}{2} d^T J(x_k)^T J(x_k) d \right],
\]

such that \( \|Dd\| \leq \Delta \). This subproblem can be efficiently solved using a dogleg strategy.

For an overview of trust-region methods, see Conn [4], and Nocedal [31].

**Trust-Region Dogleg Implementation**

The key feature of this algorithm is the use of the Powell dogleg procedure for computing the step \( d \), which minimizes Equation 6-121. For a detailed description, see Powell [34].

The step \( d \) is constructed from a convex combination of a Cauchy step (a step along the steepest descent direction) and a Gauss-Newton step for \( f(x) \). The Cauchy step is calculated as

\[
d_C = -\alpha J(x_k)^T F(x_k),
\]

where \( \alpha \) is chosen to minimize Equation 6-120.

The Gauss-Newton step is calculated by solving

\[
J(x_k) d_{GN} = -F(x_k),
\]

using the MATLAB \( \backslash \) (matrix left division) operator.

The step \( d \) is chosen so that

\[
d = d_C + \lambda(d_{GN} - d_C),
\]
where \( \lambda \) is the largest value in the interval \([0,1]\) such that \( \|d\| \leq \Delta \). If \( J_k \) is (nearly) singular, \( d \) is just the Cauchy direction.

The dogleg algorithm is efficient since it requires only one linear solve per iteration (for the computation of the Gauss-Newton step). Additionally, it can be more robust than using the Gauss-Newton method with a line search.

**Trust-Region Reflective fminunc Algorithm**

Many of the methods used in Optimization Toolbox solvers are based on trust regions, a simple yet powerful concept in optimization.

To understand the trust-region approach to optimization, consider the unconstrained minimization problem, minimize \( f(x) \), where the function takes vector arguments and returns scalars. Suppose you are at a point \( x \) in \( n \)-space and you want to improve, i.e., move to a point with a lower function value. The basic idea is to approximate \( f \) with a simpler function \( q \), which reasonably reflects the behavior of function \( f \) in a neighborhood \( N \) around the point \( x \). This neighborhood is the trust region. A trial step \( s \) is computed by minimizing (or approximately minimizing) over \( N \). This is the trust-region subproblem,

\[
\min_{s} \{ q(s), s \in N \}.
\]

(6-122)

The current point is updated to be \( x + s \) if \( f(x + s) < f(x) \); otherwise, the current point remains unchanged and \( N \), the region of trust, is shrunk and the trial step computation is repeated.

The key questions in defining a specific trust-region approach to minimizing \( f(x) \) are how to choose and compute the approximation \( q \) (defined at the current point \( x \)), how to choose and modify the trust region \( N \), and how accurately to solve the trust-region subproblem. This section focuses on the unconstrained problem. Later sections discuss additional complications due to the presence of constraints on the variables.

In the standard trust-region method ([48]), the quadratic approximation \( q \) is defined by the first two terms of the Taylor approximation to \( F \) at \( x \); the neighborhood \( N \) is usually spherical or ellipsoidal in shape. Mathematically the trust-region subproblem is typically stated.
min \left\{ \frac{1}{2} s^T H s + s^T g \right\} \text{ such that } \|Ds\| \leq \Delta, \tag{6-123}

where \(g\) is the gradient of \(f\) at the current point \(x\), \(H\) is the Hessian matrix (the symmetric matrix of second derivatives), \(D\) is a diagonal scaling matrix, \(\Delta\) is a positive scalar, and \(||\cdot||\) is the 2-norm. Good algorithms exist for solving Equation 6-123 (see [48]); such algorithms typically involve the computation of a full eigensystem and a Newton process applied to the secular equation

\[
\frac{1}{\Delta} - \frac{1}{\|s\|} = 0.
\]

Such algorithms provide an accurate solution to Equation 6-123. However, they require time proportional to several factorizations of \(H\). Therefore, for large-scale problems a different approach is needed. Several approximation and heuristic strategies, based on Equation 6-123, have been proposed in the literature ([42] and [50]). The approximation approach followed in Optimization Toolbox solvers is to restrict the trust-region subproblem to a two-dimensional subspace \(S\) ([39] and [42]). Once the subspace \(S\) has been computed, the work to solve Equation 6-123 is trivial even if full eigenvalue/eigenvector information is needed (since in the subspace, the problem is only two-dimensional). The dominant work has now shifted to the determination of the subspace.

The two-dimensional subspace \(S\) is determined with the aid of a preconditioned conjugate gradient process described below. The solver defines \(S\) as the linear space spanned by \(s_1\) and \(s_2\), where \(s_1\) is in the direction of the gradient \(g\), and \(s_2\) is either an approximate Newton direction, i.e., a solution to

\[H \cdot s_2 = -g,\tag{6-124}\]

or a direction of negative curvature,

\[s_2^T \cdot H \cdot s_2 < 0.\tag{6-125}\]

The philosophy behind this choice of \(S\) is to force global convergence (via the steepest descent direction or negative curvature direction) and achieve fast local convergence (via the Newton step, when it exists).
A sketch of unconstrained minimization using trust-region ideas is now easy to give:

1. Formulate the two-dimensional trust-region subproblem.
2. Solve Equation 6-123 to determine the trial step $s$.
3. If $f(x + s) < f(x)$, then $x = x + s$.
4. Adjust $\Delta$.

These four steps are repeated until convergence. The trust-region dimension $\Delta$ is adjusted according to standard rules. In particular, it is decreased if the trial step is not accepted, i.e., $f(x + s) \geq f(x)$. See [46] and [49] for a discussion of this aspect.

Optimization Toolbox solvers treat a few important special cases of $f$ with specialized functions: nonlinear least-squares, quadratic functions, and linear least-squares. However, the underlying algorithmic ideas are the same as for the general case. These special cases are discussed in later sections.

**Preconditioned Conjugate Gradient Method**

A popular way to solve large symmetric positive definite systems of linear equations $Hp = -g$ is the method of Preconditioned Conjugate Gradients (PCG). This iterative approach requires the ability to calculate matrix-vector products of the form $Hv$ where $v$ is an arbitrary vector. The symmetric positive definite matrix $M$ is a *preconditioner* for $H$. That is, $M = C^2$, where $C^{-1}HC^{-1}$ is a well-conditioned matrix or a matrix with clustered eigenvalues.

In a minimization context, you can assume that the Hessian matrix $H$ is symmetric. However, $H$ is guaranteed to be positive definite only in the neighborhood of a strong minimizer. Algorithm PCG exits when a direction of negative (or zero) curvature is encountered, i.e., $d^THd \leq 0$. The PCG output direction, $p$, is either a direction of negative curvature or an approximate (tol controls how approximate) solution to the Newton system $Hp = -g$. In either case $p$ is used to help define the two-dimensional subspace used in the trust-region approach discussed in “Trust-Region Methods for Nonlinear Minimization” on page 6-3.
Levenberg-Marquardt Method

The Levenberg-Marquardt [25], and [27] method uses a search direction that is a solution of the linear set of equations

\[
\begin{align*}
\left( J(x_k)^T J(x_k) + \lambda_k I \right) d_k &= -J(x_k)^T F(x_k),
\end{align*}
\]

or, optionally, of the equations

\[
\begin{align*}
\left( J(x_k)^T J(x_k) + \lambda_k \text{diag}(J(x_k)^T J(x_k)) \right) d_k &= -J(x_k)^T F(x_k),
\end{align*}
\]

where the scalar \( \lambda_k \) controls both the magnitude and direction of \( d_k \). Set option ScaleProblem to 'none' to choose Equation 6-126, and set ScaleProblem to 'Jacobian' to choose Equation 6-127.

When \( \lambda_k \) is zero, the direction \( d_k \) is identical to that of the Gauss-Newton method. As \( \lambda_k \) tends to infinity, \( d_k \) tends towards the steepest descent direction, with magnitude tending to zero. This implies that for some sufficiently large \( \lambda_k \), the term \( F(x_k + d_k) < F(x_k) \) holds true. The term \( \lambda_k \) can therefore be controlled to ensure descent even when second-order terms, which restrict the efficiency of the Gauss-Newton method, are encountered. The Levenberg-Marquardt method therefore uses a search direction that is a cross between the Gauss-Newton direction and the steepest descent direction.

Algorithm

This algorithm is described in the MATLAB arithmetic operators section for \( \backslash \) (mldivide).

fzero Algorithm

fzero attempts to find the root of a scalar function \( f \) of a scalar variable \( x \).

fzero looks for an interval around an initial point such that \( f(x) \) changes sign. If you give an initial interval instead of an initial point, fzero checks to make sure \( f(x) \) has different signs at the endpoints of the interval. The initial interval must be finite; it cannot contain \( \pm \text{Inf} \).
fzero uses a combination of interval bisection, linear interpolation, and inverse quadratic interpolation in order to locate a root of $f(x)$. See \texttt{fzero} for more information.
Equation Solving Examples

In this section...

| Example: Nonlinear Equations with Analytic Jacobian” on page 6-191 |
| “Example: Nonlinear Equations with Finite-Difference Jacobian” on page 6-194 |
| “Example: Nonlinear Equations with Jacobian” on page 6-195 |
| “Example: Nonlinear Equations with Jacobian Sparsity Pattern” on page 6-198 |

Example: Nonlinear Equations with Analytic Jacobian

This example demonstrates the use of the default large-scale `fsolve` algorithm (see “Large-Scale vs. Medium-Scale Algorithms” on page 2-48). It is intended for problems where

- The system of nonlinear equations is square, i.e., the number of equations equals the number of unknowns.
- There exists a solution $x$ such that $F(x) = 0$.

The example uses `fsolve` to obtain the minimum of the banana (or Rosenbrock) function by deriving and then solving an equivalent system of nonlinear equations. The Rosenbrock function, which has a minimum of $F(x) = 0$, is a common test problem in optimization. It has a high degree of nonlinearity and converges extremely slowly if you try to use steepest descent type methods. It is given by

$$f(x) = 100 \left( x_2 - x_1^2 \right)^2 + (1 - x_1)^2.$$ 

First generalize this function to an $n$-dimensional function, for any positive, even value of $n$: 
This function is referred to as the generalized Rosenbrock function. It consists of \( n \) squared terms involving \( n \) unknowns.

Before you can use `fsolve` to find the values of \( x \) such that \( F(x) = 0 \), i.e., obtain the minimum of the generalized Rosenbrock function, you must rewrite the function as the following equivalent system of nonlinear equations:

\[
F(1) = 1 - x_1 \\
F(2) = 10 \left( x_2 - x_1^2 \right) \\
F(3) = 1 - x_3 \\
F(4) = 10 \left( x_4 - x_3^2 \right) \\
\vdots \\
F(n-1) = 1 - x_{n-1} \\
F(n) = 10 \left( x_n - x_{n-1}^2 \right).
\]

This system is square, and you can use `fsolve` to solve it. As the example demonstrates, this system has a unique solution given by \( x_i = 1 \), \( i = 1,...,n \).

**Step 1: Write a file `bananaobj.m` to compute the objective function values and the Jacobian.**

```matlab
function [F,J] = bananaobj(x)
% Evaluate the vector function and the Jacobian matrix for
% the system of nonlinear equations derived from the general
% n-dimensional Rosenbrock function.
% Get the problem size
n = length(x);
if n == 0, error('Input vector, x, is empty.'); end
if mod(n,2) ~= 0,
    error('Input vector, x ,must have an even number of components.');
end
```
% Evaluate the vector function
odds = 1:2:n;
evens = 2:2:n;
F = zeros(n,1);
F(odds,1) = 1-x(odds);
F(evens,1) = 10.*(x(evens)-x(odds).^2);
% Evaluate the Jacobian matrix if nargout > 1
if nargout > 1
    c = -ones(n/2,1);  C = sparse(odds,odds,c,n,n);
d = 10*ones(n/2,1); D = sparse(evens,evens,d,n,n);
e = -20.*x(odds);  E = sparse(evens,odds,e,n,n);
    J = C + D + E;
end

**Step 2: Call the solve routine for the system of equations.**

n = 64;
x0(1:n,1) = -1.9;
x0(2:2:n,1) = 2;
options = optimset('Display','iter','Jacobian','on');
[x,F,exitflag,output,JAC] = fsolve(@bananaobj,x0,options);

Use the starting point \( x(i) = -1.9 \) for the odd indices, and \( x(i) = 2 \) for the even indices. Set `Display` to `'iter'` to see the solver's progress. Set `Jacobian` to `'on'` to use the Jacobian defined in `bananaobj.m`. The `fsolve` function generates the following output:

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>Norm of step</th>
<th>First-order optimality</th>
<th>Trust-region radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>8563.84</td>
<td></td>
<td>615</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3098.71</td>
<td>1</td>
<td>329</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>225.104</td>
<td>2.5</td>
<td>34.8</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>212.48</td>
<td>6.25</td>
<td>34.1</td>
<td>6.25</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>212.48</td>
<td>6.25</td>
<td>34.1</td>
<td>6.25</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>102.771</td>
<td>1.5625</td>
<td>6.39</td>
<td>1.56</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>102.771</td>
<td>3.90625</td>
<td>6.39</td>
<td>3.91</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>87.7443</td>
<td>0.976563</td>
<td>2.19</td>
<td>0.977</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>74.1426</td>
<td>2.44141</td>
<td>6.27</td>
<td>2.44</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>74.1426</td>
<td>2.44141</td>
<td>6.27</td>
<td>2.44</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>52.497</td>
<td>0.610352</td>
<td>1.52</td>
<td>0.61</td>
</tr>
</tbody>
</table>
### Example: Nonlinear Equations with Finite-Difference Jacobian

In the preceding example, the function `bananaobj` evaluates $F$ and computes the Jacobian $J$. What if the code to compute the Jacobian is not available? By default, if you do not indicate that the Jacobian can be computed in the objective function (by setting the `Jacobian` option in `options` to `'on'`), `fsolve`, `lsqnonlin`, and `lsqcurvefit` instead use finite differencing to approximate the Jacobian. This is the default Jacobian option. You can select finite differencing by setting `Jacobian` to `'off'` using `optimset`.

This example uses `bananaobj` from the preceding example as the objective function, but sets `Jacobian` to `'off'` so that `fsolve` approximates the Jacobian and ignores the second `bananaobj` output.

```matlab
n = 64;
x0(1:n,1) = -1.9;
x0(2:2:n,1) = 2;
options=optimset('Display','iter','Jacobian','off');
[x,F,exitflag,output,JAC] = fsolve(@bananaobj,x0,options);
```

The example produces the following output:

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>$f(x)$</th>
<th>Norm of step</th>
<th>First-order optimality</th>
<th>Trust-region radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>65</td>
<td>8563.84</td>
<td></td>
<td>615</td>
<td>1</td>
</tr>
</tbody>
</table>

Equation solved.

`fsolve` completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.
Equation solved.

\texttt{fsolve} completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

The finite-difference version of this example requires the same number of iterations to converge as the analytic Jacobian version in the preceding example. It is generally the case that both versions converge at about the same rate in terms of iterations. However, the finite-difference version requires many additional function evaluations. The cost of these extra evaluations might or might not be significant, depending on the particular problem.

\textbf{Example: Nonlinear Equations with Jacobian}

Consider the problem of finding a solution to a system of nonlinear equations whose Jacobian is sparse. The dimension of the problem in this example is 1000. The goal is to find \( x \) such that \( F(x) = 0 \). Assuming \( n = 1000 \), the nonlinear equations are
To solve a large nonlinear system of equations, $F(x) = 0$, you can use the trust-region reflective algorithm available in \texttt{fsolve}, a large-scale algorithm ("Large-Scale vs. Medium-Scale Algorithms" on page 2-48).

\textbf{Step 1: Write a file \texttt{nlsf1.m} that computes the objective function values and the Jacobian.}

```matlab
function [F,J] = nlsf1(x)
% Evaluate the vector function
n = length(x);
F = zeros(n,1);
i = 2:(n-1);
F(i) = (3-2*x(i)).*x(i)-x(i-1)-2*x(i+1) + 1;
F(n) = (3-2*x(n)).*x(n)-x(n-1) + 1;
F(1) = (3-2*x(1)).*x(1)-2*x(2) + 1;
% Evaluate the Jacobian if nargout > 1
if nargout > 1
    d = -4*x + 3*ones(n,1); D = sparse(1:n,1:n,d,n,n);
c = -2*ones(n-1,1); C = sparse(1:n-1,2:n,c,n,n);
e = -ones(n-1,1); E = sparse(2:n,1:n-1,e,n,n);
    J = C + D + E;
end
```

\textbf{Step 2: Call the solve routine for the system of equations.}

```matlab
xstart = -ones(1000,1);
fun = @nlsf1;
options = optimset('Display','iter',
    'Algorithm','trust-region-reflective',
    'Jacobian','on','PrecondBandWidth',0);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);
```

A starting point is given as well as the function name. The default method for \texttt{fsolve} is trust-region-dogleg, so it is necessary to specify 'Algorithm'
as 'trust-region-reflective' in the options argument in order to select the trust-region-reflective algorithm. Setting the Display option to 'iter' causes fsolve to display the output at each iteration. Setting Jacobian to 'on', causes fsolve to use the Jacobian information available in nlsf1.m.

The commands display this output:

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>Norm of step</th>
<th>First-order optimality</th>
<th>CG-iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1011</td>
<td></td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>16.1942</td>
<td>7.91898</td>
<td>2.35</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.0228027</td>
<td>1.33142</td>
<td>0.291</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.000103359</td>
<td>0.0433329</td>
<td>0.0201</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>7.3972e-007</td>
<td>0.0022606</td>
<td>0.000946</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>4.02299e-010</td>
<td>0.000268381</td>
<td>4.12e-005</td>
<td>5</td>
</tr>
</tbody>
</table>

Equation solved, inaccuracy possible.

The vector of function values is near zero, as measured by the default value of the function tolerance. However, the last step was ineffective.

A linear system is (approximately) solved in each major iteration using the preconditioned conjugate gradient method. Setting PrecondBandWidth to 0 in options means a diagonal preconditioner is used. (PrecondBandWidth specifies the bandwidth of the preconditioning matrix. A bandwidth of 0 means there is only one diagonal in the matrix.)

From the first-order optimality values, fast linear convergence occurs. The number of conjugate gradient (CG) iterations required per major iteration is low, at most five for a problem of 1000 dimensions, implying that the linear systems are not very difficult to solve in this case (though more work is required as convergence progresses).

If you want to use a tridiagonal preconditioner, i.e., a preconditioning matrix with three diagonals (or bandwidth of one), set PrecondBandWidth to the value 1:

```matlab
options = optimset('Display','iter','Jacobian','on',...
                      'Algorithm','trust-region-reflective','PrecondBandWidth',1);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);
```
In this case the output is

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>Norm of step</th>
<th>First-order optimality</th>
<th>CG-iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1011</td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>16.0839</td>
<td>7.92496</td>
<td>1.92</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.0458181</td>
<td>1.3279</td>
<td>0.579</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.000101184</td>
<td>0.0631898</td>
<td>0.0203</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3.16615e-007</td>
<td>0.00273698</td>
<td>0.00079</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>9.72481e-010</td>
<td>0.00018111</td>
<td>5.82e-005</td>
<td>2</td>
</tr>
</tbody>
</table>

Equation solved, inaccuracy possible.

The vector of function values is near zero, as measured by the default value of the function tolerance. However, the last step was ineffective.

Note that although the same number of iterations takes place, the number of PCG iterations has dropped, so less work is being done per iteration. See “Preconditioned Conjugate Gradient Method” on page 6-24.

Setting PrecondBandWidth to Inf (this is the default) means that the solver uses Cholesky factorization rather than PCG.

**Example: Nonlinear Equations with Jacobian Sparsity Pattern**

In the preceding example, the function nlsf1 computes the Jacobian J, a sparse matrix, along with the evaluation of F. What if the code to compute the Jacobian is not available? By default, if you do not indicate that the Jacobian can be computed in nlsf1 (by setting the Jacobian option in options to 'on'), fsolve, lsqnonlin, and lsqcurvefit instead uses finite differencing to approximate the Jacobian.

In order for this finite differencing to be as efficient as possible, you should supply the sparsity pattern of the Jacobian, by setting JacobPattern to 'on' in options. That is, supply a sparse matrix Jstr whose nonzero entries correspond to nonzeros of the Jacobian for all x. Indeed, the nonzeros of Jstr can correspond to a superset of the nonzero locations of J; however, in general the computational cost of the sparse finite-difference procedure will increase with the number of nonzeros of Jstr.
Providing the sparsity pattern can drastically reduce the time needed to compute the finite differencing on large problems. If the sparsity pattern is not provided (and the Jacobian is not computed in the objective function either) then, in this problem \texttt{nlsfs1}, the finite-differencing code attempts to compute all 1000-by-1000 entries in the Jacobian. But in this case there are only 2998 nonzeros, substantially less than the 1,000,000 possible nonzeros the finite-differencing code attempts to compute. In other words, this problem is solvable if you provide the sparsity pattern. If not, most computers run out of memory when the full dense finite-differencing is attempted. On most small problems, it is not essential to provide the sparsity structure.

Suppose the sparse matrix Jstr, computed previously, has been saved in file \texttt{nlsdat1.mat}. The following driver calls \texttt{fsolve} applied to \texttt{nlsf1a}, which is the same as \texttt{nlsf1} except that only the function values are returned; sparse finite-differencing is used to estimate the sparse Jacobian matrix as needed.

**Step 1: Write a file \texttt{nlsf1a.m} that computes the objective function values.**

```matlab
function F = nlsf1a(x)
    % Evaluate the vector function
    n = length(x);
    F = zeros(n,1);
    i = 2:(n-1);
    F(i) = (3-2*x(i)).*x(i)-x(i-1)-2*x(i+1) + 1;
    F(n) = (3-2*x(n)).*x(n)-x(n-1) + 1;
    F(1) = (3-2*x(1)).*x(1)-2*x(2) + 1;
```

**Step 2: Call the system of equations solve routine.**

```matlab
xstart = -ones(1000,1);
fun = @nlsf1a;
load nlsdat1 % Get Jstr
options = optimset('Display','iter','JacobPattern',Jstr,...
    'Algorithm','trust-region-reflective','PrecondBandWidth',1);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);
```

In this case, the output displayed is

\[
\begin{array}{cc}
\text{Norm of} & \text{First-order} \\
6 & 199 \\
\end{array}
\]
Equation solved, inaccuracy possible.

The vector of function values is near zero, as measured by the default value of the function tolerance. However, the last step was ineffective.

Alternatively, it is possible to choose a sparse direct linear solver (i.e., a sparse QR factorization) by indicating a “complete” preconditioner. For example, if you set \texttt{PrecondBandWidth} to \texttt{Inf}, then a sparse direct linear solver is used instead of a preconditioned conjugate gradient iteration:

\begin{verbatim}
xstart = -ones(1000,1);
fun = @nlsf1a;
load nlsdat1 % Get Jstr
options = optimset('Display','iter','JacobPattern',Jstr,...
    'Algorithm','trust-region-reflective','PrecondBandWidth',inf);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);
\end{verbatim}

and the resulting display is

\begin{verbatim}
Iteration Func-count f(x) step optimality CG-iterations
0 5 1011 19
1 10 16.0839 7.92496 1.92 1
2 15 0.0458179 1.3279 0.579 1
3 20 0.000101184 0.0631896 0.0203 2
4 25 3.16616e-007 0.00273698 0.00079 2
5 30 9.72483e-010 0.00018111 5.82e-005 2
\end{verbatim}

Equation solved.

\texttt{fsolve} completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.
When the sparse direct solvers are used, the CG iteration is 0 for that (major) iteration, as shown in the output under `CG-Iterations`. Notice that the final optimality and $f(x)$ value (which for `fsolve`, $f(x)$, is the sum of the squares of the function values) are closer to zero than using the PCG method, which is often the case.
Selected Bibliography


6-205


Optimization Algorithms and Examples
Parallel Computing for Optimization

- “Parallel Computing in Optimization Toolbox Functions” on page 7-2
- “Using Parallel Computing with fmincon, fgoalattain, and fminimax” on page 7-5
- “Improving Performance with Parallel Computing” on page 7-8
Parallel Computing in Optimization Toolbox Functions

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</table>

**Parallel Optimization Functionality**

Parallel computing is the technique of using multiple processors on a single problem. The reason to use parallel computing is to speed computations.

The Optimization Toolbox solvers `fmincon`, `fgoalattain`, and `fminimax` can automatically distribute the numerical estimation of gradients of objective functions and nonlinear constraint functions to multiple processors. These solvers use parallel gradient estimation under the following conditions:

- You have a license for Parallel Computing Toolbox software.
- The option `GradObj` is set to 'off', or, if there is a nonlinear constraint function, the option `GradConstr` is set to 'off'. Since 'off' is the default value of these options, you don’t have to set them with `optimset`; just don’t set them both to 'on'.
- Parallel computing is enabled with `matlabpool`, a Parallel Computing Toolbox function.
- The option `UseParallel` is set to 'always'. The default value of this option is 'never'.

When these conditions hold, the solvers compute estimated gradients in parallel.

**Parallel Estimation of Gradients**

One subroutine was made parallel in the functions `fmincon`, `fgoalattain`, and `fminimax`: the subroutine that estimates the gradient of the objective function and constraint functions. This calculation involves computing
function values at points near the current location \( x \). Essentially, the calculation is

\[
\nabla f(x) \approx \left[ \frac{f(x + \Delta_1 e_1) - f(x)}{\Delta_1}, \frac{f(x + \Delta_2 e_2) - f(x)}{\Delta_2}, \ldots, \frac{f(x + \Delta_n e_n) - f(x)}{\Delta_n} \right],
\]

where

- \( f \) represents objective or constraint functions
- \( e_i \) are the unit direction vectors
- \( \Delta_i \) is the size of a step in the \( e_i \) direction

To estimate \( \nabla f(x) \) in parallel, Optimization Toolbox solvers distribute the evaluation of \( (f(x + \Delta e_i) - f(x))/\Delta_i \) to extra processors.

### Parallel Central Differences

You can choose to have gradients estimated by central finite differences instead of the default forward finite differences. The basic central finite difference formula is

\[
\nabla f(x) \approx \left[ \frac{f(x + \Delta_1 e_1) - f(x - \Delta_1 e_1)}{2\Delta_1}, \ldots, \frac{f(x + \Delta_n e_n) - f(x - \Delta_n e_n)}{2\Delta_n} \right].
\]

This takes twice as many function evaluations as forward finite differences, but is usually much more accurate. Central finite differences work in parallel exactly the same as forward finite differences.

Enable central finite differences by using \texttt{optimset} to set the \texttt{FinDiffType} option to 'central'. To use forward finite differences, set the \texttt{FinDiffType} option to 'forward'.

### Nested Parallel Functions

Solvers employ the Parallel Computing Toolbox function \texttt{parfor} to perform parallel estimation of gradients. \texttt{parfor} does not work in parallel when called from within another \texttt{parfor} loop. Therefore, you cannot simultaneously use
parallel gradient estimation and parallel functionality within your objective or constraint functions.

Suppose, for example, your objective function \texttt{userfcn} calls \texttt{parfor}, and you wish to call \texttt{fmincon} in a loop. Suppose also that the conditions for parallel gradient evaluation of \texttt{fmincon}, as given in “Parallel Optimization Functionality” on page \ref{page-7-2}, are satisfied. Figure \textit{When parfor Runs In Parallel} on page \ref{page-7-4} shows three cases:

1. The outermost loop is \texttt{parfor}. Only that loop runs in parallel.

2. The outermost \texttt{parfor} loop is in \texttt{fmincon}. Only \texttt{fmincon} runs in parallel.

3. The outermost \texttt{parfor} loop is in \texttt{userfcn}. \texttt{userfcn} can use \texttt{parfor} in parallel.

\textbf{Bold} indicates the function that runs in parallel.

\begin{itemize}
    \item[1] \texttt{parfor (i=1:10)}
    \begin{verbatim}
    x(i)=fmincon(@userfcn,...)
    \end{verbatim}
    \texttt{end}
    \textcolor{blue}{Only the outermost parfor loop runs in parallel}

    \item[2] \texttt{for (i=1:10)}
    \begin{verbatim}
    x(i)=fmincon(@userfcn,...)
    \end{verbatim}
    \texttt{end}
    \textcolor{blue}{If UseParallel = ‘always’}
    \texttt{fmincon runs in parallel}

    \item[3] \texttt{for (i=1:10)}
    \begin{verbatim}
    x(i)=fmincon(@userfcn,...)
    \end{verbatim}
    \texttt{end}
    \textcolor{blue}{If UseParallel = ‘never’}
    \texttt{userfcn can use parfor in parallel}
\end{itemize}

\textit{When parfor Runs In Parallel}
Using Parallel Computing with fmincon, fgoalattain, and fminimax

In this section...

“Using Parallel Computing with Multicore Processors” on page 7-5
“Using Parallel Computing with a Multiprocessor Network” on page 7-6
“Testing Parallel Computations” on page 7-7

Using Parallel Computing with Multicore Processors

If you have a multicore processor, you might see speedup using parallel processing. You can establish a `matlabpool` of several parallel workers with a Parallel Computing Toolbox license. For a description of Parallel Computing Toolbox software, and the maximum number of parallel workers, see “Product Overview”.

Suppose you have a dual-core processor, and want to use parallel computing:

- Enter
  
  `matlabpool open 2`
  
  at the command line. The 2 specifies the number of MATLAB processes to start.

- For command-line use, enter
  
  ```
  options = optimset('UseParallel','always');
  ```

- For Optimization Tool, check **Options > Approximated derivatives > Evaluate in parallel.**

When you run an applicable solver with `options`, applicable solvers automatically use parallel computing.
To stop computing optimizations in parallel, set `UseParallel` to 'never', or set the Optimization Tool not to compute in parallel. To halt all parallel computation, enter

```matlab
matlabpool close
```

**Using Parallel Computing with a Multiprocessor Network**

If you have multiple processors on a network, use Parallel Computing Toolbox functions and MATLAB® Distributed Computing Server™ software to establish parallel computation. Here are the steps to take:

1. Make sure your system is configured properly for parallel computing. Check with your systems administrator, or refer to the Parallel Computing Toolbox documentation, or the Administrator Guide documentation for MATLAB Distributed Computing Server.

   To perform a basic check:

   a. At the command line, enter

   ```matlab
   matlabpool open conf
   ```

   or

   ```matlab
   matlabpool open conf n
   ```

   where `conf` is your configuration, and `n` is the number of processors you want to use.

   b. If `network_file_path` is the network path to your objective or constraint functions, enter

   ```matlab
   pctRunOnAll('addpath network_file_path')
   ```

   so the worker processors can access your objective or constraint files.

   c. Check whether a file is on the path of every worker by entering

   ```matlab
   pctRunOnAll('which filename')
   ```

   If any worker does not have a path to the file, it reports
Using Parallel Computing with fmincon, fgoalattain, and fminimax

filename not found.

2

• For command-line use, enter

    options = optimset('UseParallel','always');

• For Optimization Tool, check Options > Approximated derivatives > Evaluate in parallel.

After you establish your parallel computing environment, applicable solvers automatically use parallel computing whenever you call them with options.

To stop computing optimizations in parallel, set UseParallel to 'never', or set the Optimization Tool not to compute in parallel. To halt all parallel computation, enter

    matlabpool close

Testing Parallel Computations

To test see if a problem runs correctly in parallel,

1 Try your problem without parallel computation to ensure that it runs properly serially. Make sure this is successful (gives correct results) before going to the next test.

2 Set UseParallel to 'always', and ensure matlabpool is closed. Your problem runs parfor serially, with loop iterations in reverse order from a for loop. Make sure this is successful (gives correct results) before going to the next test.

3 Set UseParallel to 'always', and open matlabpool. Unless you have a multicore processor or a network set up, you won’t see any speedup. This testing is simply to verify the correctness of the computations.

Remember to call your solver using an options structure to test or use parallel functionality.
Improving Performance with Parallel Computing

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Factors That Affect Speed

Some factors may affect the speed of execution of parallel processing:

- Parallel overhead. There is overhead in calling `parfor` instead of `for`. If function evaluations are fast, this overhead could become appreciable. In particular, solving a problem in parallel can be slower than solving the problem serially.

- No nested `parfor` loops. This is described in “Nested Parallel Functions” on page 7-3. `parfor` does not work in parallel when called from within another `parfor` loop. If you have programmed your objective or constraint functions to take advantage of parallel processing, the limitation of no nested `parfor` loops may cause a solver to run more slowly than you expect. In particular, the parallel computation of finite differences takes precedence, since that is an outer loop. This causes any parallel code within the objective or constraint functions to execute serially.

- When executing serially, `parfor` loops run slower than `for` loops. Therefore, for best performance, ensure that only your outermost parallel loop calls `parfor`. For example, suppose your code calls `fmincon` within a `parfor` loop. For best performance in this case, set the `fmincon UseParallel` option to `'never'`.

- Passing parameters. Parameters are automatically passed to worker machines during the execution of parallel computations. If there are a large number of parameters, or they take a large amount of memory, passing them may slow the execution of your computation.

- Contention for resources: network and computing. If the network of worker machines has low bandwidth or high latency, computation could be slowed.
Factors That Affect Results

Some factors may affect numerical results when using parallel processing. There are more caveats related to `parfor` listed in the “Limitations” section of the Parallel Computing Toolbox documentation.

- Persistent or global variables. If your objective or constraint functions use persistent or global variables, these variables may take different values on different worker processors. Furthermore, they may not be cleared properly on the worker processors.

- Accessing external files. External files may be accessed in an unpredictable fashion during a parallel computation. The order of computations is not guaranteed during parallel processing, so external files may be accessed in unpredictable order, leading to unpredictable results.

- Accessing external files. If two or more processors try to read an external file simultaneously, the file may become locked, leading to a read error, and halting the execution of the optimization.

- If your objective function calls Simulink, results may be unreliable with parallel gradient estimation.

- Noncomputational functions, such as `input`, `plot`, and `keyboard`, might behave badly when used in objective or constraint functions. When called in a `parfor` loop, these functions are executed on worker machines. This can cause a worker to become nonresponsive, since it is waiting for input.

- `parfor` does not allow `break` or `return` statements.

Searching for Global Optima

To search for global optima, one approach is to evaluate a solver from a variety of initial points. If you distribute those evaluations over a number of processors using the `parfor` function, you disable parallel gradient estimation, since `parfor` loops cannot be nested. Your optimization usually runs more quickly if you distribute the evaluations over all the processors, rather than running them serially with parallel gradient estimation, so disabling parallel estimation probably won’t slow your computation. If you have more processors than initial points, though, it is not clear whether it is better to distribute initial points or to enable parallel gradient estimation.
If you have a Global Optimization Toolbox license, you can use the \texttt{MultiStart} solver to examine multiple start points in parallel. See “Parallel Processing” in the Global Optimization Toolbox documentation.
External Interface
ktrlink: An Interface to KNITRO Libraries

In this section...

| “What Is ktrlink?” on page 8-2 |
| “Installation and Configuration” on page 8-2 |
| “Example Using ktrlink” on page 8-4 |
| “Setting Options” on page 8-7 |
| “Sparse Matrix Considerations” on page 8-9 |

What Is ktrlink?

ktrlink calls Ziena Optimization’s KNITRO® libraries in order to perform an optimization. ktrlink can address constrained and unconstrained problems. To use ktrlink, you must purchase a copy of KNITRO libraries from Ziena Optimization, Inc. (http://www.ziena.com/).

Use ktrlink the same as any other Optimization Toolbox function.

ktrlink’s syntax is similar to fmincon’s. The main differences are:

- ktrlink has additional options input for KNITRO libraries so you can access its options.
- ktrlink has no provision for obtaining a returned Hessian or gradient, since KNITRO software doesn’t return them.
- Sparse matrix representations differ between KNITRO software and MATLAB.

Furthermore, many returned flags and messages differ from fmincon’s, because they are returned directly from KNITRO libraries.

Installation and Configuration

The system requirements for MATLAB and KNITRO software may differ. Check the system requirements for both products before attempting to use ktrlink. For recent and planned MATLAB platform support, see
Optimization Toolbox software version 6 works with versions 6 and 7 of KNITRO libraries. Contact Ziena Optimization, Inc. ([http://www.ziena.com/](http://www.ziena.com/)) if you have questions regarding other versions of the KNITRO libraries.

Perform the following steps to configure your system to use ktrlink:

1. Install MATLAB and the KNITRO libraries on your system.

2. Set the system path to include the KNITRO libraries (see “Setting the System Path to Include KNITRO Libraries” on page 8-3). Make sure to perform this step before starting MATLAB.

3. Start MATLAB.

### Setting the System Path to Include KNITRO Libraries

In order to use ktrlink, you need to tell MATLAB where the KNITRO binary file (`libknitro.so`, `libknitro.dylib`, `knitro.dll`, or a similar file) resides. You do this by setting a system-wide environment variable. Enter the following system-level commands. Replace `<file_absolute_path>` with the full path to your KNITRO libraries:

- **Linux:**

  ```
  setenv LD_LIBRARY_PATH <file_absolute_path>:$LD_LIBRARY_PATH
  ```

- **Macintosh:**

  1. Launch **Terminal**, available in Applications > Utilities.
  2. Determine the shell:

     ```
     echo $SHELL
     ```

  3. Set the path:

     - If shell is `bash`:

       ```
       export DYLD_LIBRARY_PATH=<file_absolute_path>:$DYLD_LIBRARY_PATH
       ```
• If shell is csh or tcsh:

```
setenv DYLD_LIBRARY_PATH=<file_absolute_path>:DYLD_LIBRARY_PATH
```

4 Launch MATLAB by entering `matlab` in Terminal. (Launching MATLAB by clicking an icon can lose the path to the KNITRO binary file.)

Optional: to set the path permanently:

- In bash, add the `export` line in step 3 to `$HOME/.profile`.
- In csh or tcsh, add the `setenv` line in step 3 to `$HOME/.cshrc`.

• Windows:

1 At the Windows desktop, right-click My Computer (Windows XP) or Computer (Vista or Windows 7).

2 Select Properties.

3 Click the Advanced tab (Windows XP) or Advanced System Settings (Vista or Windows 7).

4 Click Environment Variables.

5 Under System variables, edit the Path variable to add the KNITRO library folder.

Check if the installation was successful by starting MATLAB and running the following command:

```
[x fval] = ktrlink(@(x)cos(x),1)
```

If you receive an error message, check your system path, and make sure the KNITRO libraries are on the path. When installed correctly, `ktrlink` returns $x = 3.1416, fval = -1$.

**Example Using ktrlink**

1 This example uses the same constraint function as the example in “Nonlinear Constraints” on page 2-33. The constraint function is the intersection of the interior of an ellipse with the region above a parabola:

```
function [c ceq gradc gradceq]=ellipseparabola(x)
```
% Inside the ellipse bounded by (-3<x<3),(-2<y<2)
% Above the line y=x^2-1
\begin{align*}
c(1) &= x(1)^2/9 + x(2)^2/4 - 1; \text{ ellipse} \\
c(2) &= x(1)^2 - x(2) - 1; \text{ parabola} \\
\end{align*}

\text{ceq} = [];

\text{if nargout} > 2
\begin{align*}
\text{gradc} &= [2*x(1)/9, 2*x(1); \ldots \\
&\quad x(2)/2, -1]; \\
\text{gradceq} &= [];
\end{align*}
\text{end}

\textbf{2} The objective function is a tilted sinh:

\begin{verbatim}
function [f gradf]=sinhtilt(x)
A=[2,1;1,2];
m=[1,1];
f=sinh(x'*A*x/100) + sinh(m*A*x/10);
\text{if nargout} > 1
\begin{align*}
\text{gradf} &= \cosh(x'*A*x/100)*(A*x)/50; \\
\text{gradf} &= \text{gradf} + \cosh(m*A*x/10)*[3;3]/10;
\end{align*}
\text{end}
\end{verbatim}

\textbf{3} Set the options so that \textit{ktrlink} has iterative display and uses the gradients included in the objective and constraint functions:

\texttt{ktropts = optimset('Display','iter',... 'GradConstr','on','GradObj','on');}

\textbf{4} Run the optimization starting at [0;0], using the structure \texttt{ktropts}:

\texttt{[x fval flag] = ktrlink(@sinhtilt,[0;0],... [],[],[],[],[],[],@ellipseparabola,ktropts)}

\textbf{KNITRO} software returns the following output:

\begin{verbatim}
--------------------
Commercial Ziena License
KNITRO 6.0.0
Ziena Optimization, Inc.
\end{verbatim}
algorithm: 1
hessopt: 2
honorbnds: 1
maxit: 10000
outlev: 4

KNITRO changing bar_murule from AUTO to 4.
KNITRO changing bar_initpt from AUTO to 2.
KNITRO changing bar_penaltyrule from AUTO to 2.
KNITRO changing bar_penaltycons from AUTO to 1.
KNITRO changing honorbnds to 0 (because there are no bounds).

Problem Characteristics
-----------------------
Objective goal: Minimize
Number of variables: 2
  bounded below: 0
  bounded above: 0
  bounded below and above: 0
  fixed: 0
  free: 2
Number of constraints: 2
  linear equalities: 0
  nonlinear equalities: 0
  linear inequalities: 0
  nonlinear inequalities: 2
  range: 0
Number of nonzeros in Jacobian: 4
Number of nonzeros in Hessian: 3

| Iter | fCount | Objective   | FeasError | OptError | ||Step|| | CGits |
|------|--------|-------------|-----------|----------|----------|-------|
| 0    | 1      | 0.0000000e+000 | 0.000e+000 |          |          |       |
| 1    | 2      | -1.701203e-001 | 0.000e+000 | 1.969e-001 | 4.111e-001 | 0      |
| 2    | 3      | -4.135676e-001 | 2.440e-001 | 1.356e-001 | 6.054e-001 | 0      |
| 3    | 4      | -3.631949e-001 | 2.037e-002 | 4.434e-002 | 1.423e-001 | 0      |
| 4    | 5      | -3.608513e-001 | 3.776e-003 | 1.680e-002 | 8.094e-002 | 0      |
Final Statistics

----------------
Final objective value = -3.60119566305939e-001
Final feasibility error (abs / rel) = 0.00e+000 / 0.00e+000
Final optimality error (abs / rel) = 4.84e-007 / 4.84e-007
# of iterations = 7
# of CG iterations = 0
# of function evaluations = 8
# of gradient evaluations = 8
Total program time (secs) = 0.078 ( 0.109 CPU time)
Time spent in evaluations (secs) = 0.076

x =
  -0.5083
  -0.7416

fval =
  -0.3601

flag =
  0

Note Exit flags have different meanings for ktrlink and fmincon. Flag 0 for KNITRO libraries means the first-order optimality condition was satisfied; for fmincon, the corresponding flag is 1. For more information about the output, see the KNITRO documentation at http://www.ziena.com/.

Setting Options
ktrlink takes up to two options inputs: one in fmincon format, and another in KNITRO format. You can use either or both types of options. If you use
both types of options, MATLAB reads only four \texttt{fmincon}-format options: \texttt{HessFcn}, \texttt{HessMult}, \texttt{HessPattern}, and \texttt{JacobPattern}. KNITRO options override \texttt{fmincon}-format options.

To use KNITRO options, create an options text file, whose format can be found in the KNITRO documentation. For example, if you have a KNITRO options file named \texttt{knitropts}, and an \texttt{fmincon}-format options structure named \texttt{ktropts}, you can pass them both by calling \texttt{ktrlink} like this:

\begin{verbatim}
[x fval] = ktrlink(@bigtoleft,[-1,-1,-1],... 
    [],[],[],[],[],[],@twocone,ktropts,'knitropts')
\end{verbatim}

If \texttt{knitropts} resides in a different folder, pass the path to the file. For example:

\begin{verbatim}
[x fval] = ktrlink(@bigtoleft,[-1,-1,-1],... 
    [],[],[],[],[],[],@twocone,ktropts,... 
    'C:\Documents\Knitro\knitropts')
\end{verbatim}

The following shows how \texttt{fmincon}-format options are mapped to KNITRO options.

<table>
<thead>
<tr>
<th>\texttt{fmincon Option}</th>
<th>\texttt{KNITRO Option}</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>algorithm</td>
<td>'interior-point'</td>
</tr>
<tr>
<td>AlwaysHonorConstraints</td>
<td>honorbounds</td>
<td>'bounds'</td>
</tr>
<tr>
<td>Display</td>
<td>outlev</td>
<td>'none'</td>
</tr>
<tr>
<td>FinDiffType</td>
<td>gradopt</td>
<td>'forward'</td>
</tr>
<tr>
<td>GradConstr</td>
<td>gradopt</td>
<td>'off'</td>
</tr>
<tr>
<td>GradObj</td>
<td>gradopt</td>
<td>'off'</td>
</tr>
<tr>
<td>HessFcn</td>
<td>hessopt</td>
<td>[]</td>
</tr>
<tr>
<td>MaxIter</td>
<td>maxit</td>
<td>10000</td>
</tr>
<tr>
<td>TolFun</td>
<td>opttol</td>
<td>1.00E–06</td>
</tr>
<tr>
<td>TolX</td>
<td>xtol</td>
<td>1.00E–15</td>
</tr>
<tr>
<td>Hessian, LBFGS pairs</td>
<td>hessopt, lmsize</td>
<td>'bfgs'</td>
</tr>
<tr>
<td>HessMult</td>
<td>hessopt</td>
<td>[]</td>
</tr>
</tbody>
</table>
### fmincon Option | KNITRO Option | Default Value
--- | --- | ---
HessPattern | [] | 
InitBarrierParam | bar_initmu | 0.1 | 
InitTrustRegionRadius | delta | sqrt(numberOfVariables) | 
JacobPattern | [] | 
MaxProjCGIter | maxcgit | 2*(numberOfVariables–numberOfEqualities) | 
ObjectiveLimit | objrange | –1.0E20 | 
ScaleProblem | scale | 'obj-and-constr' | 
SubProblemAlgorithm | algorithm | 'ldl-factorization' | 
TolCon | feastol | 1.00E-06 | 

**Note**  KNITRO libraries allow you to pass simultaneously either the gradients of the objective function and all nonlinear constraints, or no gradients. Therefore, setting `GradObj = 'on'` and `GradConstr = 'off'` is inconsistent. If you attempt to pass inconsistent options, `ktrlink` warns you, and treats all gradients as if they had not been passed.

### Sparse Matrix Considerations
When the Hessian of the Lagrangian is sparse, or the Jacobian of the nonlinear constraints is sparse, `ktrlink` makes use of the sparsity structure to speed the optimization and use less memory doing so.

`ktrlink` handles sparse matrices differently than other MATLAB functions. If you choose to use sparse matrices, `ktrlink` requires a sparsity pattern for nonlinear constraint Jacobians and for Hessians. The next two sections give the details of the sparsity patterns for nonlinear constraint Jacobians and for Hessians.

### Sparsity Pattern for Nonlinear Constraints
The sparsity pattern for constraint Jacobians is a matrix. You pass the matrix as the `JacobPattern` option. The structure of the matrix follows.
Let \( c \) denote the vector of \( m \) nonlinear inequality constraints, and let \( ceq \) denote the vector of \( m_2 \) nonlinear equality constraints. If there are \( n \) dimensions, the Jacobian is an \((m + m_2)\)-by-\( n \) matrix. The Jacobian pattern \( J \) is

\[
J_{i,j} = \begin{cases} 
1 & \text{if } \frac{\partial c_i(x)}{\partial x_j} \neq 0, \quad 1 \leq i \leq m, \\
0 & \text{if } \frac{\partial c_i(x)}{\partial x_j} \equiv 0 
\end{cases}
\]

\[
J_{i+m,j} = \begin{cases} 
1 & \text{if } \frac{\partial ceq_i(x)}{\partial x_j} \neq 0, \quad 1 \leq i \leq m_2, \\
0 & \text{if } \frac{\partial ceq_i(x)}{\partial x_j} \equiv 0 
\end{cases}
\]

In other words, the \( i \)th row of the Jacobian pattern corresponds to the gradient of \( c_i \). Inequality gradients lie above equality gradients (they have lower row numbers).

All that matters for the Jacobian pattern is whether or not the entries are zero. You can pass single-precision numbers, doubles, or logical true or false. You can pass the sparsity pattern as a MATLAB sparse matrix. If you have a large sparse matrix of constraints, it is more efficient to pass the pattern as a sparse matrix. Linear constraint matrices are automatically passed as sparse matrices.

The gradient of the constraints, calculated in the constraint function, has the transpose of the Jacobian pattern. For more information about the form of constraint gradients, see “Nonlinear Constraints” on page 2-33.

**Sparsity Pattern for Hessians**

The Hessian is the matrix of second derivatives of the Lagrangian:

\[
H_{i,j} = \frac{\partial^2 f}{\partial x_i \partial x_j} + \sum_k \lambda_k \frac{\partial^2 c_k}{\partial x_i \partial x_j} + \sum_m \lambda_m \frac{\partial^2 ceq_m}{\partial x_i \partial x_j}.
\]

Give the matrix \( H \) as a full or sparse matrix of zero and nonzero elements. The elements can be single-precision numbers, doubles, or logical true or false.
The Hessian is a symmetric matrix. You can pass just the upper triangular pattern, or pass the whole matrix pattern.
Argument and Options Reference

- “Function Arguments” on page 9-2
- “Optimization Options Reference” on page 9-7
# Function Arguments

In this section...

"Input Arguments" on page 9-2
"Output Arguments" on page 9-5

## Input Arguments

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, b</td>
<td>The matrix A and vector b are, respectively, the coefficients of the linear inequality constraints and the corresponding right-side vector: A*x \leq b.</td>
<td>bintprog, fgoalattain, fmincon, fminimax, fseminf, linprog, lsqnonneg</td>
</tr>
<tr>
<td>Aeq, beq</td>
<td>The matrix Aeq and vector beq are, respectively, the coefficients of the linear equality constraints and the corresponding right-side vector: Aeq*x = beq.</td>
<td>bintprog, fgoalattain, fmincon, fminimax, fseminf, linprog, lsqnonneg</td>
</tr>
<tr>
<td>C, d</td>
<td>The matrix C and vector d are, respectively, the coefficients of the over or underdetermined linear system and the right-side vector to be solved.</td>
<td>lsqnonneg</td>
</tr>
<tr>
<td>f</td>
<td>The vector of coefficients for the linear term in the linear equation f'*x or the quadratic equation x'*H*x+f'*x.</td>
<td>bintprog, linprog, quadprog</td>
</tr>
<tr>
<td>fun</td>
<td>The function to be optimized. fun is either a function handle to a file or is an anonymous function. See the individual function reference pages for more information on fun.</td>
<td>fgoalattain, fminbnd, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, fzero, lsqcurvefit, lsqnonlin</td>
</tr>
</tbody>
</table>
### Input Arguments (Continued)

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>goal</td>
<td>Vector of values that the objectives attempt to attain. The vector is the same length as the number of objectives.</td>
<td>fgoalattain</td>
</tr>
<tr>
<td>H</td>
<td>The matrix of coefficients for the quadratic terms in the quadratic equation $x' * H * x + f' * x$. $H$ must be symmetric.</td>
<td>quadprog</td>
</tr>
<tr>
<td>lb, ub</td>
<td>Lower and upper bound vectors (or matrices). The arguments are normally the same size as $x$. However, if $lb$ has fewer elements than $x$, say only $m$, then only the first $m$ elements in $x$ are bounded below; upper bounds in $ub$ can be defined in the same manner. You can also specify unbounded variables using $-\text{Inf}$ (for lower bounds) or $\text{Inf}$ (for upper bounds). For example, if $lb(i) = -\text{Inf}$, the variable $x(i)$ is unbounded below.</td>
<td>fgoalattain, fmincon, fminimax, fseminf, linprog, lsqcurvefit, lsqlin, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>nonlcon</td>
<td>The function that computes the nonlinear inequality and equality constraints. “Passing Extra Parameters” on page 2-38 explains how to parameterize the function nonlcon, if necessary. See the individual reference pages for more information on nonlcon.</td>
<td>fgoalattain, fmincon, fminimax</td>
</tr>
<tr>
<td>ntheta</td>
<td>The number of semi-infinite constraints.</td>
<td>fseminf</td>
</tr>
</tbody>
</table>
# Input Arguments (Continued)

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>options</td>
<td>A structure that defines options used by the optimization functions. For information about the options, see “Optimization Options Reference” on page 9-7 or the individual function reference pages.</td>
<td>All functions</td>
</tr>
<tr>
<td>seminfcon</td>
<td>The function that computes the nonlinear inequality and equality constraints and the semi-infinite constraints. <code>seminfcon</code> is the name of a function file or MEX-file. “Passing Extra Parameters” on page 2-38 explains how to parameterize <code>seminfcon</code>, if necessary.</td>
<td><code>fseminf</code></td>
</tr>
<tr>
<td>weight</td>
<td>A weighting vector to control the relative underattainment or overattainment of the objectives.</td>
<td><code>fgoalattain</code></td>
</tr>
<tr>
<td>xdata, ydata</td>
<td>The input data <code>xdata</code> and the observed output data <code>ydata</code> that are to be fitted to an equation.</td>
<td><code>lsqcurvefit</code></td>
</tr>
<tr>
<td>x0</td>
<td>Starting point (a scalar, vector or matrix). (For <code>fzero</code>, <code>x0</code> can also be a two-element vector representing a finite interval that is known to contain a zero.)</td>
<td>All functions except <code>fminbnd</code></td>
</tr>
<tr>
<td>x1, x2</td>
<td>The interval over which the function is minimized.</td>
<td><code>fminbnd</code></td>
</tr>
</tbody>
</table>
# Output Arguments

## Output Arguments

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>attainfactor</td>
<td>The attainment factor at the solution $x$.</td>
<td>fgoalattain</td>
</tr>
<tr>
<td>exitflag</td>
<td>An integer identifying the reason the optimization algorithm terminated. See the function reference pages for descriptions of exitflag specific to each function. You can also return a message stating why an optimization terminated by calling the optimization function with the output argument output and then displaying output.message.</td>
<td>All functions</td>
</tr>
<tr>
<td>fval</td>
<td>The value of the objective function $\text{fun}$ at the solution $x$.</td>
<td>bintprog, fgoalattain, fminbnd, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, fzero, linprog, quadprog</td>
</tr>
<tr>
<td>grad</td>
<td>The value of the gradient of $\text{fun}$ at the solution $x$. If $\text{fun}$ does not compute the gradient, grad is a finite-differencing approximation of the gradient.</td>
<td>fmincon, fminunc</td>
</tr>
<tr>
<td>hessian</td>
<td>The value of the Hessian of $\text{fun}$ at the solution $x$. For large-scale methods, if $\text{fun}$ does not compute the Hessian, hessian is a finite-differencing approximation of the Hessian. For medium-scale methods, hessian is the value of the Quasi-Newton approximation to the Hessian at the solution $x$.</td>
<td>fmincon, fminunc</td>
</tr>
</tbody>
</table>
### Output Arguments (Continued)

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>jacobian</td>
<td>The value of the Jacobian of fun at the solution x. If fun does not compute the Jacobian, jacobian is a finite-differencing approximation of the Jacobian.</td>
<td>lsqcurvefit, lsqnonlin, fsolve</td>
</tr>
<tr>
<td>lambda</td>
<td>The Lagrange multipliers at the solution x. lambda is a structure where each field is for a different constraint type. For structure field names, see individual function descriptions. (For lsqnonneg, lambda is simply a vector, as lsqnonneg only handles one kind of constraint.)</td>
<td>fgoalattain, fmincon, fminimax, fseminf, linprog, lsqcurvefit, lsqlin, lsqnonlin, lsqnonneg, quadprog</td>
</tr>
<tr>
<td>maxfval</td>
<td>max{fun(x)} at the solution x.</td>
<td>fminimax</td>
</tr>
<tr>
<td>output</td>
<td>An output structure that contains information about the results of the optimization. For structure field names, see individual function descriptions.</td>
<td>All functions</td>
</tr>
<tr>
<td>residual</td>
<td>The value of the residual at the solution x.</td>
<td>lsqcurvefit, lsqlin, lsqnonlin, lsqnonneg</td>
</tr>
<tr>
<td>resnorm</td>
<td>The value of the squared 2-norm of the residual at the solution x.</td>
<td>lsqcurvefit, lsqlin, lsqnonlin, lsqnonneg</td>
</tr>
<tr>
<td>x</td>
<td>The solution found by the optimization function. If exitflag &gt; 0, then x is a solution; otherwise, x is the value of the optimization routine when it terminated prematurely.</td>
<td>All functions</td>
</tr>
</tbody>
</table>
Optimization Options Reference

In this section...

“Options Structure” on page 9-7
“Output Function” on page 9-18
“Plot Functions” on page 9-27

Options Structure

The following table describes fields in the optimization options structure options. You can set values of these fields using the function optimset. The column labeled L, M, B indicates whether the option applies to large-scale methods, medium scale methods, or both:

- L — Large-scale methods only
- M — Medium-scale methods only
- B — Both large- and medium-scale methods
- I — Interior-point method only

See the individual function reference pages for information about available option values and defaults.

The default values for the options vary depending on which optimization function you call with options as an input argument. You can determine the default option values for any of the optimization functions by entering optimset followed by the name of the function. For example,

    optimset fmincon

returns a list of the options and the default values for fmincon. Options with default values listed as [] are either not used by the function, or have different default values depending on the algorithms the solver uses.
Optimization Options

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>Chooses the algorithm used by the solver.</td>
<td>B, I</td>
<td>fmincon, fsolve, lsqcurvefit, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>AlwaysHonorConstraints</td>
<td>The default 'bounds' ensures that bound constraints are satisfied at every iteration. Turn off by setting to 'none'.</td>
<td>M, I</td>
<td>fmincon</td>
</tr>
<tr>
<td>BranchStrategy</td>
<td>Strategy bintprog uses to select branch variable.</td>
<td>M</td>
<td>bintprog</td>
</tr>
<tr>
<td>DerivativeCheck</td>
<td>Compare user-supplied analytic derivatives (gradients or Jacobian, depending on the selected solver) to finite differencing derivatives.</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf, fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Display diagnostic information about the function to be minimized or solved.</td>
<td>B</td>
<td>All but fminbnd, fminsearch, fzero, and lsqnonneg</td>
</tr>
<tr>
<td>DiffMaxChange</td>
<td>Maximum change in variables for finite differencing.</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf, fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td>DiffMinChange</td>
<td>Minimum change in variables for finite differencing.</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf, fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
</tbody>
</table>
### Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
</table>
| Display     | Level of display.  
  - 'off' displays no output.  
  - 'iter' displays output at each iteration, and gives the default exit message.  
  - 'iter-detailed' displays output at each iteration, and gives the technical exit message.  
  - 'notify' displays output only if the function does not converge, and gives the default exit message.  
  - 'notify-detailed' displays output only if the function does not converge, and gives the technical exit message.  
  - 'final' displays just the final output, and gives the default exit message.  
  - 'final-detailed' displays just the final output, and gives the technical exit message. | B, I | All. See the individual function reference pages for the values that apply. |
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>FinDiffRelStep</code></td>
<td>Scalar or vector step size factor. When you set <code>FinDiffRelStep</code> to a vector v, forward finite differences delta are</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf, fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td></td>
<td><img src="https://example.com/math_equation.png" alt="Math equation" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and central finite differences are</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><img src="https://example.com/math_equation.png" alt="Math equation" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scalar <code>FinDiffRelStep</code> expands to a vector. The default is <code>sqrt(eps)</code> for forward finite differences, and <code>eps^(1/3)</code> for central finite differences.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><code>FinDiffType</code></td>
<td>Finite differences, used to estimate gradients, are either 'forward' (the default), or 'central' (centered), which takes twice as many function evaluations but should be more accurate. 'central' differences might violate bounds during their evaluation in <code>fmincon</code> interior-point evaluations if the <code>AlwaysHonorConstraints</code> option is set to 'none'.</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf, fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
</tbody>
</table>
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FunValCheck</td>
<td>Check whether objective function and constraints values are valid. 'on' displays an error when the objective function or constraints return a value that is complex, NaN, or Inf.</td>
<td>B, I</td>
<td>fgoalattain, fminbnd, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, fzero, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td>GoalsExactAchieve</td>
<td>Specify the number of objectives required for the objective fun to equal the goal goal. Objectives should be partitioned into the first few elements of F.</td>
<td>M</td>
<td>fgoalattain</td>
</tr>
<tr>
<td>GradConstr</td>
<td>User-defined gradients for the nonlinear constraints.</td>
<td>M, I</td>
<td>fgoalattain, fmincon, fminimax</td>
</tr>
<tr>
<td>GradObj</td>
<td>User-defined gradients for the objective functions.</td>
<td>B, I</td>
<td>fgoalattain, fmincon, fminimax, fminunc, fseminf</td>
</tr>
<tr>
<td>HessFcn</td>
<td>Function handle to a user-supplied Hessian (see “Hessian” on page 11-47).</td>
<td>I</td>
<td>fmincon</td>
</tr>
</tbody>
</table>
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hessian</td>
<td>If 'user-supplied', function uses user-defined Hessian or Hessian information (when using HessMult), for the objective function. If 'off', function approximates the Hessian using finite differences.</td>
<td>L, I</td>
<td>fmincon, fminunc</td>
</tr>
<tr>
<td>HessMult</td>
<td>Handle to a user-supplied Hessian multiply function. For fmincon, ignored unless Hessian is 'user-supplied' or 'on'.</td>
<td>L, I</td>
<td>fmincon, fminunc, quadprog</td>
</tr>
<tr>
<td>HessPattern</td>
<td>Sparsity pattern of the Hessian for finite differencing. The size of the matrix is n-by-n, where n is the number of elements in x0, the starting point.</td>
<td>L</td>
<td>fmincon, fminunc</td>
</tr>
<tr>
<td>HessUpdate</td>
<td>Quasi-Newton updating scheme.</td>
<td>M</td>
<td>fminunc</td>
</tr>
<tr>
<td>InitBarrierParam</td>
<td>Initial barrier value.</td>
<td>I</td>
<td>fmincon</td>
</tr>
<tr>
<td>InitialHessMatrix</td>
<td>Initial quasi-Newton matrix.</td>
<td>M</td>
<td>fminunc</td>
</tr>
<tr>
<td>InitialHessType</td>
<td>Initial quasi-Newton matrix type.</td>
<td>M</td>
<td>fminunc</td>
</tr>
<tr>
<td>InitTrustRegionRadius</td>
<td>Initial radius of the trust region.</td>
<td>I</td>
<td>fmincon</td>
</tr>
<tr>
<td>Jacobian</td>
<td>If 'on', function uses user-defined Jacobian or Jacobian information (when using JacobMult), for the objective function. If 'off', function approximates the Jacobian using finite differences.</td>
<td>B</td>
<td>fsolve, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td>JacobMult</td>
<td>User-defined Jacobian multiply function. Ignored unless Jacobian is 'on' for fsolve, lsqcurvefit, and lsqnonlin.</td>
<td>L</td>
<td>fsolve, lsqcurvefit, lsqlin, lsqnonlin</td>
</tr>
</tbody>
</table>
### Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>JacobPattern</td>
<td>Sparsity pattern of the Jacobian for finite differencing. The size of the matrix is $m$-by-$n$, where $m$ is the number of values in the first argument returned by the user-specified function <code>fun</code>, and $n$ is the number of elements in $x0$, the starting point.</td>
<td>L</td>
<td><code>fsolve</code>, <code>lsqcurvefit</code>, <code>lsqnonlin</code></td>
</tr>
<tr>
<td>LargeScale</td>
<td>Use large-scale algorithm if possible.</td>
<td>B</td>
<td><code>fminunc</code>, <code>fsolve</code>, <code>linprog</code>, <code>lsqcurvefit</code>, <code>lsqnonlin</code></td>
</tr>
<tr>
<td>MaxFunEvals</td>
<td>Maximum number of function evaluations allowed.</td>
<td>B, I</td>
<td><code>fgoalattain</code>, <code>fminbnd</code>, <code>fmincon</code>, <code>fminimax</code>, <code>fminsearch</code>, <code>fminunc</code>, <code>fseminf</code>, <code>fsolve</code>, <code>lsqcurvefit</code>, <code>lsqnonlin</code></td>
</tr>
<tr>
<td>MaxIter</td>
<td>Maximum number of iterations allowed.</td>
<td>B, I</td>
<td>All but <code>fzero</code> and <code>lsqnonneg</code></td>
</tr>
<tr>
<td>MaxNodes</td>
<td>Maximum number of possible solutions, or <code>nodes</code>, the binary integer programming function <code>bintprog</code> searches.</td>
<td>M</td>
<td><code>bintprog</code></td>
</tr>
<tr>
<td>MaxPCGIter</td>
<td>Maximum number of iterations of preconditioned conjugate gradients method allowed.</td>
<td>L</td>
<td><code>fmincon</code>, <code>fminunc</code>, <code>fsolve</code>, <code>lsqcurvefit</code>, <code>lsqlin</code>, <code>lsqnonlin</code>, <code>quadprog</code></td>
</tr>
</tbody>
</table>
### Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MaxProjCGIter</td>
<td>A tolerance for the number of projected conjugate gradient iterations; this is an inner iteration, not the number of iterations of the algorithm.</td>
<td>I</td>
<td>fmincon</td>
</tr>
<tr>
<td>MaxRLPIter</td>
<td>Maximum number of iterations of linear programming relaxation method allowed.</td>
<td>M</td>
<td>bintprog</td>
</tr>
<tr>
<td>MaxSQPIter</td>
<td>Maximum number of iterations of sequential quadratic programming method allowed.</td>
<td>M</td>
<td>fgoalattain, fmincon, fminimax</td>
</tr>
<tr>
<td>MaxTime</td>
<td>Maximum amount of time in seconds allowed for the algorithm.</td>
<td>M</td>
<td>bintprog</td>
</tr>
<tr>
<td>MeritFunction</td>
<td>Use goal attainment/minimax merit function (multiobjective) vs. fmincon (single objective).</td>
<td>M</td>
<td>fgoalattain, fminimax</td>
</tr>
<tr>
<td>MinAbsMax</td>
<td>Number of $F(x)$ to minimize the worst case absolute values.</td>
<td>M</td>
<td>fminimax</td>
</tr>
<tr>
<td>NodeDisplayInterval</td>
<td>Node display interval for bintprog.</td>
<td>M</td>
<td>bintprog</td>
</tr>
<tr>
<td>NodeSearchStrategy</td>
<td>Search strategy that bintprog uses.</td>
<td>M</td>
<td>bintprog</td>
</tr>
<tr>
<td>ObjectiveLimit</td>
<td>If the objective function value goes below ObjectiveLimit and the iterate is feasible, then the iterations halt.</td>
<td>M, I</td>
<td>fmincon, quadprog</td>
</tr>
</tbody>
</table>
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>OutputFcn</td>
<td>Specify one or more user-defined functions that the optimization function calls at each iteration. See “Output Function” on page 9-18.</td>
<td>B, I</td>
<td>fgoalattain, fminbnd, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, fzero, lsqcurvefit, lsqnonlin</td>
</tr>
<tr>
<td>PlotFcns</td>
<td>Plots various measures of progress while the algorithm executes, select from predefined plots or write your own.</td>
<td>B, I</td>
<td>fgoalattain, fminbnd, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, fzero, lsqcurvefit, and lsqnonlin. See the individual function reference pages for the values that apply.</td>
</tr>
</tbody>
</table>

- @optimplotx plots the current point
- @optimplotfunccount plots the function count
- @optimplotfval plots the function value
- @optimplotconstrviolation plots the maximum constraint violation
- @optimplotresnorm plots the norm of the residuals
- @optimplotfirstorderopt plots the first-order of optimality
- @optimplotstepsizes plots the step size

See “Plot Functions” on page 9-27.
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PrecondBandWidth</td>
<td>Upper bandwidth of preconditioner for PCG. Setting to 'Inf' uses a direct factorization instead of CG.</td>
<td>L</td>
<td>fmincon, fminunc, fsolve, lsqcurvefit, lsqlin, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>RelLineSrchBnd</td>
<td>Relative bound on line search step length.</td>
<td>M</td>
<td>fgoalattain, fmincon, fminimax, fseminf</td>
</tr>
<tr>
<td>RelLineSrchBndDuration</td>
<td>Number of iterations for which the bound specified in RelLineSrchBnd should be active.</td>
<td>M</td>
<td>fgoalattain, fmincon, fminimax, fseminf</td>
</tr>
<tr>
<td>ScaleProblem</td>
<td>For fmincon interior-point and sqp algorithms, 'obj-and-constr' causes the algorithm to normalize all constraints and the objective function by their initial values. Disable by setting to the default 'none'. For the other solvers, when using the Algorithm option 'levenberg-marquardt', setting the ScaleProblem option to 'jacobian' sometimes helps the solver on badly-scaled problems.</td>
<td>L, I</td>
<td>fmincon, fsolve, lsqcurvefit, lsqlin, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>Simplex</td>
<td>If 'on', function uses the simplex algorithm.</td>
<td>M</td>
<td>linprog</td>
</tr>
<tr>
<td>SubproblemAlgorithm</td>
<td>Determines how the iteration step is calculated.</td>
<td>I</td>
<td>fmincon</td>
</tr>
</tbody>
</table>
## Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>L, M, B, I</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TolCon</td>
<td>Termination tolerance on the constraint violation.</td>
<td>B, I</td>
<td>bintprog, fgoalattain, fmincon, fminimax, fseminf, quadprog</td>
</tr>
<tr>
<td>TolConSQP</td>
<td>Constraint violation tolerance for the inner SQP iteration.</td>
<td>M</td>
<td>fgoalattain, fmincon, fminimax, fseminf</td>
</tr>
<tr>
<td>TolFun</td>
<td>Termination tolerance on the function value.</td>
<td>B, I</td>
<td>bintprog, fgoalattain, fmincon, fminimax, fminsearch, fminunc, fseminf, fsolve, linprog (L only), lsqlin (L only), lsqlin, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>TolPCG</td>
<td>Termination tolerance on the PCG iteration.</td>
<td>L</td>
<td>fmincon, fminunc, fsolve, lsqlin, lsqnonlin, lsqlin, lsqnonlin, quadprog</td>
</tr>
<tr>
<td>TolProjCG</td>
<td>A relative tolerance for projected conjugate gradient algorithm; this is for an inner iteration, not the algorithm iteration.</td>
<td>I</td>
<td>fmincon</td>
</tr>
<tr>
<td>TolProjCGAbs</td>
<td>Absolute tolerance for projected conjugate gradient algorithm; this is for an inner iteration, not the algorithm iteration.</td>
<td>I</td>
<td>fmincon</td>
</tr>
</tbody>
</table>
### Optimization Options (Continued)

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Description</th>
<th>Used by Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TolRLPFun</td>
<td>Termination tolerance on the function value of a linear programming relaxation problem.</td>
<td>M</td>
</tr>
<tr>
<td>TolX</td>
<td>Termination tolerance on $x$.</td>
<td>B, I</td>
</tr>
<tr>
<td>TolXInteger</td>
<td>Tolerance within which bintprog considers the value of a variable to be an integer.</td>
<td>M</td>
</tr>
<tr>
<td>TypicalX</td>
<td>Array that specifies typical magnitude of array of parameters $x$. The size of the array is equal to the size of $x_0$, the starting point.</td>
<td>B, I</td>
</tr>
<tr>
<td>UseParallel</td>
<td>When 'always', applicable solvers estimate gradients in parallel. Disable by setting to 'never'.</td>
<td>M, I</td>
</tr>
</tbody>
</table>

### Output Function

The `OutputFcn` field of the `options` structure specifies one or more functions that an optimization function calls at each iteration. Typically, you might use an output function to plot points at each iteration or to display optimization quantities from the algorithm. Using an output function you can view, but not set, optimization quantities. To set up an output function, do the following:

1. Write the output function as a function file or subfunction.
2 Use optimset to set the value of OutputFcn to be a function handle, that is, the name of the function preceded by the @ sign. For example, if the output function is outfun.m, the command

```matlab
options = optimset('OutputFcn', @outfun);
```

specifies OutputFcn to be the handle to outfun. To specify more than one output function, use the syntax

```matlab
options = optimset('OutputFcn',{@outfun, @outfun2});
```

3 Call the optimization function with options as an input argument.

See “Output Functions” on page 3-36 for an example of an output function.

“Passing Extra Parameters” on page 2-38 explains how to parameterize the output function OutputFcn, if necessary.

**Structure of the Output Function**

The function definition line of the output function has the following form:

```matlab
stop = outfun(x, optimValues, state)
```

where

- `x` is the point computed by the algorithm at the current iteration.
- `optimValues` is a structure containing data from the current iteration. “Fields in optimValues” on page 9-20 describes the structure in detail.
- `state` is the current state of the algorithm. “States of the Algorithm” on page 9-26 lists the possible values.
- `stop` is a flag that is true or false depending on whether the optimization routine should quit or continue. See “Stop Flag” on page 9-26 for more information.

The optimization function passes the values of the input arguments to `outfun` at each iteration.
**Fields in optimValues**
The following table lists the fields of the `optimValues` structure. A particular optimization function returns values for only some of these fields. For each field, the Returned by Functions column of the table lists the functions that return the field.

**Corresponding Output Arguments.** Some of the fields of `optimValues` correspond to output arguments of the optimization function. After the final iteration of the optimization algorithm, the value of such a field equals the corresponding output argument. For example, `optimValues.fval` corresponds to the output argument `fval`. So, if you call `fmincon` with an output function and return `fval`, the final value of `optimValues.fval` equals `fval`. The Description column of the following table indicates the fields that have a corresponding output argument.

**Command-Line Display.** The values of some fields of `optimValues` are displayed at the command line when you call the optimization function with the `Display` field of `options` set to `'iter'`, as described in “Iterative Display” on page 3-16. For example, `optimValues.fval` is displayed in the `f(x)` column. The Command-Line Display column of the following table indicates the fields that you can display at the command line.

In the following table, L, M, and B indicate:

- L — Function returns a value to the field when using a large-scale algorithm.
- M — Function returns a value to the field when using a medium-scale algorithm.
- B — Function returns a value to the field when using both large- and medium-scale algorithms.

<table>
<thead>
<tr>
<th>Field</th>
<th>Returned by Functions</th>
<th>Corresponding Output Arguments</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>fval</td>
<td>fmincon</td>
<td><code>fval</code></td>
<td><code>f(x)</code></td>
</tr>
<tr>
<td>x (solution)</td>
<td>fmincon</td>
<td><code>x</code> (solution)</td>
<td><code>x</code></td>
</tr>
<tr>
<td>fval (approx)</td>
<td>fmincon</td>
<td><code>fval</code> (approx)</td>
<td><code>f(x)</code></td>
</tr>
<tr>
<td>x (approx)</td>
<td>fmincon</td>
<td><code>x</code> (approx)</td>
<td><code>x</code></td>
</tr>
<tr>
<td>fval (approx)</td>
<td>fmincon</td>
<td><code>fval</code> (approx)</td>
<td><code>f(x)</code></td>
</tr>
<tr>
<td>x (final)</td>
<td>fmincon</td>
<td><code>x</code> (final)</td>
<td><code>x</code></td>
</tr>
<tr>
<td>fval (final)</td>
<td>fmincon</td>
<td><code>fval</code> (final)</td>
<td><code>f(x)</code></td>
</tr>
<tr>
<td>x (final)</td>
<td>fmincon</td>
<td><code>x</code> (final)</td>
<td><code>x</code></td>
</tr>
<tr>
<td>fval (final)</td>
<td>fmincon</td>
<td><code>fval</code> (final)</td>
<td><code>f(x)</code></td>
</tr>
</tbody>
</table>

In the following table, L, M, and B indicate:
## optimValues Fields

<table>
<thead>
<tr>
<th>OptimValues Field (optimValues.field)</th>
<th>Description</th>
<th>Returned by Functions</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>attainfactor</td>
<td>Attainment factor for multiobjective problem. For details, see “Goal Attainment Method” on page 6-171.</td>
<td>fgoalattain (M)</td>
<td>None</td>
</tr>
<tr>
<td>cgiterations</td>
<td>Number of conjugate gradient iterations at current optimization iteration.</td>
<td>fmincon (L), fsolve (L), lsqcurvefit (L), lsqnonlin (L)</td>
<td>CG-iterations See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>constrviolation</td>
<td>Maximum constraint violation.</td>
<td>fgoalattain (M), fmincon (B I), fminimax (M), fseminf (M)</td>
<td>max constraint See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>degenerate</td>
<td>Measure of degeneracy. A point is degenerate if The partial derivative with respect to one of the variables is 0 at the point. A bound constraint is active for that variable at the point. See “Degeneracy” on page 9-25.</td>
<td>fmincon (L), fsolve (L), lsqcurvefit (L), lsqnonlin (L)</td>
<td>None</td>
</tr>
<tr>
<td>directionalderivative</td>
<td>Directional derivative in the search direction.</td>
<td>fgoalattain (M), fmincon (M), fminimax (M), fminunc (M), fseminf (M), fsolve (M), lsqcurvefit (M), lsqnonlin (M)</td>
<td>Directional derivative See “Iterative Display” on page 3-16.</td>
</tr>
</tbody>
</table>
### OptimValues Fields (Continued)

<table>
<thead>
<tr>
<th>OptimValues Field (optimValues.field)</th>
<th>Description</th>
<th>Returned by Functions</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>firstorderopt</code></td>
<td>First-order optimality (depends on algorithm). Final value equals optimization function output <code>output.firstorderopt</code>.</td>
<td><code>fgoalattain</code> (M), <code>fmincon</code> (B,I), <code>fminimax</code> (M), <code>fminunc</code> (M), <code>fseminf</code> (M), <code>fsolve</code> (B), <code>lsqcurvefit</code> (B), <code>lsqnonlin</code> (B)</td>
<td>First-order optimality See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td><code>funcCount</code></td>
<td>Cumulative number of function evaluations. Final value equals optimization function output <code>output.funcCount</code>.</td>
<td><code>fgoalattain</code> (M), <code>fminbnd</code> (B), <code>fmincon</code> (B), <code>fminimax</code> (M), <code>fminsearch</code> (B), <code>fminunc</code> (B), <code>fsolve</code> (B), <code>fzero</code> (B), <code>fseminf</code> (M), <code>lsqcurvefit</code> (B), <code>lsqnonlin</code> (B)</td>
<td>F-count See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td><code>fval</code></td>
<td>Function value at current point. Final value equals optimization function output <code>fval</code>.</td>
<td><code>fgoalattain</code> (M), <code>fminbnd</code> (B), <code>fmincon</code> (B), <code>fminimax</code> (M), <code>fminsearch</code> (B), <code>fminunc</code> (B), <code>fsolve</code> (B), <code>fseminf</code> (M), <code>fsolve</code> (B), <code>fzero</code> (B)</td>
<td>f(x) See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td><code>gradient</code></td>
<td>Current gradient of objective function — either analytic gradient if you provide it or finite-differencing approximation. Final value equals optimization function output <code>grad</code>.</td>
<td><code>fgoalattain</code> (M), <code>fmincon</code> (B), <code>fminimax</code> (M), <code>fminunc</code> (M), <code>fseminf</code> (M), <code>fsolve</code> (B), <code>lsqcurvefit</code> (B), <code>lsqnonlin</code> (B)</td>
<td>None</td>
</tr>
</tbody>
</table>
optimValues Fields (Continued)

<table>
<thead>
<tr>
<th>OptimValues Field (optimValues.field)</th>
<th>Description</th>
<th>Returned by Functions</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>iteration</td>
<td>Iteration number — starts at 0. Final value equals optimization function output output.iterations.</td>
<td>fgoalattain (M), fminbnd (B), fmincon (B), fminimax (M), fminsearch (B), fminunc (B), fsolve (B), fseminf (M), fzero (B), lsqcurvefit (B), lsqnonlin (B)</td>
<td>Iteration See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>lambda</td>
<td>The Levenberg-Marquardt parameter, lambda, at the current iteration. See “Levenberg-Marquardt Method” on page 6-150.</td>
<td>fsolve (L, Levenberg-Marquardt algorithm), lsqcurvefit (L, Levenberg-Marquardt algorithm), lsqnonlin (L, Levenberg-Marquardt algorithm)</td>
<td>Lambda</td>
</tr>
<tr>
<td>maxfval</td>
<td>Maximum function value</td>
<td>fminimax (M)</td>
<td>None</td>
</tr>
<tr>
<td>positive definite</td>
<td>0 if algorithm detects negative curvature while computing Newton step. 1 otherwise.</td>
<td>fmincon (L), fsolve (L), lsqcurvefit (L), lsqnonlin (L)</td>
<td>None</td>
</tr>
<tr>
<td>procedure</td>
<td>Procedure messages.</td>
<td>fgoalattain (M), fminbnd (B), fmincon (M), fminimax (M), fminsearch (B), fseminf (M), fzero (B)</td>
<td>Procedure See “Iterative Display” on page 3-16.</td>
</tr>
</tbody>
</table>
### optimValues Fields (Continued)

<table>
<thead>
<tr>
<th>OptimValues Field (optimValues.field)</th>
<th>Description</th>
<th>Returned by Functions</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>ratio</td>
<td>Ratio of change in the objective function to change in the quadratic approximation.</td>
<td>fmincon (L), fsolve (L), lsqcurvefit (L), lsqnonlin (L)</td>
<td>None</td>
</tr>
<tr>
<td>residual</td>
<td>The residual vector. For fsolve, residual means the 2-norm of the residual squared.</td>
<td>lsqcurvefit (B), lsqnonlin (B), fsolve (B)</td>
<td>Residual See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>resnorm</td>
<td>2-norm of the residual squared.</td>
<td>lsqcurvefit (B), lsqnonlin (B)</td>
<td>Resnorm See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>searchdirection</td>
<td>Search direction.</td>
<td>fgoalattain (M), fmincon (M), fminimax (M), fminunc (M), fseminf (M), fsolve (M), lsqcurvefit (M), lsqnonlin (M)</td>
<td>None</td>
</tr>
<tr>
<td>stepaccept</td>
<td>Status of the current trust-region step. Returns true if the current trust-region step was successful, and false if the trust-region step was unsuccessful.</td>
<td>fsolve (L, NonlEqn-Algorithm='dogleg')</td>
<td>None</td>
</tr>
</tbody>
</table>
OptimValues Fields (Continued)

<table>
<thead>
<tr>
<th>OptimValues Field (optimValues.field)</th>
<th>Description</th>
<th>Returned by Functions</th>
<th>Command-Line Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>stepsize</td>
<td>Current step size (displacement in x). Final value equals optimization function output output.stepsize.</td>
<td>fgoalattain (M), fmincon (B), fminimax (M), fminunc (B), fseminf (M), fsolve (B), lsqcurvefit (B), lsqnonlin (B)</td>
<td>Step-size or Norm of Step See “Iterative Display” on page 3-16.</td>
</tr>
<tr>
<td>trustregionradius</td>
<td>Radius of trust region.</td>
<td>fmincon (L), fsolve (L, M), lsqcurvefit, lsqnonlin (L)</td>
<td>Trust-region radius See “Iterative Display” on page 3-16.</td>
</tr>
</tbody>
</table>

**Degeneracy.** The value of the field degenerate, which measures the degeneracy of the current optimization point x, is defined as follows. First, define a vector r, of the same size as x, for which r(i) is the minimum distance from x(i) to the ith entries of the lower and upper bounds, lb and ub. That is,

\[ r = \min(\text{abs}(\text{ub}-x, x-\text{lb})) \]

Then the value of degenerate is the minimum entry of the vector r + abs(grad), where grad is the gradient of the objective function. The value of degenerate is 0 if there is an index i for which both of the following are true:

- grad(i) = 0
- x(i) equals the ith entry of either the lower or upper bound.
States of the Algorithm
The following table lists the possible values for state:

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>'init'</td>
<td>The algorithm is in the initial state before the first iteration.</td>
</tr>
<tr>
<td>'interrupt'</td>
<td>The algorithm is in some computationally expensive part of the iteration. In this state, the output function can interrupt the current iteration of the optimization. At this time, the values of x and optimValues are the same as at the last call to the output function in which state='iter'.</td>
</tr>
<tr>
<td>'iter'</td>
<td>The algorithm is at the end of an iteration.</td>
</tr>
<tr>
<td>'done'</td>
<td>The algorithm is in the final state after the last iteration.</td>
</tr>
</tbody>
</table>

The following code illustrates how the output function might use the value of state to decide which tasks to perform at the current iteration:

```matlab
switch state
    case 'iter'
        % Make updates to plot or guis as needed
    case 'interrupt'
        % Probably no action here. Check conditions to see % whether optimization should quit.
    case 'init'
        % Setup for plots or guis
    case 'done'
        % Cleanup of plots, guis, or final plot
    otherwise
        % Cleanup of plots, guis, or final plot
end
```

Stop Flag
The output argument stop is a flag that is true or false. The flag tells the optimization function whether the optimization should quit or continue. The following examples show typical ways to use the stop flag.
Stopping an Optimization Based on Data in `optimValues`. The output function can stop an optimization at any iteration based on the current data in `optimValues`. For example, the following code sets `stop` to `true` if the directional derivative is less than `.01`:

```matlab
function stop = outfun(x,optimValues,state)
    stop = false;
    % Check if directional derivative is less than .01.
    if optimValues.directionalderivative < .01
        stop = true;
    end
end
```

Stopping an Optimization Based on GUI Input. If you design a GUI to perform optimizations, you can make the output function stop an optimization when a user clicks a **Stop** button on the GUI. The following code shows how to do this, assuming that the **Stop** button callback stores the value `true` in the `optimstop` field of a handles structure called `hObject`:

```matlab
function stop = outfun(x,optimValues,state)
    stop = false;
    % Check if user has requested to stop the optimization.
    stop = getappdata(hObject,'optimstop');
end
```

**Plot Functions**

The `PlotFcns` field of the `options` structure specifies one or more functions that an optimization function calls at each iteration to plot various measures of progress while the algorithm executes. The structure of a plot function is the same as that for an output function. For more information on writing and calling a plot function, see “Output Function” on page 9-18. For an example of using built-in plot functions, “Example: Using a Plot Function” on page 3-30.

To view and modify a predefined plot function listed for `PlotFcns`, you can open it in the MATLAB Editor. For example, to view the file corresponding to the norm of residuals, enter:

```matlab
edit optimplotresnorm.m
```
## Function Reference

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# Minimization

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# Equation Solving

See \ for solving linear equations of the form \( Ax = b \).
Least Squares (Curve Fitting)

See \ for minimizing \( \|Ax - b\| \).

- `fsolve`: Solve system of nonlinear equations
- `fzero`: Find root of continuous function of one variable
- `lsqcurvefit`: Solve nonlinear curve-fitting (data-fitting) problems in least-squares sense
- `lsqnonlin`: Solve nonlinear least-squares (nonlinear data-fitting) problems
- `lsqnonneg`: Solve nonnegative least-squares constraint problem

GUI

- `optimtool`: Tool to select solver, optimization options, and run problems
## Utilities

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Functions — Alphabetical List
bintprog

**Purpose**
Solve binary integer programming problems

**Equation**
Solves binary integer programming problems of the form

\[
\min_{x} f^T x \text{ such that } \begin{align*}
A \cdot x &\le b, \\
A_{eq} \cdot x &= b_{eq}, \\
x &\text{ binary.}
\end{align*}
\]

\(f, b,\) and \(b_{eq}\) are vectors, \(A\) and \(A_{eq}\) are matrices, and the solution \(x\) is required to be a binary integer vector—that is, its entries can only take on the values 0 or 1.

**Syntax**
- \(x = \text{bintprog}(f)\)
- \(x = \text{bintprog}(f,A,b)\)
- \(x = \text{bintprog}(f,A,b,A_{eq},b_{eq})\)
- \(x = \text{bintprog}(f,A,b,A_{eq},b_{eq},x_0)\)
- \(x = \text{bintprog}(f,A,b,A_{eq},b_{eq},x_0,\text{options})\)
- \(x = \text{bintprog}(\text{problem})\)
- \([x,fval] = \text{bintprog}(\ldots)\)
- \([x,fval,\text{exitflag}] = \text{bintprog}(\ldots)\)
- \([x,fval,\text{exitflag},\text{output}] = \text{bintprog}(\ldots)\)

**Description**
- \(x = \text{bintprog}(f)\) solves the binary integer programming problem

\[
\min_{x} f^T x.
\]

- \(x = \text{bintprog}(f,A,b)\) solves the binary integer programming problem

\[
\min_{x} f^T x \text{ such that } A \cdot x \le b.
\]

- \(x = \text{bintprog}(f,A,b,A_{eq},b_{eq})\) solves the preceding problem with the additional equality constraint.

\(A_{eq} x = b_{eq}.\)
x = bintprog(f,A,b,Aeq,beq,x0) sets the starting point for the algorithm to x0. If x0 is not in the feasible region, bintprog uses the default initial point.

x = bintprog(f,A,b,Aeq,beq,x0,options) minimizes with the default optimization options replaced by values in the structure options, which you can create using the function optimset.

x = bintprog(problem) finds the minimum for problem, where problem is a structure described in “Input Arguments” on page 11-3.

Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = bintprog(...) returns fval, the value of the objective function at x.

[x,fval,exitflag] = bintprog(...) returns exitflag that describes the exit condition of bintprog. See “Output Arguments” on page 11-4.

[x,fval,exitflag,output] = bintprog(...) returns a structure output that contains information about the optimization. See “Output Arguments” on page 11-4.

**Input Arguments**

The following table lists the input arguments for bintprog. “Function Arguments” on page 9-2 contains general descriptions of input arguments for optimization functions.

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>Vector containing the coefficients of the linear objective function.</td>
</tr>
<tr>
<td>A</td>
<td>Matrix containing the coefficients of the linear inequality constraints $A \ x \leq b$.</td>
</tr>
<tr>
<td>b</td>
<td>Vector corresponding to the right-hand side of the linear inequality constraints.</td>
</tr>
<tr>
<td>Aeq</td>
<td>Matrix containing the coefficients of the linear equality constraints $Aeq \ x = beq$.</td>
</tr>
</tbody>
</table>
**bintprog**

- **beq**: Vector containing the constants of the linear equality constraints.
- **x0**: Initial point for the algorithm.
- **options**: Options structure containing options for the algorithm.
- **problem**
  - **f**: Linear objective function vector $f$
  - **Aineq**: Matrix for linear inequality constraints
  - **bineq**: Vector for linear inequality constraints
  - **Aeq**: Matrix for linear equality constraints
  - **beq**: Vector for linear equality constraints
  - **x0**: Initial point for $x$
  - **solver**: 'bintprog'
  - **options**: Options structure created with `optimset`

**Output Arguments**

"Function Arguments" on page 9-2 contains general descriptions of arguments returned by `bintprog`. This section provides specific details for the arguments `exitflag` and `output`:

- **exitflag**: Integer identifying the reason the algorithm terminated. The following lists the values of `exitflag` and the corresponding reasons the algorithm terminated.
  - 1: Function converged to a solution $x$.  
  - 0: Number of iterations exceeded `options.MaxIter`.  
  - -2: The problem is infeasible.  
  - -4: Number of searched nodes exceeded `options.MaxNodes`.  
  - -5: Search time exceeded `options.MaxTime`.  

11-4
-6 Number of iterations the LP-solver performed at a node to solve the LP-relaxation problem exceeded options.MaxRLP.

output Structure containing information about the optimization. The fields of the structure are

- iterations Number of iterations taken
- nodes Number of nodes searched
- time Execution time of the algorithm
- algorithm Optimization algorithm used
- branchStrategy Strategy used to select branch variable—see “Options” on page 11-5
- nodeSearchStrategy Strategy used to select next node in search tree—see “Options” on page 11-5
- message Exit message

Options Optimization options used by bintprog. You can use optimset to set or change the values of these fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information.
### BranchStrategy
Strategy the algorithm uses to select the branch variable in the search tree—see “Branching” on page 6-137. The choices are:

- `'mininfeas'` — Choose the variable with the minimum integer infeasibility (the variable whose value is closest to 0 or 1, but not equal to 0 or 1).
- `'maxinfeas'` — Choose the variable with the maximum integer infeasibility (the variable whose value is closest to 0.5 (default)).

### Diagnostics
Display diagnostic information about the function. The choices are `'on'` or the default, `'off'`.

### Display
Level of display.

- `'off'` displays no output
- `'iter'` displays output at each iteration
- `'final'` (default) displays just the final output

### MaxIter
Maximum number of iterations allowed (a positive integer). The default is $100000 \times \text{numberOfVariables}$

### MaxNodes
Maximum number of solutions, or nodes, the function searches (a positive integer). The default is $1000 \times \text{numberOfVariables}$

### MaxRLPIter
Maximum number of iterations the LP-solver performs to solve the LP-relaxation problem at each node (a positive integer). The default is $100 \times \text{numberOfVariables}$
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MaxTime</td>
<td>Maximum amount of CPU time in seconds the function runs (a positive scalar). The default is 7200.</td>
</tr>
<tr>
<td>NodeDisplayInterval</td>
<td>Node display interval (a positive integer). Gives the number of nodes to search between reporting to the iterative display. The default is 20.</td>
</tr>
<tr>
<td>NodeSearchStrategy</td>
<td>Strategy the algorithm uses to select the next node to search in the search tree—see “Branching” on page 6-137. The choices are:</td>
</tr>
<tr>
<td></td>
<td>• 'df' — Depth-first search strategy. At each node in the search tree, if there is a child node one level down in the tree that has not already been explored, the algorithm chooses one such child to search. Otherwise, the algorithm moves to the node one level up in the tree and chooses a child node one level down from that node.</td>
</tr>
<tr>
<td></td>
<td>• 'bn' — Best-node search strategy, which chooses the node with lowest bound on the objective function (the default).</td>
</tr>
<tr>
<td>TolFun</td>
<td>Termination tolerance on the function value (a positive scalar). The default is $1.0e^{-3}$.</td>
</tr>
<tr>
<td>TolXInteger</td>
<td>Tolerance within which the value of a variable is considered to be integral (a positive scalar). The default is $1.0e^{-8}$.</td>
</tr>
</tbody>
</table>
| TolRLPFun                  | Termination tolerance on the function value of a linear programming relaxation problem (a positive scalar). The default is $1.0e^{-6}$.
bintprog uses a linear programming (LP)-based branch-and-bound algorithm to solve binary integer programming problems. The algorithm searches for an optimal solution to the binary integer programming problem by solving a series of LP-relaxation problems, in which the binary integer requirement on the variables is replaced by the weaker constraint $0 \leq x \leq 1$. The algorithm

- Searches for a binary integer feasible solution
- Updates the best binary integer feasible point found so far as the search tree grows
- Verifies that no better integer feasible solution is possible by solving a series of linear programming problems

For more information, see “bintprog Algorithm” on page 6-137

Examples

To minimize the function

$$f(x) = -9x_1 - 5x_2 - 6x_3 - 4x_4,$$

subject to the constraints

$$
\begin{bmatrix}
6 & 3 & 5 & 2 \\
0 & 0 & 1 & 1 \\
-1 & 0 & 1 & 0 \\
0 & -1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
\leq
\begin{bmatrix}
9 \\
1 \\
0 \\
0
\end{bmatrix},
$$

where $x_1$, $x_2$, $x_3$, and $x_4$ are binary integers, enter the following commands:

```matlab
f = [-9; -5; -6; -4];
A = [6 3 5 2; 0 0 1 1; -1 0 1 0; 0 -1 0 1];
b = [9; 1; 0; 0];
x = bintprog(f, A, b)
Optimization terminated.
```
\[ x = \\
1 \\
1 \\
0 \\
0 \]

**References**


**See Also**

`linprog` | `optimset` | `optimtool` | `bintprog`

**How To**

- “Binary Integer Programming Algorithms” on page 6-137
- “Binary Integer Programming Examples” on page 6-140
<table>
<thead>
<tr>
<th><strong>Purpose</strong></th>
<th>Column partition for sparse finite differences</th>
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</thead>
<tbody>
<tr>
<td><strong>Syntax</strong></td>
<td><code>group = color(J,P)</code></td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td><code>group = color(J,P)</code> returns a partition of the column corresponding to a coloring of the column-intersection graph. <code>GROUP(I) = J</code> means column I is colored J. All columns belonging to a color can be estimated in a single finite difference.</td>
</tr>
</tbody>
</table>
Purpose  
Solve multiobjective goal attainment problems

Equation  
Finds the minimum of a problem specified by

\[
\begin{align*}
\text{minimize } & \gamma \quad \text{such that} \\
& \left\{ \\
& F(x) - \text{weight} \cdot \gamma \leq \text{goal} \\
& c(x) \leq 0 \\
& \text{ceq}(x) = 0 \\
& A \cdot x \leq b \\
& \text{Aeq} \cdot x = \text{beq} \\
& lb \leq x \leq ub.
\right.
\end{align*}
\]

\[x, \text{weight, goal, b, beq, lb, and ub are vectors, A and Aeq are matrices, and c(x), ceq(x), and F(x) are functions that return vectors. F(x), c(x), and ceq(x) can be nonlinear functions.}\]

Syntax  
\[
\begin{align*}
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}) \\
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}, A, b) \\
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}, A, b, \text{Aeq}, \text{beq}) \\
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}) \\
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}, \text{nonlcon}) \\
x &= \text{fgoalattain}(\text{fun}, \text{x0}, \text{goal}, \text{weight}, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}, \text{nonlcon}, \text{... options}) \\
x &= \text{fgoalattain}(\text{problem}) \\
[x, \text{fval}] &= \text{fgoalattain}(\text{...}) \\
[x, \text{fval}, \text{attainfactor}] &= \text{fgoalattain}(\text{...}) \\
[x, \text{fval}, \text{attainfactor}, \text{exitflag}] &= \text{fgoalattain}(\text{...}) \\
[x, \text{fval}, \text{attainfactor}, \text{exitflag}, \text{output}] &= \text{fgoalattain}(\text{...}) \\
[x, \text{fval}, \text{attainfactor}, \text{exitflag}, \text{output}, \lambda &= \text{fgoalattain}(\text{...})
\end{align*}
\]

Description  
fgoalattain solves the goal attainment problem, which is one formulation for minimizing a multiobjective optimization problem.
Note "Passing Extra Parameters" on page 2-38 explains how to pass extra parameters to the objective functions and nonlinear constraint functions, if necessary.

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight})\text{ tries to make the objective functions supplied by } \text{fun} \text{ attain the goals specified by } \text{goal} \text{ by varying } x, \text{ starting at } x_0, \text{ with weight specified by } \text{weight}.
\]

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight}, A, b)\text{ solves the goal attainment problem subject to the linear inequalities } A\cdot x \leq b.
\]

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight}, A, b, A_{eq}, b_{eq})\text{ solves the goal attainment problem subject to the linear equalities } A_{eq}\cdot x = b_{eq} \text{ as well. Set } A = [] \text{ and } b = [] \text{ if no inequalities exist.}
\]

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight}, A, b, A_{eq}, b_{eq}, lb, ub)\text{ defines a set of lower and upper bounds on the design variables in } x, \text{ so that the solution is always in the range } lb \leq x \leq ub.
\]

Note See “Iterations Can Violate Constraints” on page 2-30.

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight}, A, b, A_{eq}, b_{eq}, lb, ub, \text{nonlcon})\text{ subjects the goal attainment problem to the nonlinear inequalities } c(x) \text{ or nonlinear equality constraints } ceq(x) \text{ defined in } \text{nonlcon}.
\]

fgoalattain optimizes such that \( c(x) \leq 0 \) and \( ceq(x) = 0 \). Set \( lb = [] \) and/or \( ub = [] \) if no bounds exist.

\[
x = \text{fgoalattain}(\text{fun}, x_0, \text{goal}, \text{weight}, A, b, A_{eq}, b_{eq}, lb, ub, \text{nonlcon}, \ldots \text{ options})\text{ minimizes with the optimization options specified in the structure } \text{options}. \text{ Use } \text{optimset} \text{ to set these options.}
\]

\[
x = \text{fgoalattain}(\text{problem})\text{ finds the minimum for } \text{problem}, \text{ where } \text{problem} \text{ is a structure described in “Input Arguments” on page 11-13.}
\]
Create the structure `problem` by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

```
[x,fval] = fgoalattain(...) returns the values of the objective functions computed in `fun` at the solution `x`.

[x,fval,attainfactor] = fgoalattain(...) returns the attainment factor at the solution `x`.

[x,fval,attainfactor,exitflag] = fgoalattain(...) returns a value `exitflag` that describes the exit condition of `fgoalattain`.

[x,fval,attainfactor,exitflag,output] = fgoalattain(...) returns a structure `output` that contains information about the optimization.

[x,fval,attainfactor,exitflag,output,lambda] = fgoalattain(...) returns a structure `lambda` whose fields contain the Lagrange multipliers at the solution `x`.
```

**Note** If the specified input bounds for a problem are inconsistent, the output `x` is `x0` and the output `fval` is `[]`.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into `fgoalattain`. This section provides function-specific details for `fun`, `goal`, `nonlcon`, `options`, `weight`, and `problem`:
fun The function to be minimized. fun is a function that accepts a vector x and returns a vector F, the objective functions evaluated at x. The function fun can be specified as a function handle for a function file:

\[ x = \text{fgoalattain}(@\text{myfun},x0,\text{goal},\text{weight}) \]

where myfun is a MATLAB function such as

```matlab
function F = myfun(x)
F = ... % Compute function values at x.
```

fun can also be a function handle for an anonymous function.

\[ x = \text{fgoalattain}(@(x)\sin(x.*x),x0,\text{goal},\text{weight}); \]

If the user-defined values for x and F are matrices, they are converted to a vector using linear indexing.

To make an objective function as near as possible to a goal value, (i.e., neither greater than nor less than) use optimset to set the GoalsExactAchieve option to the number of objectives required to be in the neighborhood of the goal values. Such objectives must be partitioned into the first elements of the vector F returned by fun.

If the gradient of the objective function can also be computed and the GradObj option is 'on', as set by

\[ \text{options} = \text{optimset('GradObj','on')} \]

then the function fun must return, in the second output argument, the gradient value \( G \), a matrix, at x. The gradient consists of the partial derivative \( \frac{dF}{dx} \) of each \( F \) at the point x. If \( F \) is a vector of length \( m \) and x has length \( n \), where \( n \) is the length of \( x0 \), then the gradient \( G \) of \( F(x) \) is an \( n \)-by-\( m \) matrix where \( G(i,j) \) is the partial
derivative of $F(j)$ with respect to $x(i)$ (i.e., the $j$th column of $G$ is the gradient of the $j$th objective function $F(j)$).

**Note** Setting `GradObj` to 'on' is effective only when there is no nonlinear constraint, or when the nonlinear constraint has `GradConstr` set to 'on' as well. This is because internally the objective is folded into the constraints, so the solver needs both gradients (objective and constraint) supplied in order to avoid estimating a gradient.

goal Vector of values that the objectives attempt to attain. The vector is the same length as the number of objectives $F$ returned by fun. `fgoalattain` attempts to minimize the values in the vector $F$ to attain the goal values given by `goal`.

nonlcon The function that computes the nonlinear inequality constraints $c(x) \leq 0$ and the nonlinear equality constraints $ceq(x) = 0$. The function `nonlcon` accepts a vector $x$ and returns two vectors $c$ and $ceq$. The vector $c$ contains the nonlinear inequalities evaluated at $x$, and $ceq$ contains the nonlinear equalities evaluated at $x$. The function `nonlcon` can be specified as a function handle.

```matlab
x = fgoalattain(@myfun,x0,goal,weight,A,b,Aeq,beq,...
             lb,ub,@mycon)
```

where `mycon` is a MATLAB function such as

```matlab
function [c,ceq] = mycon(x)
    c = ... % compute nonlinear inequalities at x.
    ceq = ... % compute nonlinear equalities at x.
```
If the gradients of the constraints can also be computed and the \texttt{GradConstr} option is 'on', as set by

\begin{verbatim}
options = optimset('GradConstr','on')
\end{verbatim}

then the function \texttt{nonlcon} must also return, in the third and fourth output arguments, \texttt{GC}, the gradient of \texttt{c(x)}, and \texttt{GCeq}, the gradient of \texttt{ceq(x)}. “Nonlinear Constraints” on page 2-33 explains how to “conditionalize” the gradients for use in solvers that do not accept supplied gradients.

If \texttt{nonlcon} returns a vector \texttt{c} of \texttt{m} components and \texttt{x} has length \texttt{n}, where \texttt{n} is the length of \texttt{x0}, then the gradient \texttt{GC} of \texttt{c(x)} is an \texttt{n}-by-\texttt{m} matrix, where \texttt{GC(i,j)} is the partial derivative of \texttt{c(j)} with respect to \texttt{x(i)} (i.e., the \texttt{j}th column of \texttt{GC} is the gradient of the \texttt{j}th inequality constraint \texttt{c(j)}). Likewise, if \texttt{ceq} has \texttt{p} components, the gradient \texttt{GCeq} of \texttt{ceq(x)} is an \texttt{n}-by-\texttt{p} matrix, where \texttt{GCeq(i,j)} is the partial derivative of \texttt{ceq(j)} with respect to \texttt{x(i)} (i.e., the \texttt{j}th column of \texttt{GCeq} is the gradient of the \texttt{j}th equality constraint \texttt{ceq(j)}).

\textbf{Note} Setting \texttt{GradConstr} to 'on' is effective only when \texttt{GradObj} is set to 'on' as well. This is because internally the objective is folded into the constraint, so the solver needs both gradients (objective and constraint) supplied in order to avoid estimating a gradient.
Because Optimization Toolbox functions only accept inputs of type double, user-supplied objective and nonlinear constraint functions must return outputs of type double.

"Passing Extra Parameters" on page 2-38 explains how to parameterize the nonlinear constraint function nonlcon, if necessary.

**options**

"Options" on page 11-20 provides the function-specific details for the options values.

**weight**

A weighting vector to control the relative underattainment or overattainment of the objectives in fgoalattain. When the values of goal are all nonzero, to ensure the same percentage of under- or overattainment of the active objectives, set the weighting function to abs(goal). (The active objectives are the set of objectives that are barriers to further improvement of the goals at the solution.)

**Note** Setting a component of the weight vector to zero will cause the corresponding goal constraint to be treated as a hard constraint rather than as a goal constraint. An alternative method to set a hard constraint is to use the input argument nonlcon.

When the weighting function weight is positive, fgoalattain attempts to make the objectives less than the goal values. To make the objective functions greater than the goal values, set weight to be negative rather than positive. To make an objective function as near as possible to a goal value, use the GoalsExactAchieve
option and put that objective as the first element of the vector returned by \texttt{fun} (see the preceding description of \texttt{fun} and \texttt{options}).

<table>
<thead>
<tr>
<th>problem</th>
<th>objective</th>
<th>Vector of objective functions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>\texttt{x0}</td>
<td>Initial point for \texttt{x}</td>
</tr>
<tr>
<td></td>
<td>\texttt{goal}</td>
<td>Goals to attain</td>
</tr>
<tr>
<td></td>
<td>\texttt{weight}</td>
<td>Relative importance factors of goals</td>
</tr>
<tr>
<td></td>
<td>\texttt{Aineq}</td>
<td>Matrix for linear inequality constraints</td>
</tr>
<tr>
<td></td>
<td>\texttt{bineq}</td>
<td>Vector for linear inequality constraints</td>
</tr>
<tr>
<td></td>
<td>\texttt{Aeq}</td>
<td>Matrix for linear equality constraints</td>
</tr>
<tr>
<td></td>
<td>\texttt{beq}</td>
<td>Vector for linear equality constraints</td>
</tr>
<tr>
<td></td>
<td>\texttt{lb}</td>
<td>Vector of lower bounds</td>
</tr>
<tr>
<td></td>
<td>\texttt{ub}</td>
<td>Vector of upper bounds</td>
</tr>
<tr>
<td></td>
<td>\texttt{nonlcon}</td>
<td>Nonlinear constraint function</td>
</tr>
<tr>
<td></td>
<td>\texttt{solver}</td>
<td>'fgoalattain'</td>
</tr>
<tr>
<td></td>
<td>\texttt{options}</td>
<td>Options structure created with \texttt{optimset}</td>
</tr>
</tbody>
</table>

**Output Arguments**

"Function Arguments" on page 9-2 contains general descriptions of arguments returned by \texttt{fgoalattain}. This section provides function-specific details for \texttt{attainfactor}, \texttt{exitflag}, \texttt{lambda}, and \texttt{output}:
attainfactor  The amount of over- or underachievement of the
goals. If attainfactor is negative, the goals have
been overachieved; if attainfactor is positive, the
goals have been underachieved.

attainfactor contains the value of $\gamma$ at the solution.
A negative value of $\gamma$ indicates overattainment in
the goals.

exitflag  Integer identifying the reason the algorithm
terminated. The following lists the values of
exitflag and the corresponding reasons the
algorithm terminated.

1  Function converged to a solutions $x$.

4  Magnitude of the search direction
less than the specified tolerance
and constraint violation less than
options.TolCon

5  Magnitude of directional
derivative less than the specified
tolerance and constraint violation
less than options.TolCon

0  Number of iterations exceeded
options.MaxIter or number of
function evaluations exceeded
options.FunEvals

-1  Algorithm was terminated by the
output function.

-2  No feasible point was found.

lambda  Structure containing the Lagrange multipliers at
the solution $x$ (separated by constraint type). The
fields of the structure are

lower  Lower bounds $lb$
fgoalattain

upper
ineqlin
eqlin
ineqnonlin
eqnonlin
output

Structure containing information about the optimization. The fields of the structure are:

iterations
Number of iterations taken
funcCount
Number of function evaluations
lssteplength
Size of line search step relative to search direction
stepsize
Final displacement in x
algorithm
Optimization algorithm used
firstorderopt
Measure of first-order optimality
constrviolation
Maximum of constraint functions
message
Exit message

Options
Optimization options used by fgoalattain. You can use optimset to set or change the values of these fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information.
**DerivativeCheck**

Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default, 'off'.

**Diagnostics**

Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default, 'off'.

**DiffMaxChange**

Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.

**DiffMinChange**

Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.

**Display**

Level of display.

- 'off' displays no output.
- 'iter' displays output at each iteration, and gives the default exit message.
- 'iter-detailed' displays output at each iteration, and gives the technical exit message.
- 'notify' displays output only if the function does not converge, and gives the default exit message.
- 'notify-detailed' displays output only if the function does not converge, and gives the technical exit message.
- 'final' (default) displays just the final output, and gives the default exit message.
• 'final-detailed' displays just the final output, and gives the technical exit message.

**FinDiffRelStep**  
Scalar or vector step size factor. When you set `FinDiffRelStep` to a vector `v`, forward finite differences `delta` are

\[
\text{delta} = v \cdot \text{sign}(x) \cdot \max(\text{abs}(x), \text{TypicalX});
\]

and central finite differences are

\[
\text{delta} = v \cdot \max(\text{abs}(x), \text{TypicalX});
\]

Scalar `FinDiffRelStep` expands to a vector. The default is `sqrt(eps)` for forward finite differences, and `eps^(1/3)` for central finite differences.

**FinDiffType**  
Finite differences, used to estimate gradients, are either 'forward' (default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.

The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FunValCheck</strong></td>
<td>Check whether objective function and constraints values are valid. 'on' displays an error when the objective function or constraints return a value that is complex, Inf, or NaN. The default, 'off', displays no error.</td>
</tr>
<tr>
<td><strong>GoalsExactAchieve</strong></td>
<td>Specifies the number of objectives for which it is required for the objective fun to equal the goal goal (a nonnegative integer). Such objectives should be partitioned into the first few elements of F. The default is 0.</td>
</tr>
<tr>
<td><strong>GradConstr</strong></td>
<td>Gradient for nonlinear constraint functions defined by the user. When set to 'on', fgoalattain expects the constraint function to have four outputs, as described in nonlcon in the “Input Arguments” on page 11-13 section. When set to the default, 'off', gradients of the nonlinear constraints are estimated by finite differences.</td>
</tr>
<tr>
<td><strong>GradObj</strong></td>
<td>Gradient for the objective function defined by the user. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have fgoalattain use a user-defined gradient of the objective function. The default, 'off', causes fgoalattain to estimate gradients using finite differences.</td>
</tr>
<tr>
<td><strong>MaxFunEvals</strong></td>
<td>Maximum number of function evaluations allowed (a positive integer). The default is 100*numberOfVariables.</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>MaxIter</strong></td>
<td>Maximum number of iterations allowed (a positive integer). The default is 400.</td>
</tr>
<tr>
<td><strong>MaxSQPIter</strong></td>
<td>Maximum number of SQP iterations allowed (a positive integer). The default is (10 \times \max(\text{numberOfVariables}, \text{numberOfInequalities} + \text{numberOfBounds}))</td>
</tr>
<tr>
<td><strong>MeritFunction</strong></td>
<td>Use goal attainment/minimax merit function if set to 'multiobj', the default. Use fmincon merit function if set to 'singleobj'.</td>
</tr>
<tr>
<td><strong>OutputFcn</strong></td>
<td>Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([ ]). See “Output Function” on page 9-18.</td>
</tr>
<tr>
<td><strong>PlotFcns</strong></td>
<td>Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]).</td>
</tr>
</tbody>
</table>

- @optimplotx plots the current point
- @optimplotfunccount plots the function count
- @optimplotfval plots the function value
- @optimplotconstrviolation plots the maximum constraint violation
• @optimplotstepsizes plots the step size

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

**RelLineSrchBnd**

Relative bound (a real nonnegative scalar value) on the line search step length such that the total displacement in x satisfies $|\Delta x(i)| \leq \text{relLineSrchBnd} \cdot \max(|x(i)|,|typical x(i)|)$. This option provides control over the magnitude of the displacements in x for cases in which the solver takes steps that are considered too large. The default is none ([]).

**RelLineSrchBndDuration**

Number of iterations for which the bound specified in RelLineSrchBnd should be active (default is 1).

**TolCon**

Termination tolerance on the constraint violation, a positive scalar. The default is 1e-6.

**TolConSQP**

Termination tolerance on inner iteration SQP constraint violation, a positive scalar. The default is 1e-6.

**TolFun**

Termination tolerance on the function value, a positive scalar. The default is 1e-6.

**TolX**

Termination tolerance on x, a positive scalar. The default is 1e-6.
TypicalX

Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1).

fgoalattain uses TypicalX for scaling finite differences for gradient estimation.

UseParallel

When 'always', estimate gradients in parallel. Disable by setting to the default, 'never'.

Examples

Consider a linear system of differential equations.

An output feedback controller, K, is designed producing a closed loop system

\[ \dot{x} = (A + BKC)x + Bu, \]
\[ y = Cx. \]

The eigenvalues of the closed loop system are determined from the matrices A, B, C, and K using the command eig(A+B*K*C). Closed loop eigenvalues must lie on the real axis in the complex plane to the left of the points [-5, -3, -1]. In order not to saturate the inputs, no element in K can be greater than 4 or be less than -4.

The system is a two-input, two-output, open loop, unstable system, with state-space matrices.

\[
A = \begin{bmatrix}
-0.5 & 0 & 0 \\
0 & -2 & 10 \\
0 & 1 & -2
\end{bmatrix}, \quad
B = \begin{bmatrix}
1 & 0 \\
-2 & 2 \\
0 & 1
\end{bmatrix}, \quad
C = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}.
\]

The set of goal values for the closed loop eigenvalues is initialized as

\[ \text{goal} = [-5, -3, -1]; \]
To ensure the same percentage of under- or overattainment in the active objectives at the solution, the weighting matrix, weight, is set to \( \text{abs}(\text{goal}) \).

Starting with a controller, \( K = [-1, -1; -1, -1] \), first write a function file, \texttt{eigfun.m}.

```matlab
function F = eigfun(K,A,B,C)
F = sort(eig(A+B*K*C)); % Evaluate objectives
```

Next, enter system matrices and invoke an optimization routine.

\[
A = \begin{bmatrix}
-0.5 & 0 & 0 \\
0 & -2 & 10 \\
0 & 1 & -2
\end{bmatrix};
\]

\[
B = \begin{bmatrix}
10 \\
-22 \\
0 & 1
\end{bmatrix};
\]

\[
C = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix};
\]

\[
K0 = [-1 -1; -1 -1]; % Initialize controller matrix
\]

\[
goal = [-5 -3 -1]; % Set goal values for the eigenvalues
\]

\[
weight = \text{abs}(\text{goal}); % Set weight for same percentage
\]

\[
lb = -4*\text{ones(size(K0))}; % Set lower bounds on the controller
\]

\[
ub = 4*\text{ones(size(K0))}; % Set upper bounds on the controller
\]

\[
\text{options} = \text{optimset}('Display','iter'); % Set display parameter
\]

\[
[K,fval,attainfactor] = \text{fgoalattain} (@(K)eigfun(K,A,B,C),...
     K0,goal,weight,[],[],[],[],lb,ub,[],options)
\]

You can run this example by using the demonstration script \texttt{goaldemo}. (From the MATLAB Help browser or the MathWorks Web site documentation, you can click the demo name to display the demo.) After about 11 iterations, a solution is

Active inequalities (to within options.TolCon = 1e-006):
lower  upper  ineqlin  ineqnonlin
1      1
2      2
4

\[
K =
\begin{bmatrix}
-4 & 0.0000 \\
-0.2564
\end{bmatrix}
\]
The attainment factor indicates that each of the objectives has been overachieved by at least 38.63% over the original design goals. The active constraints, in this case constraints 1 and 2, are the objectives that are barriers to further improvement and for which the percentage of overattainment is met exactly. Three of the lower bound constraints are also active.

In the preceding design, the optimizer tries to make the objectives less than the goals. For a worst-case problem where the objectives must be as near to the goals as possible, use `optimset` to set the `GoalsExactAchieve` option to the number of objectives for which this is required.

Consider the preceding problem when you want all the eigenvalues to be equal to the goal values. A solution to this problem is found by invoking `fgoalattain` with the `GoalsExactAchieve` option set to 3.

```matlab
goal = [-6.9313; -4.1588; -1.4099];
attainfactor = -0.3863
```

Discussion

The attainment factor indicates that each of the objectives has been overachieved by at least 38.63% over the original design goals. The active constraints, in this case constraints 1 and 2, are the objectives that are barriers to further improvement and for which the percentage of overattainment is met exactly. Three of the lower bound constraints are also active.

In the preceding design, the optimizer tries to make the objectives less than the goals. For a worst-case problem where the objectives must be as near to the goals as possible, use `optimset` to set the `GoalsExactAchieve` option to the number of objectives for which this is required.

Consider the preceding problem when you want all the eigenvalues to be equal to the goal values. A solution to this problem is found by invoking `fgoalattain` with the `GoalsExactAchieve` option set to 3.

```matlab
options = optimset('GoalsExactAchieve',3);
[K, fval, attainfactor] = fgoalattain(...
    @(K)eigfun(K,A,B,C),K0,goal,weight,[],[],[],[],lb,ub,[],...
    options);
```

After about seven iterations, a solution is

```matlab
K, fval, attainfactor
```

K =

```
-1.5954    1.2040
```
-0.4201  -2.9046

fval =
-5.0000
-3.0000
-1.0000

attainfactor =
1.1304e-022

In this case the optimizer has tried to match the objectives to the goals. The attainment factor (of 1.1304e-22 or so, depending on your system) indicates that the goals have been matched almost exactly.

Notes
This problem has discontinuities when the eigenvalues become complex; this explains why the convergence is slow. Although the underlying methods assume the functions are continuous, the method is able to make steps toward the solution because the discontinuities do not occur at the solution point. When the objectives and goals are complex, fgoalattain tries to achieve the goals in a least-squares sense.

Algorithms
Multiobjective optimization concerns the minimization of a set of objectives simultaneously. One formulation for this problem, and implemented in fgoalattain, is the goal attainment problem of Gembicki [3]. This entails the construction of a set of goal values for the objective functions. Multiobjective optimization is discussed in “Multiobjective Optimization Algorithms” on page 6-170.

In this implementation, the slack variable $y$ is used as a dummy argument to minimize the vector of objectives $F(x)$ simultaneously; goal is a set of values that the objectives attain. Generally, prior to the optimization, it is not known whether the objectives will reach the goals (under attainment) or be minimized less than the goals (overattainment). A weighting vector, weight, controls the relative underattainment or overattainment of the objectives.

fgoalattain uses a sequential quadratic programming (SQP) method, which is described in “Sequential Quadratic Programming (SQP)” on
page 6-28. Modifications are made to the line search and Hessian. In the line search an exact merit function (see [1] and [4]) is used together with the merit function proposed by [5] and [6]. The line search is terminated when either merit function shows improvement. A modified Hessian, which takes advantage of the special structure of the problem, is also used (see [1] and [4]). A full description of the modifications used is found in “Goal Attainment Method” on page 6-171 in “Introduction to Algorithms.” Setting the MeritFunction option to 'singleobj' with

```matlab
options = optimset(options,'MeritFunction','singleobj')
```

uses the merit function and Hessian used in \texttt{fmincon}.

See also “SQP Implementation” on page 6-30 for more details on the algorithm used and the types of procedures displayed under the Procedures heading when the Display option is set to 'iter'.

**Limitations**

The objectives must be continuous. \texttt{fgoalattain} might give only local solutions.

**References**


**See Also**

fmincon | fminimax | optimset | optimtool | fgoalattain

**How To**

- @(function_handle)
- “Multiobjective Optimization Algorithms” on page 6-170
- “Multiobjective Optimization Examples” on page 6-176
**fminbnd**

**Purpose**
Find minimum of single-variable function on fixed interval

**Equation**
Finds a minimum for a problem specified by

\[
\min_x f(x) \text{ such that } x_1 < x < x_2.
\]

\( x, x_1, \text{ and } x_2 \) are scalars and \( f(x) \) is a function that returns a scalar.

**Syntax**

\[
\begin{align*}
  x &= \texttt{fminbnd}(\texttt{fun},x_1,x_2) \\
  x &= \texttt{fminbnd}(\texttt{fun},x_1,x_2,\texttt{options}) \\
  x &= \texttt{fminbnd}(\texttt{problem}) \\
  [x,fval] &= \texttt{fminbnd}(\ldots) \\
  [x,fval,\texttt{exitflag}] &= \texttt{fminbnd}(\ldots) \\
  [x,fval,\texttt{exitflag},\texttt{output}] &= \texttt{fminbnd}(\ldots)
\end{align*}
\]

**Description**
fminbnd attempts to find a minimum of a function of one variable within a fixed interval.

**Note**
“Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function, if necessary.

\[
x = \texttt{fminbnd}(\texttt{fun},x_1,x_2) \text{ returns a value } x \text{ that is a local minimizer of the scalar valued function that is described in } \texttt{fun} \text{ in the interval } x_1 < x < x_2. \texttt{fun} \text{ is either a function handle to a file or is an anonymous function.}
\]

\[
x = \texttt{fminbnd}(\texttt{fun},x_1,x_2,\texttt{options}) \text{ minimizes with the optimization options specified in the structure } \texttt{options}. \texttt{Use optimset} \text{ to set these options.}
\]

\[
x = \texttt{fminbnd}(\texttt{problem}) \text{ finds the minimum for } \texttt{problem}, \text{ where } \texttt{problem} \text{ is a structure described in “Input Arguments” on page 11-33.}
\]

Create the structure \texttt{problem} by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.
[x,fval] = fminbnd(...) returns the value of the objective function computed in \( \text{fun} \) at the solution \( x \).

\[ [x,fval,exitflag] = \text{fminbnd}(...) \]
returns a value \( \text{exitflag} \) that describes the exit condition of \text{fminbnd}.

\[ [x,fval,exitflag,output] = \text{fminbnd}(...) \]
returns a structure \( \text{output} \) that contains information about the optimization.

"Function Arguments" on page 9-2 contains general descriptions of arguments passed into \text{fminbnd}. This section provides function-specific details for \( \text{fun} \), \( \text{options} \), and \( \text{problem} \):

**fun**

The function to be minimized. \( \text{fun} \) is a function handle for a function that accepts a scalar \( x \) and returns a scalar \( f \), the objective function evaluated at \( x \). The function \( \text{fun} \) can be specified as a function handle for a file:

\[
x = \text{fminbnd}(\text{@myfun},x1,x2)
\]

where \( \text{myfun} \) is a MATLAB function such as

```matlab
function f = myfun(x)
f = ... % Compute function value at x.
```

\( \text{fun} \) can also be a function handle for an anonymous function.

\[
x = \text{fminbnd}(\text{@(x)sin(x^2)},x1,x2);
\]

**options**

"Options" on page 11-34 provides the function-specific details for the \( \text{options} \) values.
problem  f  Objective function
x1  Left endpoint
x2  Right endpoint
solver  'fminbnd'
options  Options structure created with optimset

Output Arguments

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by fminbnd. This section provides function-specific details for exitflag and output:

exitflag  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.
1          Function converged to a solution x.
0          Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
-1         Algorithm was terminated by the output function.
-2         The bounds are inconsistent.

output  Structure containing information about the optimization. The fields of the structure are
iterations  Number of iterations taken
funcCount  Number of function evaluations
algorithm  Optimization algorithm used
message  Exit message

Options

Optimization options used by fminbnd. You can use optimset to set or change the values of these fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Display</strong></td>
<td>Level of display. 'off' displays no output; 'iter' displays output at each iteration; 'final' displays just the final output; 'notify' (default) displays output only if the function does not converge.</td>
</tr>
<tr>
<td><strong>FunValCheck</strong></td>
<td>Check whether objective function values are valid. 'on' displays an error when the objective function returns a value that is complex, Inf, or NaN. The default 'off' displays no error.</td>
</tr>
<tr>
<td><strong>MaxFunEvals</strong></td>
<td>Maximum number of function evaluations allowed, a positive integer. The default is 500.</td>
</tr>
<tr>
<td><strong>MaxIter</strong></td>
<td>Maximum number of iterations allowed, a positive integer. The default is 500.</td>
</tr>
<tr>
<td><strong>OutputFcn</strong></td>
<td>Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([ ]). See “Output Function” on page 9-18.</td>
</tr>
<tr>
<td><strong>PlotFcns</strong></td>
<td>Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]).</td>
</tr>
<tr>
<td></td>
<td>- @optimplotx plots the current point</td>
</tr>
<tr>
<td></td>
<td>- @optimplotfunccount plots the function count</td>
</tr>
<tr>
<td></td>
<td>- @optimplotfval plots the function value</td>
</tr>
<tr>
<td><strong>TolX</strong></td>
<td>Termination tolerance on x, a positive scalar. The default is $1e^{-4}$.</td>
</tr>
</tbody>
</table>
Examples

A minimum of \( \sin(x) \) occurs at

\[
x = \text{fminbnd}(\@\sin, 0, 2\pi) \\
x = 4.7124
\]

The value of the function at the minimum is

\[
y = \sin(x) \\
y = -1.0000
\]

To find the minimum of the function

\[
f(x) = (x - 3)^2 - 1,
\]
on the interval \((0, 5)\), first write a function file.

```matlab
function f = myfun(x) 
    f = (x-3)^2 - 1;
end
```

Next, call an optimization routine.

\[
x = \text{fminbnd}(\@\text{myfun}, 0, 5)
\]

This generates the solution

\[
x = 3
\]

The value at the minimum is

\[
y = \text{myfun}(x) \\
y = -1
\]

If \texttt{fun} is parameterized, you can use anonymous functions to capture the problem-dependent parameters. For example, suppose you want to
minimize the objective function `myfun` defined by the following function file:

```matlab
function f = myfun(x,a)
    f = (x - a)^2;
```

Note that `myfun` has an extra parameter `a`, so you cannot pass it directly to `fminbnd`. To optimize for a specific value of `a`, such as `a = 1.5`.

1. Assign the value to `a`.
   ```matlab
   a = 1.5; % define parameter first
   ```

2. Call `fminbnd` with a one-argument anonymous function that captures that value of `a` and calls `myfun` with two arguments:
   ```matlab
   x = fminbnd(@(x) myfun(x,a),0,1)
   x =
   0.9999
   ```

**Algorithms**

`fminbnd` is a function file. The algorithm is based on golden section search and parabolic interpolation. Unless the left endpoint `x_1` is very close to the right endpoint `x_2`, `fminbnd` never evaluates `fun` at the endpoints, so `fun` need only be defined for `x` in the interval `x_1 < x < x_2`. If the minimum actually occurs at `x_1` or `x_2`, `fminbnd` returns an interior point at a distance of no more than `2*TolX` from `x_1` or `x_2`, where `TolX` is the termination tolerance. See [1] or [2] for details about the algorithm.

**Limitations**

The function to be minimized must be continuous. `fminbnd` might only give local solutions.

`fminbnd` often exhibits slow convergence when the solution is on a boundary of the interval. In such a case, `fmincon` often gives faster and more accurate solutions.

`fminbnd` only handles real variables.
References


See Also

fminsearch | fmincon | fminunc | optimset | optimtool

How To

- @ (function_handle)
- “Anonymous Functions”
Purpose
Find minimum of constrained nonlinear multivariable function

Equation
Finds the minimum of a problem specified by

\[
\min_f(x) \text{ such that } \begin{align*}
    c(x) &\leq 0 \\
    ceq(x) &= 0 \\
    A \cdot x &\leq b \\
    Aeq \cdot x &= beq \\
    lb &\leq x \leq ub,
\end{align*}
\]

\(x, b, beq, lb, \) and \(ub\) are vectors, \(A\) and \(Aeq\) are matrices, \(c(x)\) and \(ceq(x)\) are functions that return vectors, and \(f(x)\) is a function that returns a scalar. \(f(x), c(x),\) and \(ceq(x)\) can be nonlinear functions.

Syntax
\[
\begin{align*}
    x &= \text{fmincon}(\text{fun}, x0, A, b) \\
    x &= \text{fmincon}(\text{fun}, x0, A, b, Aeq, beq) \\
    x &= \text{fmincon}(\text{fun}, x0, A, b, Aeq, beq, lb, ub) \\
    x &= \text{fmincon}(\text{fun}, x0, A, b, Aeq, beq, lb, ub, nonlcon) \\
    x &= \text{fmincon}(\text{fun}, x0, A, b, Aeq, beq, lb, ub, nonlcon, options) \\
    x &= \text{fmincon}(\text{problem}) \\
    [x,fval] &= \text{fmincon}(...) \\
    [x,fval,exitflag] &= \text{fmincon}(...) \\
    [x,fval,exitflag,output] &= \text{fmincon}(...) \\
    [x,fval,exitflag,output,lambda] &= \text{fmincon}(...) \\
    [x,fval,exitflag,output,lambda,grad] &= \text{fmincon}(...) \\
    [x,fval,exitflag,output,lambda,grad,hessian] &= \text{fmincon}(...)
\end{align*}
\]

Description
fmincon attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as constrained nonlinear optimization or nonlinear programming.
**fmincon**

Note “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function and nonlinear constraint functions, if necessary.

\[
x = \text{fmincon}(\text{fun},x0,A,b)\text{ starts at }x0\text{ and attempts to find a minimizer }x\text{ of the function described in }\text{fun}\text{ subject to the linear inequalities }A*x \leq b.\] 
\[
x = \text{fmincon}(\text{fun},x0,A,b,Aeq,beq)\text{ minimizes }\text{fun}\text{ subject to the linear equalities }Aeq*x = beq\text{ and }A*x \leq b.\] 
\[
x = \text{fmincon}(\text{fun},x0,A,b,Aeq,beq,lb,ub)\text{ defines a set of lower and upper bounds on the design variables in }x\text{, so that the solution is always in the range }lb \leq x \leq ub.\] 
\[
\text{Note } \text{If the specified input bounds for a problem are inconsistent, the output }x\text{ is }x0\text{ and the output }fval\text{ is }[].
\]

Components of \(x0\) that violate the bounds \(lb \leq x \leq ub\) are reset to the interior of the box defined by the bounds. Components that respect the bounds are not changed.

See “Iterations Can Violate Constraints” on page 2-30.

\[
x = \text{fmincon}(\text{fun},x0,A,b,Aeq,beq,lb,ub,nonlcon)\text{ subjects the minimization to the nonlinear inequalities }c(x)\text{ or equalities }ceq(x)\text{ defined in }nonlcon. \text{fmincon optimizes such that }c(x) \leq 0\text{ and }ceq(x) = 0.\] 
\[
x = \text{fmincon}(\text{fun},x0,A,b,Aeq,beq,lb,ub,nonlcon,options)\text{ minimizes with the optimization options specified in the structure}
\]
options. Use optimset to set these options. If there are no nonlinear inequality or equality constraints, set nonlcon = [].

x = fmincon(problem) finds the minimum for problem, where problem is a structure described in “Input Arguments” on page 11-41. Create the problem structure by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = fmincon(...) returns the value of the objective function fun at the solution x.

[x,fval,exitflag] = fmincon(...) returns a value exitflag that describes the exit condition of fmincon.

[x,fval,exitflag,output] = fmincon(...) returns a structure output with information about the optimization.

[x,fval,exitflag,output,lambda] = fmincon(...) returns a structure lambda whose fields contain the Lagrange multipliers at the solution x.

[x,fval,exitflag,output,lambda,grad] = fmincon(...) returns the value of the gradient of fun at the solution x.

[x,fval,exitflag,output,lambda,grad,hessian] = fmincon(...) returns the value of the Hessian at the solution x. See “Hessian” on page 11-47.

**Input Arguments**

“Function Arguments” on page 9-2 describes the arguments passed to fmincon. “Options” on page 11-49 provides the function-specific details for the options values. This section provides function-specific details for fun, nonlcon, and problem.
The function to be minimized. `fun` is a function that accepts a vector `x` and returns a scalar `f`, the objective function evaluated at `x`. `fun` can be specified as a function handle for a file:

\[ x = \text{fmincon}(@\text{myfun},x_0,A,b) \]

where `myfun` is a MATLAB function such as

```matlab
function f = myfun(x)
f = ... % Compute function value at x
```

`fun` can also be a function handle for an anonymous function:

\[ x = \text{fmincon}(@(x)\|x\|^2,x_0,A,b); \]

If the gradient of `fun` can also be computed and the `GradObj` option is `'on'`, as set by

```matlab
options = \text{optimset}('GradObj','on')
```

then `fun` must return the gradient vector `g(x)` in the second output argument.

If the Hessian matrix can also be computed and the `Hessian` option is `'on'` via options = `optimset('Hessian', 'user-supplied')` and the `Algorithm` option is `trust-region-reflective`, `fun` must return the Hessian value `H(x)`, a symmetric matrix, in a third output argument. `fun` can give a sparse Hessian. See “Writing Objective Functions” on page 2-16 for details.

If the Hessian matrix can be computed and the `Algorithm` option is `interior-point`, there are several ways to pass the Hessian to `fmincon`. For more information, see “Hessian” on page 11-47.

Linear constraint matrices `A` and `Aeq`, and their corresponding vectors `b` and `beq`, can be sparse or dense. The `trust-region-reflective` and `interior-point` algorithms use sparse linear algebra. If `A` or `Aeq` is large, with relatively few nonzero entries, save running time and memory in the `trust-region-reflective` or `interior-point` algorithms by using sparse matrices.
The function that computes the nonlinear inequality constraints \( c(x) \leq 0 \) and the nonlinear equality constraints \( ceq(x) = 0 \). `nonlcon` accepts a vector \( x \) and returns the two vectors \( c \) and \( ceq \). \( c \) is a vector that contains the nonlinear inequalities evaluated at \( x \), and \( ceq \) is a vector that contains the nonlinear equalities evaluated at \( x \). `nonlcon` should be specified as a function handle to a file or to an anonymous function, such as `mycon`:

\[
x = \text{fmincon}(@\text{myfun},x0,A,b,Aeq,beq,lb,ub,@\text{mycon})
\]

where `mycon` is a MATLAB function such as

```matlab
function [c,ceq] = mycon(x)
c = ...  % Compute nonlinear inequalities at x.
ceq = ... % Compute nonlinear equalities at x.
```

If the gradients of the constraints can also be computed and the `GradConstr` option is 'on', as set by

```matlab
options = optimset('GradConstr','on')
```

then `nonlcon` must also return, in the third and fourth output arguments, \( GC \), the gradient of \( c(x) \), and \( GCeq \), the gradient of \( ceq(x) \). \( GC \) and \( GCeq \) can be sparse or dense. If \( GC \) or \( GCeq \) is large, with relatively few nonzero entries, save running time and memory in the interior-point algorithm by representing them as sparse matrices. For more information, see “Nonlinear Constraints” on page 2-33.

**Note** Because Optimization Toolbox functions only accept inputs of type `double`, user-supplied objective and nonlinear constraint functions must return outputs of type `double`. 
### fmincon

<table>
<thead>
<tr>
<th>problem</th>
<th>objective</th>
<th>Objective function</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>Initial point for ( x )</td>
<td></td>
</tr>
<tr>
<td>Aineq</td>
<td>Matrix for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>bineq</td>
<td>Vector for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>Aeq</td>
<td>Matrix for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>beq</td>
<td>Vector for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
<tr>
<td>ub</td>
<td>Vector of upper bounds</td>
<td></td>
</tr>
<tr>
<td>nonlcon</td>
<td>Nonlinear constraint function</td>
<td></td>
</tr>
<tr>
<td>solver</td>
<td>'fmincon'</td>
<td></td>
</tr>
<tr>
<td>options</td>
<td>Options structure created with optimset</td>
<td></td>
</tr>
</tbody>
</table>

#### Output Arguments

“Function Arguments” on page 9-2 describes arguments returned by fmincon. This section provides function-specific details for exitflag, lambda, and output:

<table>
<thead>
<tr>
<th>exitflag</th>
<th>Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Algorithms:</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>First-order optimality measure was less than options.TolFun, and maximum constraint violation was less than options.TolCon.</td>
</tr>
<tr>
<td>0</td>
<td>Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.</td>
</tr>
</tbody>
</table>
-1 The output function terminated the algorithm.

-2 No feasible point was found.

**trust-region-reflective** and **interior-point** algorithms:

2 Change in x was less than options.TolX and maximum constraint violation was less than options.TolCon.

**trust-region-reflective** algorithm only:

3 Change in the objective function value was less than options.TolFun and maximum constraint violation was less than options.TolCon.

**active-set** algorithm only:

4 Magnitude of the search direction was less than 2*options.TolX and maximum constraint violation was less than options.TolCon.

5 Magnitude of directional derivative in search direction was less than 2*options.TolFun and maximum constraint violation was less than options.TolCon.

**interior-point** algorithm only:

-3 Current point x went below options.ObjectiveLimit and maximum constraint violation was less than options.TolCon.
Gradient at $x$

Hessian at $x$

Structure containing the Lagrange multipliers at the solution $x$ (separated by constraint type). The fields of the structure are:

- `lower`: Lower bounds $lb$
- `upper`: Upper bounds $ub$
- `ineqlin`: Linear inequalities
- `eqlin`: Linear equalities
- `ineqnonlin`: Nonlinear inequalities
- `eqnonlin`: Nonlinear equalities

Structure containing information about the optimization. The fields of the structure are:

- `iterations`: Number of iterations taken
- `funcCount`: Number of function evaluations
- `lssteplength`: Size of line search step relative to search direction (active-set algorithm only)
- `constrviolation`: Maximum of constraint functions
- `stepsize`: Length of last displacement in $x$ (active-set and interior-point algorithms)
- `algorithm`: Optimization algorithm used
- `cgiterations`: Total number of PCG iterations (trust-region-reflective and interior-point algorithms)
- `firstorderopt`: Measure of first-order optimality
- `message`: Exit message
The **fmincon** algorithms handle Hessians differently:

- The **active-set** and **sqp** algorithms do not accept a user-supplied Hessian. They compute a quasi-Newton approximation to the Hessian of the Lagrangian.

- The **trust-region-reflective** can accept a user-supplied Hessian as the final output of the objective function. Since this algorithm has only bounds or linear constraints, the Hessian of the Lagrangian is same as the Hessian of the objective function. See “Writing Scalar Objective Functions” on page 2-17 for details on how to pass the Hessian to **fmincon**. Indicate that you are supplying a Hessian by

  ```matlab
  options = optimset('Hessian','user-supplied');
  ```

  If you do not pass a Hessian, the algorithm computes a finite-difference approximation.

- The **interior-point** algorithm can accept a user-supplied Hessian as a separately defined function—it is not computed in the objective function. The syntax is

  ```matlab
  hessian = hessianfcn(x, lambda)
  ```

  `hessian` is an `n`-by-`n` matrix, sparse or dense, where `n` is the number of variables. If `hessian` is large and has relatively few nonzero entries, save running time and memory by representing `hessian` as a sparse matrix. `lambda` is a structure with the Lagrange multiplier vectors associated with the nonlinear constraints:

  ```matlab
  lambda.ineqnonlin
  lambda.eqnonlin
  ```

---

**Hessian**

**fmincon** uses a Hessian, the second derivatives of the Lagrangian (see Equation 3-1), namely,

\[
\nabla^2_{xx} L(x, \lambda) = \nabla^2 f(x) + \sum \lambda_i \nabla^2 c_i(x) + \sum \lambda_i \nabla^2 ceq_i(x).
\]

(11-1)

The **fmincon** algorithms handle Hessians differently:

- The **active-set** and **sqp** algorithms do not accept a user-supplied Hessian. They compute a quasi-Newton approximation to the Hessian of the Lagrangian.

- The **trust-region-reflective** can accept a user-supplied Hessian as the final output of the objective function. Since this algorithm has only bounds or linear constraints, the Hessian of the Lagrangian is same as the Hessian of the objective function. See “Writing Scalar Objective Functions” on page 2-17 for details on how to pass the Hessian to **fmincon**. Indicate that you are supplying a Hessian by

  ```matlab
  options = optimset('Hessian','user-supplied');
  ```

  If you do not pass a Hessian, the algorithm computes a finite-difference approximation.

- The **interior-point** algorithm can accept a user-supplied Hessian as a separately defined function—it is not computed in the objective function. The syntax is

  ```matlab
  hessian = hessianfcn(x, lambda)
  ```

  `hessian` is an `n`-by-`n` matrix, sparse or dense, where `n` is the number of variables. If `hessian` is large and has relatively few nonzero entries, save running time and memory by representing `hessian` as a sparse matrix. `lambda` is a structure with the Lagrange multiplier vectors associated with the nonlinear constraints:

  ```matlab
  lambda.ineqnonlin
  lambda.eqnonlin
  ```

---

**fmincon**
fmincon computes the structure lambda. hessianfcn must calculate the sums in Equation 11-1. Indicate that you are supplying a Hessian by

\[
\text{options} = \text{optimset('Hessian','user-supplied',... 'HessFcn',@hessianfcn)};
\]

For an example, see “Example: Constrained Minimization Using fmincon’s Interior-Point Algorithm with Analytic Hessian” on page 6-53.

The interior-point algorithm has several more options for Hessians:

- **options = optimset('Hessian','lbfgs');**
  fmincon calculates the Hessian by a limited-memory, large-scale quasi-Newton approximation.

- **options = optimset('Hessian',{'lbfgs',positive integer});**
  fmincon calculates the Hessian by a limited-memory, large-scale quasi-Newton approximation. The positive integer specifies how many past iterations should be remembered.

- **options = optimset('Hessian','lbfgs');**
  fmincon calculates the Hessian by a limited-memory, large-scale quasi-Newton approximation. The default memory, 10 iterations, is used.

- **options = optimset('Hessian','fin-diff-grads',... 'SubproblemAlgorithm','cg','GradObj','on',... 'GradConstr','on');**
  fmincon calculates a Hessian-times-vector product by finite differences of the gradient(s). You must supply the gradient of the objective function, and also gradients of nonlinear constraints if they exist.

- **options = optimset('Hessian','user-supplied',... 'SubproblemAlgorithm','cg','HessMult',@HessMultFcn);**
fmincon uses a Hessian-times-vector product. You must supply the function HessMultFcn, which returns an \( n \)-by-1 vector. The HessMult option enables you to pass the result of multiplying the Hessian by a vector without calculating the Hessian.

The 'HessMult' option for the interior-point algorithm has a different syntax than that of the trust-region-reflective algorithm. The syntax for the interior-point algorithm is

\[
W = \text{HessMultFcn}(x, \lambda, v);
\]

The result \( W \) should be the product \( H \cdot v \), where \( H \) is the Hessian at \( x \), \( \lambda \) is the Lagrange multiplier (computed by \textit{fmincon} ), and \( v \) is a vector. In contrast, the syntax for the trust-region-reflective algorithm does not involve \( \lambda \):

\[
W = \text{HessMultFcn}(H, v);
\]

Again, the result \( W = H \cdot v \). \( H \) is the function returned in the third output of the objective function (see “Writing Scalar Objective Functions” on page 2-17), and \( v \) is a vector. \( H \) does not have to be the Hessian; rather, it can be any function that enables you to calculate \( W = H \cdot v \). For an example using a Hessian multiply function with the trust-region-reflective algorithm, see “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68.

**Options**

Optimization options used by \textit{fmincon}. Some options apply to all algorithms, and others are relevant for particular algorithms. You can use \textit{optimset} to set or change the values of these fields in the structure \textit{options}. See “Optimization Options Reference” on page 9-7 for detailed information.

\textit{fmincon} uses one of four algorithms: active-set, interior-point, sqp, or trust-region-reflective. Choose the algorithm at the command line with \textit{optimset}. For example:

\[
\text{options} = \text{optimset}('\text{Algorithm}', '\text{active-set}');
\]
The default trust-region-reflective requires:

- A gradient to be supplied in the objective function
- GradObj to be set to 'on'
- Either bound constraints or linear equality constraints, but not both

If these conditions are not all satisfied, the active-set algorithm is the default.

The active-set algorithm is not a large-scale algorithm.

**All Algorithms**

All four algorithms use these options:

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Choose the optimization algorithm:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• 'trust-region-reflective' (default)</td>
</tr>
<tr>
<td></td>
<td>• 'active-set'</td>
</tr>
<tr>
<td></td>
<td>• 'interior-point'</td>
</tr>
<tr>
<td></td>
<td>• 'sqp'</td>
</tr>
</tbody>
</table>

For information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

- **DerivativeCheck** Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default, 'off'.

- **Diagnostics** Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default, 'off'.

- **DiffMaxChange** Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.
DiffMinChange Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.

Display Level of display:

- 'off' displays no output.
- 'iter' displays output at each iteration, and gives the default exit message.
- 'iter-detailed' displays output at each iteration, and gives the technical exit message.
- 'notify' displays output only if the function does not converge, and gives the default exit message.
- 'notify-detailed' displays output only if the function does not converge, and gives the technical exit message.
- 'final' (default) displays just the final output, and gives the default exit message.
- 'final-detailed' displays just the final output, and gives the technical exit message.
FinDiffRelStep  
Scalar or vector step size factor. When you set FinDiffRelStep to a vector $v$, forward finite differences $\delta$ are

$$
\delta = v \cdot \text{sign}(x) \cdot \max(\text{abs}(x),\text{TypicalX}) ;
$$

and central finite differences are

$$
\delta = v \cdot \max(\text{abs}(x),\text{TypicalX}) ;
$$

Scalar FinDiffRelStep expands to a vector. The default is $\sqrt{\text{eps}}$ for forward finite differences, and $\text{eps}^{(1/3)}$ for central finite differences.

FinDiffType  
Finite differences, used to estimate gradients, are either 'forward' (default), or 'central' (centered). 'central' takes twice as many function evaluations but should be more accurate.

fmincon is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds. However, for the interior-point algorithm, 'central' differences might violate bounds during their evaluation if the AlwaysHonorConstraints option is set to 'none'.

FunValCheck  
Check whether objective function and constraints values are valid. 'on' displays an error when the objective function or constraints return a value that is complex, Inf, or NaN. The default, 'off', displays no error.
GradConstr: Gradient for nonlinear constraint functions defined by the user. When set to 'on', fmincon expects the constraint function to have four outputs, as described in nonlcon in the “Input Arguments” on page 11-41 section. When set to the default, 'off', gradients of the nonlinear constraints are estimated by finite differences. The trust-region-reflective algorithm does not accept nonlinear constraints.

GradObj: Gradient for the objective function defined by the user. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have fmincon use a user-defined gradient of the objective function. The default, 'off', causes fmincon to estimate gradients using finite differences. You must provide the gradient, and set GradObj to 'on', to use the trust-region-reflective method.

MaxFunEvals: Maximum number of function evaluations allowed, a positive integer. The default value for all algorithms except interior-point is 100*numberOfVariables; for the interior-point algorithm the default is 3000.

MaxIter: Maximum number of iterations allowed, a positive integer. The default value for all algorithms except interior-point is 400; for the interior-point algorithm the default is 1000.

OutputFcn: Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.
<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PlotFcns</strong></td>
<td>Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([]).</td>
</tr>
<tr>
<td></td>
<td>- @optimplotx plots the current point</td>
</tr>
<tr>
<td></td>
<td>- @optimplotfunccount plots the function count</td>
</tr>
<tr>
<td></td>
<td>- @optimplotfval plots the function value</td>
</tr>
<tr>
<td></td>
<td>- @optimplotconstrviolation plots the maximum constraint violation</td>
</tr>
<tr>
<td></td>
<td>- @optimplotstepsize plots the step size</td>
</tr>
<tr>
<td></td>
<td>- @optimplotfirstorderopt plots the first-order optimality measure</td>
</tr>
<tr>
<td></td>
<td>For information on writing a custom plot function, see “Plot Functions” on page 9-27.</td>
</tr>
<tr>
<td><strong>TolFun</strong></td>
<td>Termination tolerance on the function value, a positive scalar. The default is 1e-6.</td>
</tr>
<tr>
<td><strong>TolCon</strong></td>
<td>Tolerance on the constraint violation, a positive scalar. The default is 1e-6.</td>
</tr>
<tr>
<td><strong>TolX</strong></td>
<td>Termination tolerance on x, a positive scalar. The default value for all algorithms except interior-point is 1e-6; for the interior-point algorithm the default is 1e-10.</td>
</tr>
</tbody>
</table>
TypicalX  
Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). fmincon uses TypicalX for scaling finite differences for gradient estimation.

The 'trust-region-reflective' algorithm uses TypicalX only for the DerivativeCheck option.

UseParallel  
When 'always', estimate gradients in parallel. Disable by setting to the default, 'never'. trust-region-reflective requires a gradient in the objective, so UseParallel does not apply.

---

**Trust-Region-Reflective Algorithm**

The trust-region-reflective algorithm uses these options:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hessian</td>
<td>If 'on', fmincon uses a user-defined Hessian (defined in fun), or Hessian information (when using HessMult), for the objective function. If 'off' (default), fmincon approximates the Hessian using finite differences.</td>
</tr>
<tr>
<td>HessMult</td>
<td>Function handle for Hessian multiply function. For large-scale structured problems, this function computes the Hessian matrix product H*Y without actually forming H. The function is of the form</td>
</tr>
</tbody>
</table>

\[ W = \text{hmfun}(\text{Hinfo}, Y) \]

where Hinfo contains a matrix used to compute H*Y.
The first argument must be the same as the third argument returned by the objective function `fun`, for example:

```
[f,g,Hinfo] = fun(x)
```

`Y` is a matrix that has the same number of rows as there are dimensions in the problem. `W = H*Y`, although `H` is not formed explicitly. `fmincon` uses `Hinfo` to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply values for any additional parameters that `hmfun` needs.

**Note** Hessian must be set to 'on' for `fmincon` to pass `Hinfo` from `fun` to `hmfun`.

See “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68 for an example.

**HessPattern**

Sparsity pattern of the Hessian for finite differencing. If it is not convenient to compute the sparse Hessian matrix `H` in `fun`, the trust-region-reflective method in `fmincon` can approximate `H` via sparse finite differences (of the gradient) provided that you supply the *sparsity structure* of `H`—i.e., locations of the nonzeros—as the value for `HessPattern`. In the worst case, if the structure is unknown, you can set `HessPattern` to be a dense matrix and a full finite-difference approximation is computed at each iteration (this is the default). This can be very expensive for large problems,
so it is usually worth the effort to determine the sparsity structure.

**MaxPCGIter**
Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is \( \max(1, \text{floor}(\text{numberOfVariables}/2)) \). For more information, see “Preconditioned Conjugate Gradient Method” on page 6-24.

**PrecondBandWidth**
Upper bandwidth of preconditioner for PCG, a nonnegative integer. By default, diagonal preconditioning is used (upper bandwidth of 0). For some problems, increasing the bandwidth reduces the number of PCG iterations. Setting **PrecondBandWidth** to Inf uses a direct factorization (Cholesky) rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution.

**TolPCG**
Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.
Active-Set Algorithm

The active-set algorithm uses these options:

MaxSQPIter  Maximum number of SQP iterations allowed, a positive integer. The default is $10 \times \max(\text{numberOfVariables}, \text{numberOfInequalities} + \text{numberOfBounds})$.

RelLineSrchBnd  Relative bound (a real nonnegative scalar value) on the line search step length such that the total displacement in $x$ satisfies $|\Delta x(i)| \leq \text{relLineSrchBnd} \times \max(|x(i)|, |\text{typical}x(i)|)$. This option provides control over the magnitude of the displacements in $x$ for cases in which the solver takes steps that are considered too large. The default is no bounds ($[]$).

RelLineSrchBndDuration  Number of iterations for which the bound specified in RelLineSrchBnd should be active (default is 1).

TolConSQP  Termination tolerance on inner iteration SQP constraint violation, a positive scalar. The default is $1e^{-6}$.

Interior-Point Algorithm

The interior-point algorithm uses these options:
AlwaysHonorConstraints  The default 'bounds' ensures that bound constraints are satisfied at every iteration. Disable by setting to 'none'.

HessFcn  Function handle to a user-supplied Hessian (see “Hessian” on page 11-47). This is used when the Hessian option is set to 'user-supplied'.

Hessian  Chooses how fmincon calculates the Hessian (see “Hessian” on page 11-47). The choices are:

- 'bfgs' (default)
- 'fin-diff-grads'
- 'lbfgs'
- {'lbfgs',Positive Integer}
- 'user-supplied'

HessMult  Handle to a user-supplied function that gives a Hessian-times-vector product (see “Hessian” on page 11-47). This is used when the Hessian option is set to 'user-supplied'.

InitBarrierParam  Initial barrier value, a positive scalar. Sometimes it might help to try a value above the default 0.1, especially if the objective or constraint functions are large.

InitTrustRegionRadius  Initial radius of the trust region, a positive scalar. On badly scaled problems it might help to choose a value smaller than the default $\sqrt{n}$, where $n$ is the number of variables.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MaxProjCGIter</td>
<td>A tolerance (stopping criterion) for the number of projected conjugate gradient iterations; this is an inner iteration, not the number of iterations of the algorithm. This positive integer has a default value of 2*(numberOfVariables - numberOfEqualities).</td>
</tr>
<tr>
<td>ObjectiveLimit</td>
<td>A tolerance (stopping criterion) that is a scalar. If the objective function value goes below ObjectiveLimit and the iterate is feasible, the iterations halt, since the problem is presumably unbounded. The default value is -1e20.</td>
</tr>
<tr>
<td>ScaleProblem</td>
<td>'obj-and-constr' causes the algorithm to normalize all constraints and the objective function. Disable by setting to the default 'none'.</td>
</tr>
<tr>
<td>SubproblemAlgorithm</td>
<td>Determines how the iteration step is calculated. The default, 'ldl-factorization', is usually faster than 'cg' (conjugate gradient), though 'cg' might be faster for large problems with dense Hessians.</td>
</tr>
<tr>
<td>TolProjCG</td>
<td>A relative tolerance (stopping criterion) for projected conjugate gradient algorithm; this is for an inner iteration, not the algorithm iteration. This positive scalar has a default of 0.01.</td>
</tr>
<tr>
<td>TolProjCGAbs</td>
<td>Absolute tolerance (stopping criterion) for projected conjugate gradient algorithm; this is for an inner iteration, not the algorithm iteration. This positive scalar has a default of 1e-10.</td>
</tr>
</tbody>
</table>
**SQP Algorithm**

The sqp algorithm uses these options:

- **ObjectiveLimit**: A tolerance (stopping criterion) that is a scalar. If the objective function value goes below `ObjectiveLimit` and the iterate is feasible, the iterations halt, since the problem is presumably unbounded. The default value is `-1e20`.

- **ScaleProblem**: 'obj-and-constr' causes the algorithm to normalize all constraints and the objective function. Disable by setting to the default 'none'.

**Examples**

Find values of $x$ that minimize $f(x) = -x_1 x_2 x_3$, starting at the point $x = [10;10;10]$, subject to the constraints:

$0 \leq x_1 + 2x_2 + 2x_3 \leq 72$.

1. Write a file that returns a scalar value $f$ of the objective function evaluated at $x$:

   ```matlab
   function f = myfun(x)
   f = -x(1) * x(2) * x(3);
   ```

2. Rewrite the constraints as both less than or equal to a constant,

   $-x_1 - 2x_2 - 2x_3 \leq 0$
   $x_1 + 2x_2 + 2x_3 \leq 72$

3. Since both constraints are linear, formulate them as the matrix inequality $Ax \leq b$, where

   ```matlab
   A = [-1 -2 -2; 1 2 2];
   b = [0;72];
   ```
Supply a starting point and invoke an optimization routine:

\[ x0 = [10;10;10]; \quad \% \text{Starting guess at the solution} \]
\[
[x,fval] = \text{fmincon}(\text{@myfun},x0,A,b);
\]

After 11 iterations, the solution is

\[ x =
\begin{align*}
24.0000 \\
12.0000 \\
12.0000
\end{align*}
\]

where the function value is

\[ fval = -3.4560e+03 \]

and linear inequality constraints evaluate to be less than or equal to 0:

\[ A*x-b \]
\[
\begin{align*}
\text{ans} &= -72 \\
&\quad 0
\end{align*}
\]

Notes  
Trust-Region-Reflective Optimization

To use the trust-region-reflective algorithm, you must

- Supply the gradient of the objective function in \text{fun}.
- Set GradObj to 'on' in options.
- Specify the feasible region using one, but not both, of the following types of constraints:
  - Upper and lower bounds constraints
- Linear equality constraints, in which the equality constraint matrix \( A_{eq} \) cannot have more rows than columns

You cannot use inequality constraints with the trust-region-reflective algorithm. If the preceding conditions are not met, \texttt{fmincon} reverts to the active-set algorithm.

\texttt{fmincon} returns a warning if you do not provide a gradient and the \texttt{Algorithm} option is \texttt{trust-region-reflective}. \texttt{fmincon} permits an approximate gradient to be supplied, but this option is not recommended; the numerical behavior of most optimization methods is considerably more robust when the true gradient is used.

The trust-region-reflective method in \texttt{fmincon} is in general most effective when the matrix of second derivatives, i.e., the Hessian matrix \( H(x) \), is also computed. However, evaluation of the true Hessian matrix is not required. For example, if you can supply the Hessian sparsity structure (using the \texttt{HessPattern} option in \texttt{options}), \texttt{fmincon} computes a sparse finite-difference approximation to \( H(x) \).

If \( x_0 \) is not strictly feasible, \texttt{fmincon} chooses a new strictly feasible (centered) starting point.

If components of \( x \) have no upper (or lower) bounds, \texttt{fmincon} prefers that the corresponding components of \( ub \) (or \( lb \)) be set to \( \text{Inf} \) (or \( -\text{Inf} \) for \( lb \)) as opposed to an arbitrary but very large positive (or negative in the case of lower bounds) number.

Take note of these characteristics of linearly constrained minimization:

- A dense (or fairly dense) column of matrix \( A_{eq} \) can result in considerable fill and computational cost.
- \texttt{fmincon} removes (numerically) linearly dependent rows in \( A_{eq} \); however, this process involves repeated matrix factorizations and therefore can be costly if there are many dependencies.
- Each iteration involves a sparse least-squares solution with matrix

\[
\bar{A}_{eq} = A_{eq}^T R^T,
\]
where $R^T$ is the Cholesky factor of the preconditioner. Therefore, there is a potential conflict between choosing an effective preconditioner and minimizing fill in $\overline{A_{eq}}$.

**Active-Set Optimization**

If equality constraints are present and dependent equalities are detected and removed in the quadratic subproblem, 'dependent' appears under the Procedures heading (when you ask for output by setting the Display option to 'iter'). The dependent equalities are only removed when the equalities are consistent. If the system of equalities is not consistent, the subproblem is infeasible and 'infeasible' appears under the Procedures heading.

**Algorithms**

**Trust-Region-Reflective Optimization**

The trust-region-reflective algorithm is a subspace trust-region method and is based on the interior-reflective Newton method described in [3] and [4]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). See the trust-region and preconditioned conjugate gradient method descriptions in “fmincon Trust Region Reflective Algorithm” on page 6-21.

**Active-Set Optimization**

`fmincon` uses a sequential quadratic programming (SQP) method. In this method, the function solves a quadratic programming (QP) subproblem at each iteration. `fmincon` updates an estimate of the Hessian of the Lagrangian at each iteration using the BFGS formula (see `fminunc` and references [7] and [8]).

`fmincon` performs a line search using a merit function similar to that proposed by [6], [7], and [8]. The QP subproblem is solved using an active set strategy similar to that described in [5]. “fmincon Active Set Algorithm” on page 6-27 describes this algorithm in detail.

See also “SQP Implementation” on page 6-30 for more details on the algorithm used.
**Interior-Point Optimization**

This algorithm is described in “fmincon Interior Point Algorithm” on page 6-38. There is more extensive description in [1], [41], and [9].

**SQP Optimization**

The `fmincon 'sqp'` algorithm is similar to the 'active-set' algorithm described in “Active-Set Optimization” on page 11-64. “fmincon SQP Algorithm” on page 6-37 describes the main differences. In summary, these differences are:

- “Strict Feasibility With Respect to Bounds” on page 6-37
- “Robustness to Non-Multiple Results” on page 6-37
- “Refactored Linear Algebra Routines” on page 6-37
- “Reformulated Feasibility Routines” on page 6-37

**Limitations**

`fmincon` is a gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives.

When the problem is infeasible, `fmincon` attempts to minimize the maximum constraint value.

The trust-region-reflective algorithm does not allow equal upper and lower bounds. For example, if `lb(2)==ub(2)`, `fmincon` gives this error:

```
Equal upper and lower bounds not permitted in this large-scale method.
Use equality constraints and the medium-scale method instead.
```

There are two different syntaxes for passing a Hessian, and there are two different syntaxes for passing a `HessMult` function; one for trust-region-reflective, and another for interior-point.
For trust-region-reflective, the Hessian of the Lagrangian is the same as the Hessian of the objective function. You pass that Hessian as the third output of the objective function.

For interior-point, the Hessian of the Lagrangian involves the Lagrange multipliers and the Hessians of the nonlinear constraint functions. You pass the Hessian as a separate function that takes into account both the position $x$ and the Lagrange multiplier structure $\lambda$.

**Trust-Region-Reflective Coverage and Requirements**

<table>
<thead>
<tr>
<th>Additional Information Needed</th>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must provide gradient for $f(x)$ in <code>fun</code>.</td>
<td>• Provide sparsity structure of the Hessian or compute the Hessian in <code>fun</code>.</td>
</tr>
<tr>
<td></td>
<td>• The Hessian should be sparse.</td>
</tr>
<tr>
<td></td>
<td>• $A_{eq}$ should be sparse.</td>
</tr>
</tbody>
</table>

**References**


**See Also**
- `fminbnd`
- `fminsearch`
- `fminunc`
- `optimset`
- `optimtool`
- `fmincon`

**How To**
- `@(function_handle)`
- “Constrained Nonlinear Optimization Algorithms” on page 6-21
- “Constrained Nonlinear Optimization Examples” on page 6-47
**fminimax**

**Purpose**
Solve minimax constraint problem

**Equation**
Finds the minimum of a problem specified by

\[
\min_{x} \max_{i} F_i(x) \quad \text{such that} \quad \begin{cases} 
  c(x) \leq 0 \\
  ceq(x) = 0 \\
  A \cdot x \leq b \\
  Aeq \cdot x = beq \\
  lb \leq x \leq ub 
\end{cases}
\]

where \( x, b, beq, lb, \) and \( ub \) are vectors, \( A \) and \( Aeq \) are matrices, and \( c(x), ceq(x), \) and \( F(x) \) are functions that return vectors. \( F(x), c(x), \) and \( ceq(x) \) can be nonlinear functions.

You can also solve max-min problems with \texttt{fminimax}, using the identity

\[
\max_{x} \min_{i} F_i(x) = -\min_{x} \max_{i} (-F_i(x)).
\]

You can solve problems of the form

\[
\min_{x} \max_{i} |F_i(x)|
\]

by using the MinAbsMax option; see “Notes” on page 11-82.

**Syntax**

\[
\begin{align*}
  x &= \texttt{fminimax}(\texttt{fun},x0) \\
  x &= \texttt{fminimax}(\texttt{fun},x0,A,b) \\
  x &= \texttt{fminimax}(\texttt{fun},x,A,b,Aeq,beq) \\
  x &= \texttt{fminimax}(\texttt{fun},x,A,b,Aeq,beq,lb,ub) \\
  x &= \texttt{fminimax}(\texttt{fun},x0,A,b,Aeq,beq,lb,ub,\texttt{nonlcon}) \\
  x &= \texttt{fminimax}(\texttt{fun},x0,A,b,Aeq,beq,lb,ub,\texttt{nonlcon},\texttt{options}) \\
  x &= \texttt{fminimax}(\texttt{problem}) \\
  [x,fval] &= \texttt{fminimax}(...) \\
  [x,fval,maxfval] &= \texttt{fminimax}(...) \\
  [x,fval,maxfval,exitflag] &= \texttt{fminimax}(...) \\
  [x,fval,maxfval,exitflag,output] &= \texttt{fminimax}(...) \\
  [x,fval,maxfval,exitflag,output,lambda] &= \texttt{fminimax}(...)
\end{align*}
\]
Description

fminimax minimizes the worst-case (largest) value of a set of multivariable functions, starting at an initial estimate. This is generally referred to as the minimax problem.

Note “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective functions and nonlinear constraint functions, if necessary.

\[ x = \text{fminimax}(\text{fun},x0) \] starts at \( x0 \) and finds a minimax solution \( x \) to the functions described in \( \text{fun} \).

\[ x = \text{fminimax}(\text{fun},x0,A,b) \] solves the minimax problem subject to the linear inequalities \( Ax \leq b \).

\[ x = \text{fminimax}(\text{fun},x,A,b,Aeq,beq) \] solves the minimax problem subject to the linear equalities \( Aeqx = beq \) as well. Set \( A = [\] \) and \( b = [\] \) if no inequalities exist.

\[ x = \text{fminimax}(\text{fun},x,A,b,Aeq,beq,lb,ub) \] defines a set of lower and upper bounds on the design variables in \( x \), so that the solution is always in the range \( lb \leq x \leq ub \).

Note See “Iterations Can Violate Constraints” on page 2-30.

\[ x = \text{fminimax}(\text{fun},x0,A,b,Aeq,beq,lb,ub,\text{nonlcon}) \] subjects the minimax problem to the nonlinear inequalities \( c(x) \) or equality constraints \( ceq(x) \) defined in \( \text{nonlcon} \). \( \text{fminimax} \) optimizes such that \( c(x) \leq 0 \) and \( ceq(x) = 0 \). Set \( lb = [\] \) and/or \( ub = [\] \) if no bounds exist.

\[ x = \text{fminimax}(\text{fun},x0,A,b,Aeq,beq,lb,ub,\text{nonlcon},\text{options}) \] minimizes with the optimization options specified in the structure \( \text{options} \). Use \( \text{optimset} \) to set these options.
x = fminimax(problem) finds the minimum for problem, where
problem is a structure described in “Input Arguments” on page 11-70.

Create the structure problem by exporting a problem from Optimization
Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = fminimax(...) returns the value of the objective function
fun at the solution x.

[x,fval,maxfval] = fminimax(...) returns the maximum of the
objective functions in the input fun evaluated at the solution x.

[x,fval,maxfval,exitflag] = fminimax(...) returns a value
exitflag that describes the exit condition of fminimax.

[x,fval,maxfval,exitflag,output] = fminimax(...) returns a
structure output with information about the optimization.

[x,fval,maxfval,exitflag,output,lambda] = fminimax(...) returns a structure lambda whose fields contain the Lagrange
multipliers at the solution x.

Note If the specified input bounds for a problem are inconsistent, the
output x is x0 and the output fval is [].

Input
Arguments

“Function Arguments” on page 9-2 contains general descriptions of
arguments passed into fminimax. This section provides function-specific
details for fun, nonlcon, and problem:
fun

The function to be minimized. \texttt{fun} is a function that accepts a vector \texttt{x} and returns a vector \texttt{F}, the objective functions evaluated at \texttt{x}. The function \texttt{fun} can be specified as a function handle for a file:

\[
x = \text{fminimax}(\text{@myfun},x0)
\]

where \texttt{myfun} is a MATLAB function such as

\begin{verbatim}
function F = myfun(x)
    F = ... % Compute function values at x
\end{verbatim}

\texttt{fun} can also be a function handle for an anonymous function.

\[
x = \text{fminimax}(\text@(x)\text{sin}(x.*x),x0);
\]

If the user-defined values for \texttt{x} and \texttt{F} are matrices, they are converted to a vector using linear indexing.

To minimize the worst case absolute values of any of the elements of the vector \texttt{F(x)} (i.e., \(\min\{\max \abs{F(x)}\}\)), partition those objectives into the first elements of \texttt{F} and use \texttt{optimset} to set the \texttt{MinAbsMax} option to be the number of such objectives.

If the gradient of the objective function can also be computed \textit{and} the \texttt{GradObj} option is \texttt{'on'}, as set by

\[
\text{options} = \text{optimset}('GradObj','on')
\]

then the function \texttt{fun} must return, in the second output argument, the gradient value \texttt{G}, a matrix, at \texttt{x}. The gradient consists of the partial derivative \(dF/dx\) of each \texttt{F} at the point \texttt{x}. If \texttt{F} is a vector of length \texttt{m} and \texttt{x} has length \texttt{n}, where \texttt{n} is the length of \texttt{x0}, then the gradient \texttt{G} of \texttt{F(x)} is an \texttt{n}\text{-by-}\texttt{m} matrix where \texttt{G(i,j)} is the partial derivative of \texttt{F(j)} with respect to \texttt{x(i)} (i.e., the \texttt{j}th column of \texttt{G} is the gradient of the \texttt{j}th objective function \texttt{F(j)}).

By checking the value of \texttt{nargout}, the function can avoid computing \texttt{G} when \texttt{myfun} is called with only one output argument (in the case where the optimization algorithm only needs the value of \texttt{F} but not \texttt{G}).
function [F,G] = myfun(x)
F = ... % Compute the function values at x
if nargout > 1 % Two output arguments
    G = ... % Gradients evaluated at x
end

**Note** Setting **GradObj** to 'on' is effective only when there is no nonlinear constraint, or when the nonlinear constraint has **GradConstr** set to 'on' as well. This is because internally the objective is folded into the constraints, so the solver needs both gradients (objective and constraint) supplied in order to avoid estimating a gradient.

**nonlcon** The function that computes the nonlinear inequality constraints \( c(x) \leq 0 \) and nonlinear equality constraints \( ceq(x) = 0 \). The function **nonlcon** accepts a vector \( x \) and returns two vectors \( c \) and \( ceq \). The vector \( c \) contains the nonlinear inequalities evaluated at \( x \), and \( ceq \) contains the nonlinear equalities evaluated at \( x \). The function **nonlcon** can be specified as a function handle.

\[
x = \text{fminimax}(@\text{myfun},x0,A,b,Aeq,beq,lb,ub,@\text{mycon})
\]

where **mycon** is a MATLAB function such as

function [c,ceq] = mycon(x)
c = ... % Compute nonlinear inequalities at x
ceq = ... % Compute nonlinear equalities at x

If the gradients of the constraints can also be computed and the **GradConstr** option is 'on', as set by

\[
\text{options} = \text{optimset('GradConstr','on')}
\]

then the function **nonlcon** must also return, in the third and fourth output arguments, \( GC \), the gradient of \( c(x) \), and \( Gceq \), the gradient of \( ceq(x) \).

“Nonlinear Constraints” on page 2-33 explains how to “conditionalize” the
gradients for use in solvers that do not accept supplied gradients, and explains the syntax of gradients.

**Note** Setting GradConstr to 'on' is effective only when GradObj is set to 'on' as well. This is because internally the objective is folded into the constraint, so the solver needs both gradients (objective and constraint) supplied in order to avoid estimating a gradient.

**Note** Because Optimization Toolbox functions only accept inputs of type double, user-supplied objective and nonlinear constraint functions must return outputs of type double.

<table>
<thead>
<tr>
<th>problem</th>
<th>objective</th>
<th>Objective function</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>Initial point for x</td>
<td></td>
</tr>
<tr>
<td>Aineq</td>
<td>Matrix for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>bineq</td>
<td>Vector for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>Aeq</td>
<td>Matrix for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>beq</td>
<td>Vector for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
<tr>
<td>ub</td>
<td>Vector of upper bounds</td>
<td></td>
</tr>
<tr>
<td>nonlcon</td>
<td>Nonlinear constraint function</td>
<td></td>
</tr>
<tr>
<td>solver</td>
<td>'fminimax'</td>
<td></td>
</tr>
<tr>
<td>options</td>
<td>Options structure created with optimset</td>
<td></td>
</tr>
</tbody>
</table>

**Output Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by fminimax. This section provides function-specific details for exitflag, lambda, maxfval, and output:
exitflag

Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated:

1  Function converged to a solution x.
4  Magnitude of the search direction less than the specified tolerance and constraint violation less than options.TolCon.
5  Magnitude of directional derivative less than the specified tolerance and constraint violation less than options.TolCon.
0  Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
-1  Algorithm was terminated by the output function.
-2  No feasible point was found.

lambda

Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields of the structure are

lower  Lower bounds lb
upper  Upper bounds ub
ineqlin  Linear inequalities
eqlin  Linear equalities
ineqnonlin  Nonlinear inequalities
eqnonlin  Nonlinear equalities

maxfval

Maximum of the function values evaluated at the solution x, that is, maxfval = max{fun(x)}. 
output

Structure containing information about the optimization. The fields of the structure are

- **iterations**: Number of iterations taken.
- **funcCount**: Number of function evaluations.
- **lssteplength**: Size of line search step relative to search direction.
- **stepsize**: Final displacement in x.
- **algorithm**: Optimization algorithm used.
- **firstorderopt**: Measure of first-order optimality.
- **constrviolation**: Maximum of constraint functions.
- **message**: Exit message.

**Options**

Optimization options used by `fminimax`. You can use `optimset` to set or change the values of these fields in the options structure `options`. See “Optimization Options Reference” on page 9-7 for detailed information.

- **DerivativeCheck**: Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default, 'off'.
- **Diagnostics**: Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default, 'off'.
- **DiffMaxChange**: Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.
- **DiffMinChange**: Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.
Display | Level of display:
--- | ---
'off' | displays no output.
'iter' | displays output at each iteration, and gives the default exit message.
'iter-detailed' | displays output at each iteration, and gives the technical exit message.
'notify' | displays output only if the function does not converge, and gives the default exit message.
'notify-detailed' | displays output only if the function does not converge, and gives the technical exit message.
'final' (default) | displays just the final output, and gives the default exit message.
'final-detailed' | displays just the final output, and gives the technical exit message.
FinDiffRelStep

Scalar or vector step size factor. When you set `FinDiffRelStep` to a vector `v`, forward finite differences `delta` are

\[
\text{delta} = v.*\text{sign}(x).*\max(\text{abs}(x),\text{TypicalX});
\]

and central finite differences are

\[
\text{delta} = v.*\max(\text{abs}(x),\text{TypicalX});
\]

Scalar `FinDiffRelStep` expands to a vector. The default is `sqrt(eps)` for forward finite differences, and `eps^(1/3)` for central finite differences.

FinDiffType

Finite differences, used to estimate gradients, are either 'forward' (the default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.

The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.

FunValCheck

Check whether objective function and constraints values are valid. 'on' displays an error when the objective function or constraints return a value that is `complex`, `Inf`, or `NaN`. The default 'off' displays no error.
GradConstr Gradient for the user-defined constraints. When set to 'on', fminimax expects the constraint function to have four outputs, as described in nonlcon in “Input Arguments” on page 11-70. When set to the default 'off', fminimax estimates gradients of the nonlinear constraints by finite differences.

GradObj Gradient for the user-defined objective function. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have fminimax use a user-defined gradient of the objective function. The default 'off' causes fminimax to estimate gradients using finite differences.

MaxFunEvals Maximum number of function evaluations allowed, a positive integer. The default value is 100*numberOfVariables.

MaxIter Maximum number of iterations allowed, a positive integer. The default value is 400.

MaxSQPIter Maximum number of SQP iterations allowed, a positive integer. The default is 10*max(numberOfVariables, numberOfInequalities + numberOfBounds).

MeritFunction Use the goal attainment/minimax merit function if set to 'multiobj' (default). Use the fmincon merit function if set to 'singleobj'.
### MinAbsMax

Number of elements of $F_i(x)$ to minimize the maximum absolute value of $F_i$. See “Notes” on page 11-82. The default is 0.

### OutputFcn

Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([ ]). See “Output Function” on page 9-18.

### PlotFcns

Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]).

- @optimplotx plots the current point.
- @optimplotfunccount plots the function count.
- @optimplotfval plots the function value.
- @optimplotconstrviolation plots the maximum constraint violation.
- @optimplotstepsize plots the step size.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.
<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RelLineSrchBnd</td>
<td>Relative bound (a real nonnegative scalar value) on the line search step length such that the total displacement in x satisfies $</td>
</tr>
<tr>
<td>RelLineSrchBndDuration</td>
<td>Number of iterations for which the bound specified in RelLineSrchBnd should be active (default is 1).</td>
</tr>
<tr>
<td>TolCon</td>
<td>Termination tolerance on the constraint violation, a positive scalar. The default is $1e^{-6}$.</td>
</tr>
<tr>
<td>TolConSQP</td>
<td>Termination tolerance on inner iteration SQP constraint violation, a positive scalar. The default is $1e^{-6}$.</td>
</tr>
<tr>
<td>TolFun</td>
<td>Termination tolerance on the function value, a positive scalar. The default is $1e^{-6}$.</td>
</tr>
<tr>
<td>TolX</td>
<td>Termination tolerance on x, a positive scalar. The default value is $1e^{-6}$.</td>
</tr>
<tr>
<td>TypicalX</td>
<td>Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). \ fminimax uses TypicalX for scaling finite differences for gradient estimation.</td>
</tr>
<tr>
<td>UseParallel</td>
<td>When 'always', estimate gradients in parallel. Disable by setting to the default 'never'.</td>
</tr>
</tbody>
</table>
Examples

Find values of $x$ that minimize the maximum value of

\[ [f_1(x), f_2(x), f_3(x), f_4(x), f_5(x)] \]

where

\[
\begin{align*}
  f_1(x) &= 2x_1^2 + x_2^2 - 48x_1 - 40x_2 + 304, \\
  f_2(x) &= -x_1^2 - 3x_2^2, \\
  f_3(x) &= x_1 + 3x_2 - 18, \\
  f_4(x) &= -x_1 - x_2, \\
  f_5(x) &= x_1 + x_2 - 8. \\
\end{align*}
\]

First, write a file that computes the five functions at $x$.

```matlab
function f = myfun(x)
    f(1)= 2*x(1)^2+x(2)^2-48*x(1)-40*x(2)+304; % Objectives
    f(2)= -x(1)^2 - 3*x(2)^2;
    f(3)= x(1) + 3*x(2) -18;
    f(4)= -x(1) - x(2);
    f(5)= x(1) + x(2) - 8;
end
```

Next, invoke an optimization routine.

```matlab
x0 = [0.1; 0.1]; % Make a starting guess at solution
[x,fval] = fminimax(@myfun,x0);
```

After seven iterations, the solution is

```
x, fval

x =
    4.0000
    4.0000

fval =
    0.0000   -64.0000   -2.0000   -8.0000   -0.0000
```
Notes

You can solve problems of the form

$$\min_{x} \max_{i} G_{i}(x),$$

where

$$G_{i}(x) = \begin{cases} 
|F_{i}(x)| & 1 \leq i \leq m \\
F_{i}(x) & i > m.
\end{cases}$$

Here $m$ is the value of the MinAbsMax option. The advantage of this formulation is you can minimize the absolute value of some components of $F$, even though the absolute value function is not smooth.

In order to use this option, reorder the elements of $F$, if necessary, so the first elements are those for which you want the minimum absolute value.

For example, consider the problem in “Examples” on page 11-81. Modify the problem to find the minimum of the maximum absolute values of all $f_{i}(x)$. Solve this problem by invoking fminimax with the commands

```matlab
x0 = [0.1; 0.1]; % Make a starting guess at the solution
options = optimset('MinAbsMax',5); % Minimize abs. values
[x,fval] = fminimax(@myfun,x0,...
    [],[],[],[],[],[],options);
```

After seven iterations, the solution is

$$x = 
\begin{bmatrix}
4.9256 \\
2.0796
\end{bmatrix}$$

$$fval = 
\begin{bmatrix}
37.2356 \\
37.2356 \\
-6.8357 \\
-7.0052 \\
-0.9948
\end{bmatrix}$$

Algorithms

fminimax internally reformulates the minimax problem into an equivalent Nonlinear Linear Programming problem by appending additional (reformulation) constraints of the form $F_{i}(x) \leq \gamma$ to the
constraints given in “Equation” on page 11-68, and then minimizing $y$ over $x$. \texttt{fminimax} uses a sequential quadratic programming (SQP) method [1] to solve this problem.

Modifications are made to the line search and Hessian. In the line search an exact merit function (see [2] and [4]) is used together with the merit function proposed by [3] and [5]. The line search is terminated when either merit function shows improvement. The function uses a modified Hessian that takes advantage of the special structure of this problem. Using \texttt{optimset} to set the MeritFunction option to ‘singleobj’ uses the merit function and Hessian used in \texttt{fmincon}.

See also “SQP Implementation” on page 6-30 for more details on the algorithm used and the types of procedures printed under the Procedures heading when you set the Display option to ‘iter’.

**Limitations**

The function to be minimized must be continuous. \texttt{fminimax} might only give local solutions.

**References**


See Also  

fgoalattain | lsqnonlin | optimset | optimtool | fminimax

How To  

• @(function_handle)

• “Multiobjective Optimization Algorithms” on page 6-170

• “Multiobjective Optimization Examples” on page 6-176
Purpose
Find minimum of unconstrained multivariable function using derivative-free method

Equation
Finds the minimum of a problem specified by

$$\min_{x} f(x)$$

where $x$ is a vector and $f(x)$ is a function that returns a scalar.

Syntax
$x = \text{fminsearch}(\text{fun},x0)$
$x = \text{fminsearch}(\text{fun},x0,\text{options})$
$x = \text{fminsearch}(\text{problem})$
$[x,fval] = \text{fminsearch}(\ldots)$
$[x,fval,\text{exitflag}] = \text{fminsearch}(\ldots)$
$[x,fval,\text{exitflag},\text{output}] = \text{fminsearch}(\ldots)$

Description
fminsearch attempts to find a minimum of a scalar function of several variables, starting at an initial estimate. This is generally referred to as unconstrained nonlinear optimization.

Note
“Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function, if necessary.

$x = \text{fminsearch}(\text{fun},x0)$ starts at the point $x0$ and returns a value $x$ that is a local minimizer of the function described in $\text{fun}$. $\text{fun}$ is either a function handle to a file or is an anonymous function. $x0$ can be a scalar, vector, or matrix.

$x = \text{fminsearch}(\text{fun},x0,\text{options})$ minimizes with the optimization options specified in the structure $\text{options}$. Use optimset to set these options.

$x = \text{fminsearch}(\text{problem})$ finds the minimum for $\text{problem}$, where $\text{problem}$ is a structure described in “Input Arguments” on page 11-86.
Create the structure \texttt{problem} by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

\[ \text{x, fval} = \text{fminsearch(...)} \] returns in \text{fval} the value of the objective function \text{fun} at the solution \text{x}.

\[ \text{x, fval, exitflag} = \text{fminsearch(...)} \] returns a value \text{exitflag} that describes the exit condition of \text{fminsearch}.

\[ \text{x, fval, exitflag, output} = \text{fminsearch(...)} \] returns a structure \text{output} that contains information about the optimization.

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into \text{fminsearch}. This section provides function-specific details for \text{fun}, \text{options}, and \text{problem}:

- **fun**: The function to be minimized. \text{fun} is a function handle for a function that accepts a vector \text{x} and returns a scalar \text{f}, the objective function evaluated at \text{x}. The function \text{fun} can be specified as a function handle for a file:

  \[ \text{x} = \text{fminsearch(@myfun,x0)} \]

  where \text{myfun} is a MATLAB function such as

  \[ \text{function f = myfun(x)} \]
  \[ \text{f = ...} \quad \% \text{Compute function value at x} \]

  \text{fun} can also be a function handle for an anonymous function, such as

  \[ \text{x} = \text{fminsearch(@(x)norm(x)^2,x0,A,b);} \]

- **options**: “Options” on page 11-88 provides the function-specific details for the \text{options} values.
problem  objective  Objective function
x0  Initial point for x
solver  'fminsearch'
options  Options structure created with optimset

Output Arguments

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by fminsearch. This section provides function-specific details for exitflag and output:

exitflag  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.

1  The function converged to a solution x.
0  Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
-1  The algorithm was terminated by the output function.

output  Structure containing information about the optimization. The fields of the structure are

iterations  Number of iterations
funcCount  Number of function evaluations
algorithm  'Nelder-Mead simplex direct search'
message  Exit message
## Options

Optimization options used by `fminsearch`. You can use `optimset` to set or change the values of these fields in the options structure `options`. See “Optimization Options Reference” on page 9-7 for detailed information.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Display</strong></td>
<td>Level of display:</td>
</tr>
<tr>
<td>'off'</td>
<td>displays no output.</td>
</tr>
<tr>
<td>'iter'</td>
<td>displays output at each iteration.</td>
</tr>
<tr>
<td>'notify'</td>
<td>displays output only if the function does not converge.</td>
</tr>
<tr>
<td>'final'</td>
<td>(default) displays just the final output.</td>
</tr>
<tr>
<td><strong>FunValCheck</strong></td>
<td>Check whether objective function values are valid. 'on' displays an error when the objective function returns a value that is complex, Inf, or NaN. The default 'off' displays no error.</td>
</tr>
<tr>
<td><strong>MaxFunEvals</strong></td>
<td>Maximum number of function evaluations allowed, a positive integer. The default is $200 \times \text{numberOfVariables}$.</td>
</tr>
<tr>
<td><strong>MaxIter</strong></td>
<td>Maximum number of iterations allowed, a positive integer. The default value is $200 \times \text{numberOfVariables}$.</td>
</tr>
<tr>
<td><strong>OutputFcn</strong></td>
<td>Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.</td>
</tr>
</tbody>
</table>
PlotFcns

Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([]):

- @optimplotx plots the current point.
- @optimplotfval plots the function value.
- @optimplotfunccount plots the function count.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

TolFun

Termination tolerance on the function value, a positive scalar. The default is 1e-4.

TolX

Termination tolerance on x, a positive scalar. The default value is 1e-4.

Examples

Example 1: Minimizing Rosenbrock’s Function with fminsearch

A classic test example for multidimensional minimization is the Rosenbrock banana function:

\[ f(x) = 100 \left( x_2 - x_1^2 \right)^2 + (1 - x_1)^2. \]

The minimum is at (1,1) and has the value 0. The traditional starting point is (-1.2,1). The anonymous function shown here defines the function and returns a function handle called banana:

\[
\text{banana} = @(x)100*(x(2)-x(1)^2)^2+(1-x(1))^2;
\]

Pass the function handle to fminsearch:

\[
[x,fval,exitflag] = \text{fminsearch}(\text{banana},[-1.2, 1])
\]
This produces

\[
x = \\
1.0000 
1.0000
\]

\[
fval = \\
8.1777e-010
\]

\[
exitflag = \\
1
\]

This indicates that the minimizer was found at [1 1] with a value near zero.

**Example 2**

You can modify the first example by adding a parameter \(a\) to the second term of the banana function:

\[
f(x) = 100\left(x_2 - x_1^2\right)^2 + (a - x_1)^2.
\]

This changes the location of the minimum to the point \([a,a^2]\). To minimize this function for a specific value of \(a\), for example \(a = \sqrt{2}\), create a one-argument anonymous function that captures the value of \(a\).

\[
a = \sqrt{2}; \\
banana = @(x)100*(x(2)-x(1)^2)^2+(a-x(1))^2;
\]

Then the statement

\[
[x,fval,exitflag] = fminsearch(banana, [-1.2, 1], ... \\
\text{optimset}('TolX',1e-8))
\]

seeks the minimum \([\sqrt{2}, 2]\) to an accuracy higher than the default on \(x\). The result is

\[
x = \\
1.4142 
2.0000
\]
fval = 4.2065e-018

exitflag = 1

**Algorithms**

`fminsearch` uses the simplex search method of [1]. This is a direct search method that does not use numerical or analytic gradients as in `fminunc`. The algorithm is described in detail in “fminsearch Algorithm” on page 6-12.

`fminsearch` is generally less efficient than `fminunc` for problems of order greater than two. However, when the problem is highly discontinuous, `fminsearch` might be more robust.

**Limitations**

`fminsearch` solves nondifferentiable problems and can often handle discontinuity, particularly if it does not occur near the solution. `fminsearch` might only give local solutions.

`fminsearch` only minimizes over the real numbers, that is, $x$ must only consist of real numbers and $f(x)$ must only return real numbers. When $x$ has complex variables, they must be split into real and imaginary parts.

**Notes**

`fminsearch` is not the preferred choice for solving problems that are sums of squares, that is, of the form

$$
\min_{x} \| f(x) \|_2^2 = \min_{x} \left( f_1(x)^2 + f_2(x)^2 + \ldots + f_n(x)^2 \right)
$$

Instead use the `lsqnonlin` function, which has been optimized for problems of this form.

**References**

See Also
fminbnd | fminunc | optimset | optimtool

How To
• @(function_handle)
• “Anonymous Functions”
**Purpose**

Find minimum of unconstrained multivariable function

**Equation**

Finds the minimum of a problem specified by

$$\min_{x} f(x)$$

where $x$ is a vector and $f(x)$ is a function that returns a scalar.

**Syntax**

- $x = \text{fminunc}(\text{fun},x0)$
- $x = \text{fminunc}(\text{fun},x0,\text{options})$
- $x = \text{fminunc}(\text{problem})$
- $[x,fval] = \text{fminunc}(\ldots)$
- $[x,fval,\text{exitflag}] = \text{fminunc}(\ldots)$
- $[x,fval,\text{exitflag},\text{output}] = \text{fminunc}(\ldots)$
- $[x,fval,\text{exitflag},\text{output},\text{grad}] = \text{fminunc}(\ldots)$
- $[x,fval,\text{exitflag},\text{output},\text{grad},\text{hessian}] = \text{fminunc}(\ldots)$

**Description**

fminunc attempts to find a minimum of a scalar function of several variables, starting at an initial estimate. This is generally referred to as *unconstrained nonlinear optimization*.

**Note**

“Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function, if necessary.

$x = \text{fminunc}(\text{fun},x0)$ starts at the point $x0$ and attempts to find a local minimum $x$ of the function described in $\text{fun}$. $x0$ can be a scalar, vector, or matrix.

$x = \text{fminunc}(\text{fun},x0,\text{options})$ minimizes with the optimization options specified in the structure $\text{options}$. Use $\text{optimset}$ to set these options.

$x = \text{fminunc}(\text{problem})$ finds the minimum for $\text{problem}$, where $\text{problem}$ is a structure described in “Input Arguments” on page 11-94.
Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = fminunc(...) returns in fval the value of the objective function fun at the solution x.

[x,fval,exitflag] = fminunc(...) returns a value exitflag that describes the exit condition.

[x,fval,exitflag,output] = fminunc(...) returns a structure output that contains information about the optimization.

[x,fval,exitflag,output,grad] = fminunc(...) returns in grad the value of the gradient of fun at the solution x.

[x,fval,exitflag,output,grad,hessian] = fminunc(...) returns in hessian the value of the Hessian of the objective function fun at the solution x. See “Hessian” on page 11-97.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into fminunc. This section provides function-specific details for fun, options, and problem:

**fun**

The function to be minimized. fun is a function that accepts a vector x and returns a scalar f, the objective function evaluated at x. The function fun can be specified as a function handle for a file

\[ x = \text{fminunc}(@\text{myfun},x0) \]

where myfun is a MATLAB function such as

function \( f = \text{myfun}(x) \)  
\( f = \ldots \) \quad \% \text{Compute function value at } x

fun can also be a function handle for an anonymous function.

\[ x = \text{fminunc}(@(x)\text{norm}(x)^2,x0); \]
If the gradient of \( \text{fun} \) can also be computed \textit{and} the GradObj option is 'on', as set by

\[
\text{options} = \text{optimset('GradObj','on')}
\]

then the function \( \text{fun} \) must return, in the second output argument, the gradient value \( g \), a vector, at \( x \). The gradient is the partial derivatives \( \partial f / \partial x_i \) of \( f \) at the point \( x \). That is, the \( i \)th component of \( g \) is the partial derivative of \( f \) with respect to the \( i \)th component of \( x \).

If the Hessian matrix can also be computed \textit{and} the Hessian option is 'on', i.e., \( \text{options} = \text{optimset('Hessian','on')} \), then the function \( \text{fun} \) must return the Hessian value \( H \), a symmetric matrix, at \( x \) in a third output argument. The Hessian matrix is the second partial derivatives matrix of \( f \) at the point \( x \). That is, the \((i,j)\)th component of \( H \) is the second partial derivative of \( f \) with respect to \( x_i \) and \( x_j \), \( \partial^2 f / \partial x_i \partial x_j \). The Hessian is by definition a symmetric matrix.

“Writing Scalar Objective Functions” on page 2-17 explains how to “conditionalize” the gradients and Hessians for use in solvers that do not accept them. “Passing Extra Parameters” on page 2-38 explains how to parameterize \( \text{fun} \), if necessary.

\mid\begin{array}{l}
\textbf{options} \\
\textbf{problem} \\
\textbf{objective} \\
x0 \\
solver \\
options
\end{array}
\mid\begin{array}{l}
“Options” on page 11-97 provides the function-specific details for the options values.

Objective function \\
Initial point for \( x \) \\
‘fminunc’ \\
Options structure created with \text{optimset}
\end{array}

\textbf{Output Arguments} \\
“Function Arguments” on page 9-2 contains general descriptions of arguments returned by \text{fminunc}. This section provides function-specific details for \text{exitflag} and \text{output}:
exitflag  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.

1  Magnitude of gradient smaller than the TolFun tolerance.
2  Change in x was smaller than the TolX tolerance.
3  Change in the objective function value was less than the TolFun tolerance.
5  Predicted decrease in the objective function was less than the TolFun tolerance.
0  Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
-1  Algorithm was terminated by the output function.

grad  Gradient at x
hessian  Hessian at x
output  Structure containing information about the optimization. The fields of the structure are

iterations  Number of iterations taken
funcCount  Number of function evaluations
firstorderopt  Measure of first-order optimality
algorithm  Optimization algorithm used
fminunc

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cgiterations</td>
<td>Total number of PCG iterations (large-scale algorithm only)</td>
</tr>
<tr>
<td>stepsizes</td>
<td>Final displacement in x (medium-scale algorithm only)</td>
</tr>
<tr>
<td>message</td>
<td>Exit message</td>
</tr>
</tbody>
</table>

**Hessian**

fminunc computes the output argument hessian as follows:

- When using the medium-scale algorithm, the function computes a finite-difference approximation to the Hessian at x using:
  - The gradient grad if you supply it
  - The objective function fun if you do not supply the gradient
- When using the large-scale algorithm, the function uses:
  - options.Hessian, if you supply it, to compute the Hessian at x
  - A finite-difference approximation to the Hessian at x, if you supply only the gradient

**Options**

fminunc uses these optimization options. Some options apply to all algorithms, some are only relevant when you are using the large-scale algorithm, and others are only relevant when you are using the medium-scale algorithm. Use optimset to set or change the values of these fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information.

**Large-Scale and Medium-Scale Algorithms**

Both the large-scale and medium-scale algorithms use the following options:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DerivativeCheck</td>
<td>Compare user-supplied derivatives (gradient of objective) to finite-differencing derivatives. The choices are 'on' or the default 'off'.</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.</td>
</tr>
<tr>
<td>DiffMaxChange</td>
<td>Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.</td>
</tr>
<tr>
<td>DiffMinChange</td>
<td>Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.</td>
</tr>
<tr>
<td>Display</td>
<td>Level of display:</td>
</tr>
<tr>
<td></td>
<td>- 'off' displays no output.</td>
</tr>
<tr>
<td></td>
<td>- 'iter' displays output at each iteration, and gives the default exit message.</td>
</tr>
<tr>
<td></td>
<td>- 'iter-detailed' displays output at each iteration, and gives the technical exit message.</td>
</tr>
<tr>
<td></td>
<td>- 'notify' displays output only if the function does not converge, and gives the default exit message.</td>
</tr>
<tr>
<td></td>
<td>- 'notify-detailed' displays output only if the function does not converge, and gives the technical exit message.</td>
</tr>
<tr>
<td></td>
<td>- 'final' (default) displays just the final output, and gives the default exit message.</td>
</tr>
<tr>
<td></td>
<td>- 'final-detailed' displays just the final output, and gives the technical exit message.</td>
</tr>
</tbody>
</table>
**FinDiffRelStep**  Scalar or vector step size factor. When you set `FinDiffRelStep` to a vector $v$, forward finite differences $\delta$ are

$$
\delta = v.*\text{sign}(x).*\max(\text{abs}(x),\text{TypicalX});
$$

and central finite differences are

$$
\delta = v.*\max(\text{abs}(x),\text{TypicalX});
$$

Scalar `FinDiffRelStep` expands to a vector. The default is $\sqrt{\text{eps}}$ for forward finite differences, and $\text{eps}^{(1/3)}$ for central finite differences.

The large-scale algorithm uses `FinDiffRelStep` only when `DerivativeCheck` is `'on'`.

**FinDiffType**  Finite differences, used to estimate gradients, are either `'forward'` (the default), or `'central'` (centered). `'central'` takes twice as many function evaluations, but should be more accurate. The large-scale algorithm uses `FinDiffType` only when `DerivativeCheck` is `'on'`.

**FunValCheck**  Check whether objective function values are valid. `'on'` displays an error when the objective function returns a value that is complex, Inf, or NaN. The default, `'off'`, displays no error.
fminunc

GradObj  Gradient for the objective function defined by the user. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have fminunc use a user-defined gradient of the objective function. The default 'off' causes fminunc to estimate gradients using finite differences. You must provide the gradient, and set GradObj to 'on', to use the large-scale algorithm. This option is not required for the medium-scale algorithm.

LargeScale  Use large-scale algorithm if possible when set to the default 'on'. Use medium-scale algorithm when set to 'off'.

The LargeScale algorithm requires you to provide the gradient (see the preceding description of fun), or else fminunc uses the medium-scale algorithm. For information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

MaxFunEvals  Maximum number of function evaluations allowed, a positive integer. The default value is 100*numberOfVariables.

MaxIter  Maximum number of iterations allowed, a positive integer. The default value is 400.

OutputFcn  Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.
Plots various measures of progress while the algorithm executes. Select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([]).

- @optimplotx plots the current point.
- @optimplotfunccount plots the function count.
- @optimplotfval plots the function value.
- @optimplotstepsize plots the step size.
- @optimplotfirstorderopt plots the first-order optimality measure.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

TolFun
Termination tolerance on the function value, a positive scalar. The default is 1e-6.

TolX
Termination tolerance on x, a positive scalar. The default value is 1e-6.

TypicalX
Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). fminunc uses TypicalX for scaling finite differences for gradient estimation.

The 'LargeScale' algorithm uses TypicalX only for the DerivativeCheck option.

Large-Scale Algorithm Only

The large-scale algorithm uses the following options:
If 'on', fminunc uses a user-defined Hessian for the objective function. The Hessian is either defined in the objective function (see fun), or is indirectly defined when using HessMult.

If 'off' (default), fminunc approximates the Hessian using finite differences.

HessMult Function handle for Hessian multiply function. For large-scale structured problems, this function computes the Hessian matrix product $H*Y$ without actually forming $H$. The function is of the form

$$W = \text{hmfun}(\text{Hinfo},Y)$$

where $\text{Hinfo}$ contains the matrix used to compute $H*Y$.

The first argument must be the same as the third argument returned by the objective function fun, for example by

$$[f,g,\text{Hinfo}] = \text{fun}(x)$$

$Y$ is a matrix that has the same number of rows as there are dimensions in the problem. $W = H*Y$ although $H$ is not formed explicitly. fminunc uses $\text{Hinfo}$ to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply values for any additional parameters hmfun needs.

**Note** 'Hessian' must be set to 'on' for fminunc to pass $\text{Hinfo}$ from fun to hmfun.
See “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68 for an example.

**HessPattern**  
Sparsity pattern of the Hessian for finite differencing. If it is not convenient to compute the sparse Hessian matrix $\mathbf{H}$ in `fun`, the large-scale method in `fminunc` can approximate $\mathbf{H}$ via sparse finite differences (of the gradient) provided the *sparsity structure* of $\mathbf{H}$ —i.e., locations of the nonzeros—is supplied as the value for `HessPattern`. In the worst case, if the structure is unknown, you can set `HessPattern` to be a dense matrix and a full finite-difference approximation is computed at each iteration (this is the default). This can be very expensive for large problems, so it is usually worth the effort to determine the sparsity structure.

**MaxPCGIter**  
Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is  
$max(1,\text{floor(numberOfVariables/2)})$. For more information, see “Algorithms” on page 11-107.
PrecondBandWidth  Upper bandwidth of preconditioner for PCG, a nonnegative integer. By default, fminunc uses diagonal preconditioning (upper bandwidth of 0). For some problems, increasing the bandwidth reduces the number of PCG iterations. Setting PrecondBandWidth to Inf uses a direct factorization (Cholesky) rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution.

TolPCG  Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.

Medium-Scale Algorithm Only
The medium-scale algorithm uses the following options:

HessUpdate  Method for choosing the search direction in the Quasi-Newton algorithm. The choices are:

• 'bfgs', the default
• 'dfp'
• 'steepdesc'

See “Hessian Update” on page 6-11 for a description of these methods.

InitialHessMatrix  Initial quasi-Newton matrix. This option is only available if you set InitialHessType to 'user-supplied'. In that case, you can set InitialHessMatrix to one of the following:

• A positive scalar — The initial matrix is the scalar times the identity.
• A vector of positive values—The initial matrix is a diagonal matrix with the entries of the vector on the diagonal. This vector should be the same size as the x0 vector, the initial point.

**InitialHessType**

Initial quasi-Newton matrix type. The options are:

• 'identity'
• 'scaled-identity', the default
• 'user-supplied' — See InitialHessMatrix

**Examples**

Minimize the function \( f(x) = 3x_1^2 + 2x_1x_2 + x_2^2 \).

Create a file `myfun.m`:

```matlab
function f = myfun(x)
f = 3*x(1)^2 + 2*x(1)*x(2) + x(2)^2; % Cost function
```

Then call `fminunc` to find a minimum of `myfun` near \([1,1]\):

```matlab
x0 = [1,1];
[x,fval] = fminunc(@myfun,x0);
```

After a few iterations, `fminunc` returns the solution, x, and the value of the function at x, fval:

```matlab
x,fval
```

```
x =
  1.0e-006 *
    0.2541   -0.2029
fval =
```
To minimize this function with the gradient provided, modify myfun.m so the gradient is the second output argument:

```matlab
function [f,g] = myfun(x)
    f = 3*x(1)^2 + 2*x(1)*x(2) + x(2)^2;  % Cost function
    if nargout > 1
        g(1) = 6*x(1)+2*x(2);
        g(2) = 2*x(1)+2*x(2);
    end
```

Indicate that the gradient value is available by creating an optimization options structure with the GradObj option set to 'on' using optimset.

```matlab
options = optimset('GradObj','on');
x0 = [1,1];
[x,fval] = fminunc(@myfun,x0,options);
```

After several iterations fminunc returns the solution, x, and the value of the function at x, fval:

```matlab
x,fval
```

```matlab
x =
    1.0e-015 *
    0.1110   -0.8882

fval =
    6.2862e-031
```

To minimize the function \( f(x) = \sin(x) + 3 \) using an anonymous function

```matlab
f = @(x)sin(x)+3;
x = fminunc(f,4)
```

fminunc returns a solution
fminunc is not the preferred choice for solving problems that are sums of squares, that is, of the form

$$\min_x \|f(x)\|_2^2 = \min_x \left( f_1(x)^2 + f_2(x)^2 + \ldots + f_n(x)^2 \right)$$

Instead use the lsqnonlin function, which has been optimized for problems of this form.

To use the large-scale method, you must provide the gradient in fun (and set the GradObj option to 'on' using optimset). A warning is given if no gradient is provided and the LargeScale option is not 'off'.

Algorithms

Large-Scale Optimization

By default fminunc chooses the large-scale algorithm if you supply the gradient in fun and set GradObj to 'on' using optimset. This algorithm is a subspace trust-region method and is based on the interior-reflective Newton method described in [2] and [3]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). See “Large Scale fminunc Algorithm” on page 6-3, “Trust-Region Methods for Nonlinear Minimization” on page 6-3 and “Preconditioned Conjugate Gradient Method” on page 6-6.

Medium-Scale Optimization

fminunc, with the LargeScale option set to 'off' with optimset, uses the BFGS Quasi-Newton method with a cubic line search procedure. This quasi-Newton method uses the BFGS ([1],[5],[8], and [9]) formula for updating the approximation of the Hessian matrix. You can select the DFP ([4],[6], and [7]) formula, which approximates the inverse Hessian matrix, by setting the HessUpdate option to 'dfp' (and the LargeScale option to 'off'). You can select a steepest descent method
by setting HessUpdate to 'steepdesc' (and LargeScale to 'off'), although this is not recommended.

Limitations

The function to be minimized must be continuous. fminunc might only give local solutions.

fminunc only minimizes over the real numbers, that is, \( x \) must only consist of real numbers and \( f(x) \) must only return real numbers. When \( x \) has complex variables, they must be split into real and imaginary parts.

Large-Scale Optimization

To use the large-scale algorithm, you must supply the gradient in \( \text{fun} \) (and GradObj must be set 'on' in options).

Large-Scale Problem Coverage and Requirements

<table>
<thead>
<tr>
<th>Additional Information Needed</th>
<th>For Large Problems</th>
</tr>
</thead>
</table>
| Must provide gradient for \( f(x) \) in \( \text{fun} \). | • Provide sparsity structure of the Hessian, or compute the Hessian in \( \text{fun} \).  
• The Hessian should be sparse. |

References


**See Also**

fminsearch | optimset | optimtool | fminunc

**How To**

- @(function_handle)
- “Anonymous Functions”
- “Unconstrained Nonlinear Optimization Algorithms” on page 6-3
- “Unconstrained Nonlinear Optimization Examples” on page 6-15
Purpose
Find minimum of semi-infinitely constrained multivariable nonlinear function

Equation
Finds the minimum of a problem specified by

\[
\min_x f(x) \quad \text{such that} \quad
\begin{align*}
A \cdot x & \leq b, \\
A_{eq} \cdot x & = b_{eq}, \\
lb \leq x & \leq ub, \\
c(x) & \leq 0, \\
ceq(x) & = 0, \\
K_i(x,w_i) & \leq 0, \quad 1 \leq i \leq n.
\end{align*}
\]

\(x, b, b_{eq}, lb,\) and \(ub\) are vectors, \(A\) and \(A_{eq}\) are matrices, \(c(x), ceq(x),\) and \(K_i(x,w_i)\) are functions that return vectors, and \(f(x)\) is a function that returns a scalar. \(f(x), c(x),\) and \(ceq(x)\) can be nonlinear functions. The vectors (or matrices) \(K_i(x,w_i) \leq 0\) are continuous functions of both \(x\) and an additional set of variables \(w_1,w_2,\ldots,w_n\). The variables \(w_1,w_2,\ldots,w_n\) are vectors of, at most, length two.

Syntax
\[
x = \text{fseminf}(\text{fun},x0,\text{ntheta},\text{seminfcon})
\]
\[
x = \text{fseminf}(\text{fun},x0,\text{ntheta},\text{seminfcon},A,b)
\]
\[
x = \text{fseminf}(\text{fun},x0,\text{ntheta},\text{seminfcon},A,b,A_{eq},b_{eq})
\]
\[
x = \text{fseminf}(\text{fun},x0,\text{ntheta},\text{seminfcon},A,b,A_{eq},b_{eq},lb,ub)
\]
\[
x = \text{fseminf}(\text{fun},x0,\text{ntheta},\text{seminfcon},A,b,A_{eq},b_{eq},lb,ub,\text{options})
\]
\[
x = \text{fseminf}(\text{problem})
\]
\[
[x,\text{fval}] = \text{fseminf}(\ldots)
\]
\[
[x,\text{fval},\text{exitflag}] = \text{fseminf}(\ldots)
\]
\[
[x,\text{fval},\text{exitflag},\text{output}] = \text{fseminf}(\ldots)
\]
\[
[x,\text{fval},\text{exitflag},\text{output},\text{lambda}] = \text{fseminf}(\ldots)
\]

Description
fseminf finds a minimum of a semi-infinitely constrained scalar function of several variables, starting at an initial estimate. The aim is to minimize \(f(x)\) so the constraints hold for all possible values of \(w_i \mathbb{R}^1\) (or \(w_i \mathbb{R}^2\)). Because it is impossible to calculate all possible values
of $K_i(x,w_i)$, a region must be chosen for $w_i$ over which to calculate an appropriately sampled set of values.

**Note** “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function and nonlinear constraint functions, if necessary.

$x = \text{fseminf}(\text{fun},x0,ntheta,\text{seminfcon})$ starts at $x0$ and finds a minimum of the function $\text{fun}$ constrained by $ntheta$ semi-infinite constraints defined in $\text{seminfcon}$.

$x = \text{fseminf}(\text{fun},x0,ntheta,\text{seminfcon},A,b)$ also tries to satisfy the linear inequalities $A*x \leq b$.

$x = \text{fseminf}(\text{fun},x0,ntheta,\text{seminfcon},A,b,Aeq,beq)$ minimizes subject to the linear equalities $Aeq*x = beq$ as well. Set $A = []$ and $b = []$ if no inequalities exist.

$x = \text{fseminf}(\text{fun},x0,ntheta,\text{seminfcon},A,b,Aeq,beq,lb,ub)$ defines a set of lower and upper bounds on the design variables in $x$, so that the solution is always in the range $lb \leq x \leq ub$.

**Note** See “Iterations Can Violate Constraints” on page 2-30.

$x = \text{fseminf}(\text{fun},x0,ntheta,\text{seminfcon},A,b,Aeq,beq,lb,ub,options)$ minimizes with the optimization options specified in the structure $options$. Use $\text{optimset}$ to set these options.

$x = \text{fseminf}(\text{problem})$ finds the minimum for $\text{problem}$, where $\text{problem}$ is a structure described in “Input Arguments” on page 11-112.

Create the structure $\text{problem}$ by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.
[\textbf{fseminf}] [x,fval] = \textbf{fseminf}(\ldots)\text{ returns the value of the objective function fun at the solution } x.\n
[x,fval,exitflag] = \textbf{fseminf}(\ldots)\text{ returns a value exitflag that describes the exit condition.}\n
[x,fval,exitflag,output] = \textbf{fseminf}(\ldots)\text{ returns a structure output that contains information about the optimization.}\n
[x,fval,exitflag,output,lambda] = \textbf{fseminf}(\ldots)\text{ returns a structure lambda whose fields contain the Lagrange multipliers at the solution } x.\n
\textbf{Note}\ If the specified input bounds for a problem are inconsistent, the output \( x \) is \( x_0 \) and the output \( \text{fval} \) is \([\,]\).\n
\textbf{Input Arguments}\n
"Function Arguments" on page 9-2 contains general descriptions of arguments passed into \textbf{fseminf}. This section provides function-specific details for \texttt{fun}, \texttt{ntheta}, \texttt{options}, \texttt{seminfcon}, and \texttt{problem}:

\texttt{fun}\n
The function to be minimized. \texttt{fun} is a function that accepts a vector \( x \) and returns a scalar \( f \), the objective function evaluated at \( x \). The function \texttt{fun} can be specified as a function handle for a file

\[
x = \textbf{fseminf}(@\texttt{myfun},x_0,\texttt{ntheta},\texttt{seminfcon})
\]

where \texttt{myfun} is a MATLAB function such as

\[
\text{function } f = \texttt{myfun}(x)\\
f = \ldots % \text{ Compute function value at } x
\]

\texttt{fun} can also be a function handle for an anonymous function.

\[
\texttt{fun} = @(x)\sin(x''*x);
\]

If the gradient of \texttt{fun} can also be computed \textit{and} the \texttt{GradObj} option is 'on', as set by
options = optimset('GradObj','on')

then the function fun must return, in the second output argument, the gradient value g, a vector, at x.

ntheta
The number of semi-infinite constraints.

options
“Options” on page 11-116 provides the function-specific details for the options values.

seminfcon
The function that computes the vector of nonlinear inequality constraints, c, a vector of nonlinear equality constraints, ceq, and ntheta semi-infinite constraints (vectors or matrices) K1, K2, ..., Kntheta evaluated over an interval S at the point x. The function seminfcon can be specified as a function handle.

x = fseminf(@myfun,x0,ntheta,@myinfcon)

where myinfcon is a MATLAB function such as

function [c,ceq,K1,K2,...,Kntheta,S] = myinfcon(x,S)
% Initial sampling interval
if isnan(S(1,1)),
  S = ...% S has ntheta rows and 2 columns
end
w1 = ...% Compute sample set
w2 = ...% Compute sample set
...
wntheta = ...% Compute sample set
K1 = ...% 1st semi-infinite constraint at x and w
K2 = ...% 2nd semi-infinite constraint at x and w
...
Kntheta = ...% Last semi-infinite constraint at x and w
c = ...% Compute nonlinear inequalities at x
ceq = ...% Compute the nonlinear equalities at x

S is a recommended sampling interval, which might or might not be used. Return [] for c and ceq if no such constraints exist.
The vectors or matrices $K_1$, $K_2$, ..., $K_{n\theta}$ contain the semi-infinite constraints evaluated for a sampled set of values for the independent variables $w_1, w_2, \ldots, w_{n\theta}$, respectively. The two-column matrix, $S$, contains a recommended sampling interval for values of $w_1, w_2, \ldots, w_{n\theta}$, which are used to evaluate $K_1$, $K_2$, ..., $K_{n\theta}$. The $i$th row of $S$ contains the recommended sampling interval for evaluating $K_i$. When $K_i$ is a vector, use only $S(i,1)$ (the second column can be all zeros). When $K_i$ is a matrix, $S(i,2)$ is used for the sampling of the rows in $K_i$, $S(i,1)$ is used for the sampling interval of the columns of $K_i$ (see “Example: Two-Dimensional Semi-Infinite Constraint” on page 6-90). On the first iteration $S$ is NaN, so that some initial sampling interval must be determined by `seminfcon`.

**Note** Because Optimization Toolbox functions only accept inputs of type `double`, user-supplied objective and nonlinear constraint functions must return outputs of type `double`.

“Passing Extra Parameters” on page 2-38 explains how to parameterize `seminfcon`, if necessary. “Example of Creating Sampling Points” on page 6-44 contains an example of both one- and two-dimensional sampling points.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Objective</th>
<th>Objective function</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>Initial point for x</td>
<td></td>
</tr>
<tr>
<td>ntheta</td>
<td>Number of semi-infinite constraints</td>
<td></td>
</tr>
<tr>
<td>seminfcon</td>
<td>Semi-infinite constraint function</td>
<td></td>
</tr>
<tr>
<td>Aineq</td>
<td>Matrix for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>bineq</td>
<td>Vector for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td>Aeq</td>
<td>Matrix for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>beq</td>
<td>Vector for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
</tbody>
</table>
Vector of upper bounds
'sfeminf'
Options structure created with optimset

**Output Arguments**

"Function Arguments" on page 9-2 contains general descriptions of arguments returned by fseminf. This section provides function-specific details for exitflag, lambda, and output:

**exitflag** Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.

1  Function converged to a solution $x$.
4  Magnitude of the search direction was less than the specified tolerance and constraint violation was less than options.TolCon.
5  Magnitude of directional derivative was less than the specified tolerance and constraint violation was less than options.TolCon.
0  Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
-1  Algorithm was terminated by the output function.
-2  No feasible point was found.

**lambda** Structure containing the Lagrange multipliers at the solution $x$ (separated by constraint type). The fields of the structure are

lower  Lower bounds $lb$
fseminf

upper          Upper bounds ub
ineqlin        Linear inequalities
eqlin          Linear equalities
ineqnonlin     Nonlinear inequalities
eqnonlin       Nonlinear equalities

output         Structure containing information about the optimization. The fields of the structure are
iterations     Number of iterations taken
funcCount      Number of function evaluations
lssteplength   Size of line search step relative to search direction
stepsize       Final displacement in x
algorithm      Optimization algorithm used
constrviolation Maximum of constraint functions
firstorderopt  Measure of first-order optimality
message        Exit message

Options

Optimization options used by fseminf. You can use optimset to set or change the values of these fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information.

DerivativeCheck Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default 'off'.

Diagnostics  Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.

11-116
DiffMaxChange  Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.

DiffMinChange  Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.

Display  Level of display:

- 'off' displays no output.
- 'iter' displays output at each iteration, and gives the default exit message.
- 'iter-detailed' displays output at each iteration, and gives the technical exit message.
- 'notify' displays output only if the function does not converge, and gives the default exit message.
- 'notify-detailed' displays output only if the function does not converge, and gives the technical exit message.
- 'final' (default) displays just the final output, and gives the default exit message.
- 'final-detailed' displays just the final output, and gives the technical exit message.
Scalar or vector step size factor. When you set `FinDiffRelStep` to a vector `v`, forward finite differences `delta` are

\[
delta = v.*\text{sign}(x).*\text{max(abs}(x),\text{TypicalX});
\]

and central finite differences are

\[
delta = v.*\text{max}(\text{abs}(x),\text{TypicalX});
\]

Scalar `FinDiffRelStep` expands to a vector. The default is \(\text{sqrt}(\text{eps})\) for forward finite differences, and \(\text{eps}^{1/3}\) for central finite differences.

Finite differences, used to estimate gradients, are either 'forward' (the default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.

The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.

Check whether objective function and constraints values are valid. 'on' displays an error when the objective function or constraints return a value that is complex, Inf, or NaN. The default 'off' displays no error.
GradObj
Gradient for the objective function defined by the user. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have fseminf use a user-defined gradient of the objective function. The default 'off' causes fseminf to estimate gradients using finite differences.

MaxFunEvals
Maximum number of function evaluations allowed, a positive integer. The default is 100*numberOfVariables.

MaxIter
Maximum number of iterations allowed, a positive integer. The default is 400.

MaxSQPIter
Maximum number of SQP iterations allowed, a positive integer. The default is 10*max(numberOfVariables, numberOfInequalities + numberOfBounds).

OutputFcn
Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.
PlotFcns

Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([]):

- @optimplotx plots the current point.
- @optimplotfunccount plots the function count.
- @optimplotfval plots the function value.
- @optimplotconstrviolation plots the maximum constraint violation.
- @optimplotstepsize plots the step size.
- @optimplotfirstorderopt plots the first-order optimality measure.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

RelLineSrchBnd

Relative bound (a real nonnegative scalar value) on the line search step length such that the total displacement in x satisfies $|\Delta x(i)| \leq \text{relLineSrchBnd} \cdot \max(|x(i)|, |typicalx(i)|)$. This option provides control over the magnitude of the displacements in x for cases in which the solver takes steps that fseminf considers too large. The default is no bounds ([]).

RelLineSrchBndDuration

Number of iterations for which the bound specified in RelLineSrchBnd should be active (default is 1)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>TolCon</td>
<td>Termination tolerance on the constraint violation, a positive scalar. The default is 1e-6.</td>
<td></td>
</tr>
<tr>
<td>TolConSQP</td>
<td>Termination tolerance on inner iteration SQP constraint violation, a positive scalar. The default is 1e-6.</td>
<td></td>
</tr>
<tr>
<td>TolFun</td>
<td>Termination tolerance on the function value, a positive scalar. The default is 1e-4.</td>
<td></td>
</tr>
<tr>
<td>TolX</td>
<td>Termination tolerance on x, a positive scalar. The default value is 1e-4.</td>
<td></td>
</tr>
<tr>
<td>TypicalX</td>
<td>Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). fseminf uses TypicalX for scaling finite differences for gradient estimation.</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

The optimization routine fseminf might vary the recommended sampling interval, S, set in seminfcon, during the computation because values other than the recommended interval might be more appropriate for efficiency or robustness. Also, the finite region $w_i$, over which $K_i(x,w_i)$ is calculated, is allowed to vary during the optimization, provided that it does not result in significant changes in the number of local minima in $K_i(x,w_i)$.

**Examples**

This example minimizes the function

$$(x - 1)^2,$$

subject to the constraints
0 ≤ x ≤ 2
\[ g(x, t) = (x - 1/2) - (t - 1/2)^2 \leq 0 \text{ for all } 0 \leq t \leq 1. \]

The unconstrained objective function is minimized at x = 1. However, the constraint,
\[ g(x, t) \leq 0 \text{ for all } 0 \leq t \leq 1, \]
implies x ≤ 1/2. You can see this by noticing that \((t - 1/2)^2 \geq 0\), so
\[ \max_t g(x, t) = (x - 1/2). \]

Therefore
\[ \max_t g(x, t) \leq 0 \text{ when } x \leq 1/2. \]

To solve this problem using fseminf:

1. Write the objective function as an anonymous function:
   \[
   \text{objfun} = @(x)(x-1)^2;
   \]

2. Write the semi-infinite constraint function, which includes the nonlinear constraints ([ ] in this case), initial sampling interval for t (0 to 1 in steps of 0.01 in this case), and the semi-infinite constraint function \( g(x, t) \):
   \[
   \text{function } [c, ceq, K1, s] = \text{seminfcon}(x,s)
   \]
   \[
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   \%
t = 0:s(1):1;

% Evaluate the semi-infinite constraint
K1 = (x - 0.5) - (t - 0.5).^2;

3 Call fseminf with initial point 0.2, and view the result:

x = fseminf(objfun,0.2,1,@seminfcon)

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

Active inequalities (to within options.TolCon = 1e-006):
lower upper ineqlin ineqnonlin

1

x =
0.5000

Algorithms

fseminf uses cubic and quadratic interpolation techniques to estimate peak values in the semi-infinite constraints. The peak values are used to form a set of constraints that are supplied to an SQP method as in the fmincon function. When the number of constraints changes, Lagrange multipliers are reallocated to the new set of constraints.

The recommended sampling interval calculation uses the difference between the interpolated peak values and peak values appearing in the data set to estimate whether the function needs to take more or fewer points. The function also evaluates the effectiveness of the interpolation by extrapolating the curve and comparing it to other points in the curve. The recommended sampling interval is decreased when the peak values are close to constraint boundaries, i.e., zero.
For more details on the algorithm used and the types of procedures displayed under the Procedures heading when the Display option is set to 'iter' with optimset, see also “SQP Implementation” on page 6-30. For more details on the fseminf algorithm, see “fseminf Problem Formulation and Algorithm” on page 6-42.

**Limitations**

The function to be minimized, the constraints, and semi-infinite constraints, must be continuous functions of x and w. fseminf might only give local solutions.

When the problem is not feasible, fseminf attempts to minimize the maximum constraint value.

**See Also**

fmincon | optimset | optimtool | fseminf

**How To**

- @ (function_handle)
- “fseminf Problem Formulation and Algorithm” on page 6-42
- “Constrained Nonlinear Optimization Examples” on page 6-47
Purpose
Solve system of nonlinear equations

Equation
Solves a problem specified by

\[ F(x) = 0 \]

for \( x \), where \( x \) is a vector and \( F(x) \) is a function that returns a vector value.

Syntax
\[
\begin{align*}
x &= \text{fsolve}(\text{fun},x0) \\
x &= \text{fsolve}(\text{fun},x0,\text{options}) \\
x &= \text{fsolve}(\text{problem}) \\
[x,fval] &= \text{fsolve}(\text{fun},x0) \\
[x,fval,\text{exitflag}] &= \text{fsolve}(\text{...}) \\
[x,fval,\text{exitflag},\text{output}] &= \text{fsolve}(\text{...}) \\
[x,fval,\text{exitflag},\text{output},\text{jacobian}] &= \text{fsolve}(\text{...})
\end{align*}
\]

Description
fsolve finds a root (zero) of a system of nonlinear equations.

Note “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the system of equations, if necessary.

\[
x = \text{fsolve}(\text{fun},x0) \text{ starts at } x0 \text{ and tries to solve the equations described in } \text{fun}.
\]

\[
x = \text{fsolve}(\text{fun},x0,\text{options}) \text{ solves the equations with the optimization options specified in the structure } \text{options}. \text{ Use optimset to set these options.}
\]

\[
x = \text{fsolve}(\text{problem}) \text{ solves problem, where } \text{problem} \text{ is a structure described in “Input Arguments” on page 11-126.}
\]

Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

\[
[x,fval] = \text{fsolve}(\text{fun},x0) \text{ returns the value of the objective function } \text{fun at the solution } x.
\]
[x,fval,exitflag] = fsolve(...) returns a value exitflag that describes the exit condition.

[x,fval,exitflag,output] = fsolve(...) returns a structure output that contains information about the optimization.

[x,fval,exitflag,output,jacobian] = fsolve(...) returns the Jacobian of fun at the solution x.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into fsolve. This section provides function-specific details for fun and problem:

**fun**

The nonlinear system of equations to solve. fun is a function that accepts a vector x and returns a vector F, the nonlinear equations evaluated at x. The function fun can be specified as a function handle for a file

\[ x = \text{fsolve}(@\text{myfun},x0) \]

where myfun is a MATLAB function such as

```matlab
function F = myfun(x)
    F = ... % Compute function values at x
```

fun can also be a function handle for an anonymous function.

\[ x = \text{fsolve}(@(x)\sin(x.*x),x0); \]

If the user-defined values for x and F are matrices, they are converted to a vector using linear indexing.

If the Jacobian can also be computed and the Jacobian option is 'on', set by

```matlab
options = optimset('Jacobian','on')
```

the function fun must return, in a second output argument, the Jacobian value J, a matrix, at x.
If `fun` returns a vector (matrix) of \( m \) components and \( x \) has length \( n \), where \( n \) is the length of \( x_0 \), the Jacobian \( J \) is an \( m \)-by-\( n \) matrix where \( J(i, j) \) is the partial derivative of \( F(i) \) with respect to \( x(j) \). (The Jacobian \( J \) is the transpose of the gradient of \( F \).)

### Problem
- `objective`: Objective function
- `x0`: Initial point for \( x \)
- `solver`: `'fsolve'`
- `options`: Options structure created with `optimset`

### Output Arguments
“Function Arguments” on page 9-2 contains general descriptions of arguments returned by `fsolve`. For more information on the output headings for `fsolve`, see “Function-Specific Headings” on page 3-17.

This section provides function-specific details for `exitflag` and `output`:

- **exitflag**: Integer identifying the reason the algorithm terminated.
  - 1: Function converged to a solution \( x \).
  - 2: Change in \( x \) was smaller than the specified tolerance.
  - 3: Change in the residual was smaller than the specified tolerance.
  - 4: Magnitude of search direction was smaller than the specified tolerance.
  - 0: Number of iterations exceeded `options.MaxIter` or number of function evaluations exceeded `options.FunEvals`.
  - -1: Output function terminated the algorithm.
Algorithm appears to be converging to a point that is not a root.

Trust region radius became too small (trust-region-dogleg algorithm) or regularization parameter became too large (levenberg-marquardt algorithm).

Line search cannot sufficiently decrease the residual along the current search direction.

Structure containing information about the optimization. The fields of the structure are:

- iterations: Number of iterations taken
- funcCount: Number of function evaluations
- algorithm: Optimization algorithm used
- cgiterations: Total number of PCG iterations (large-scale algorithm only)
- stepsize: Final displacement in x (Levenberg-Marquardt algorithm)
- firstorderopt: Measure of first-order optimality (dogleg or large-scale algorithm, [] for others)
- message: Exit message

Optimization options used by fsolve. Some options apply to all algorithms, some are only relevant when using the trust-region-reflective algorithm, and others are only relevant when using the other algorithms. You can use optimset to set or change the values of these fields in the options structure, options. See “Optimization Options Reference” on page 9-7 for detailed information.
All Algorithms

All algorithms use the following options:

Algorithm Choose between 'trust-region-dogleg' (default), 'trust-region-reflective', and 'levenberg-marquardt'. Set the initial Levenberg-Marquardt parameter λ by setting Algorithm to a cell array such as {'levenberg-marquardt',.005}. The default λ = 0.01.

The Algorithm option specifies a preference for which algorithm to use. It is only a preference because for the trust-region-reflective algorithm, the nonlinear system of equations cannot be underdetermined; that is, the number of equations (the number of elements of F returned by fun) must be at least as many as the length of x. Similarly, for the trust-region-dogleg algorithm, the number of equations must be the same as the length of x. fsolve uses the Levenberg-Marquardt algorithm when the selected algorithm is unavailable. For more information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

DerivativeCheck Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default 'off'.

Diagnostics Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.

DiffMaxChange Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DiffMinChange</strong></td>
<td>Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.</td>
</tr>
<tr>
<td><strong>Display</strong></td>
<td>Level of display:</td>
</tr>
<tr>
<td></td>
<td>• 'off' displays no output.</td>
</tr>
<tr>
<td></td>
<td>• 'iter' displays output at each iteration.</td>
</tr>
<tr>
<td></td>
<td>• 'notify' displays output only if the function does not converge.</td>
</tr>
<tr>
<td></td>
<td>• 'final' (default) displays just the final output.</td>
</tr>
<tr>
<td><strong>FinDiffRelStep</strong></td>
<td>Scalar or vector step size factor. When you set FinDiffRelStep to a vector $v$, forward finite differences $\delta$ are</td>
</tr>
<tr>
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<td>$\delta = v.<em>\text{sign}(x).</em>\max(\text{abs}(x),\text{TypicalX})$;</td>
</tr>
<tr>
<td></td>
<td>and central finite differences are $\delta = v.*\max(\text{abs}(x),\text{TypicalX})$;</td>
</tr>
<tr>
<td></td>
<td>Scalar FinDiffRelStep expands to a vector. The default is $\sqrt{\epsilon}$ for forward finite differences, and $\epsilon^{(1/3)}$ for central finite differences.</td>
</tr>
<tr>
<td><strong>FinDiffType</strong></td>
<td>Finite differences, used to estimate gradients, are either 'forward' (default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.</td>
</tr>
<tr>
<td></td>
<td>The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------</td>
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</tr>
<tr>
<td>FunValCheck</td>
<td>Check whether objective function values are valid. 'on' displays an error when the objective function returns a value that is complex, Inf, or NaN. The default, 'off', displays no error.</td>
</tr>
<tr>
<td>Jacobian</td>
<td>If 'on', fsolve uses a user-defined Jacobian (defined in fun), or Jacobian information (when using JacobMult), for the objective function. If 'off' (default), fsolve approximates the Jacobian using finite differences.</td>
</tr>
<tr>
<td>MaxFunEvals</td>
<td>Maximum number of function evaluations allowed, a positive integer. The default is 100*numberOfVariables.</td>
</tr>
<tr>
<td>MaxIter</td>
<td>Maximum number of iterations allowed, a positive integer. The default is 400.</td>
</tr>
<tr>
<td>OutputFcn</td>
<td>Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([ ]). See “Output Function” on page 9-18.</td>
</tr>
<tr>
<td>PlotFcns</td>
<td>Plots various measures of progress while the algorithm executes. Select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]):</td>
</tr>
</tbody>
</table>
- @optimplotfirstorderopt plots the first-order optimality measure.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

**TolFun**
Termination tolerance on the function value, a positive scalar. The default is 1e-6.

**TolX**
Termination tolerance on x, a positive scalar. The default is 1e-6.

**TypicalX**
Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is `ones(numberofvariables,1)`. fsolve uses TypicalX for scaling finite differences for gradient estimation.

The trust-region-dogleg algorithm uses TypicalX as the diagonal terms of a scaling matrix.

**Trust-Region-Reflective Algorithm Only**
The trust-region-reflective algorithm uses the following options:

**JacobMult**
Function handle for Jacobian multiply function. For large-scale structured problems, this function computes the Jacobian matrix product J*Y, J'*Y, or J'*(J*Y) without actually forming J. The function is of the form

\[ W = jmfun(Jinfo,Y,flag) \]

where Jinfo contains a matrix used to compute J*Y (or J'*Y, or J'*(J*Y)). The first argument Jinfo must be the same as the second argument.
returned by the objective function fun, for example, in

\[ [F,J\text{info}] = \text{fun}(x) \]

Y is a matrix that has the same number of rows as there are dimensions in the problem. flag determines which product to compute:

- If flag == 0, \( W = J' \ast (J \ast Y) \).
- If flag > 0, \( W = J \ast Y \).
- If flag < 0, \( W = J' \ast Y \).

In each case, J is not formed explicitly. fsolve uses Jinfo to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply values for any additional parameters jmfun needs.

**Note** 'Jacobian' must be set to 'on' for fsolve to pass Jinfo from fun to jmfun.

See “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68 for a similar example.
**fsolve**

**JacobPattern**  Sparsity pattern of the Jacobian for finite differencing. If it is not convenient to compute the Jacobian matrix $J$ in `fun`, `lsqnonlin` can approximate $J$ via sparse finite differences, provided you supply the structure of $J$ (i.e., locations of the nonzeros) as the value for `JacobPattern`. In the worst case, if the structure is unknown, you can set `JacobPattern` to be a dense matrix and a full finite-difference approximation is computed in each iteration (this is the default if `JacobPattern` is not set). This can be very expensive for large problems, so it is usually worth the effort to determine the sparsity structure.

**MaxPCGIter**  Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is \( \max(1, \text{floor(numberOfVariables/2)}) \). For more information, see “Algorithms” on page 11-138.

**PrecondBandWidth**  Upper bandwidth of preconditioner for PCG, a nonnegative integer. The default `PrecondBandWidth` is Inf, which means a direct factorization (Cholesky) is used rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution. Set `PrecondBandWidth` to 0 for diagonal preconditioning (upper bandwidth of 0). For some problems, an intermediate bandwidth reduces the number of PCG iterations.

**To1PCG**  Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.
Levenberg-Marquardt Algorithm Only

The Levenberg-Marquardt algorithm uses the following option:

ScaleProblem 'Jacobian' can sometimes improve the convergence of a poorly scaled problem. The default is 'none'.

Examples

Example 1

This example solves the system of two equations and two unknowns:

\[
\begin{align*}
2x_1 - x_2 &= e^{-x_1} \\
-x_1 + 2x_2 &= e^{-x_2}.
\end{align*}
\]

Rewrite the equations in the form \( F(x) = 0 \):

\[
\begin{align*}
2x_1 - x_2 - e^{-x_1} &= 0 \\
-x_1 + 2x_2 - e^{-x_2} &= 0.
\end{align*}
\]

Start your search for a solution at \( x_0 = [-5, -5] \).

First, write a file that computes \( F \), the values of the equations at \( x \).

```matlab
function F = myfun(x)
F = [2*x(1) - x(2) - exp(-x(1));
    -x(1) + 2*x(2) - exp(-x(2))];
```

Save this function file as `myfun.m` somewhere on your MATLAB path.

Next, set up the initial point and options and call `fsolve`:

```matlab
x0 = [-5; -5]; % Make a starting guess at the solution
options=optimset('Display','iter'); % Option to display output
[x,fval] = fsolve(@myfun,x0,options) % Call solver
```

After several iterations, `fsolve` finds an answer:

```matlab
Norm of First-order Trust-region
```
## fsolve

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Func-count</th>
<th>f(x)</th>
<th>step</th>
<th>optimality</th>
<th>radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>23535.6</td>
<td></td>
<td>2.29e+004</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>6001.72</td>
<td>1</td>
<td>5.75e+003</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1573.51</td>
<td>1</td>
<td>1.47e+003</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>427.226</td>
<td>1</td>
<td>388</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>119.763</td>
<td>1</td>
<td>107</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>33.5206</td>
<td>1</td>
<td>30.8</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>8.35208</td>
<td>1</td>
<td>9.05</td>
<td>1</td>
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<tr>
<td>7</td>
<td>24</td>
<td>1.21394</td>
<td>1</td>
<td>2.26</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>27</td>
<td>0.016329</td>
<td>0.759511</td>
<td>0.206</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>3.51575e-006</td>
<td>0.111927</td>
<td>0.00294</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>33</td>
<td>1.64763e-013</td>
<td>0.00169132</td>
<td>6.36e-007</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

\[ x = \begin{bmatrix} 0.5671 \\ 0.5671 \end{bmatrix} \]

\[ fval = \begin{bmatrix} -0.4059 \\ -0.4059 \end{bmatrix} \]

### Example 2

Find a matrix \( x \) that satisfies the equation

\[
X \ast X \ast X = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix},
\]

starting at the point \( x = [1,1; 1,1] \).

First, write a file that computes the equations to be solved.
function F = myfun(x)
F = x*x*x-[1,2;3,4];

Save this function file as myfun.m somewhere on your MATLAB path. Next, set up an initial point and options and call fsolve:

\[
x0 = \text{ones}(2,2); \quad \% \text{Make a starting guess at the solution}
\]
\[
\text{options} = \text{optimset}('\text{Display}', '\text{off}'); \quad \% \text{Turn off display}
\]
\[
[x,Fval,exitflag] = \text{fsolve}(@\text{myfun},x0,\text{options})
\]

The solution is

\[
x =
\begin{bmatrix}
-0.1291 & 0.8602 \\
1.2903 & 1.1612
\end{bmatrix}
\]

\[
Fval =
\begin{bmatrix}
1.0e-009 & -0.1621 & 0.0780 \\
0.1164 & -0.0467
\end{bmatrix}
\]

\[
\text{exitflag} =
\begin{bmatrix}
1
\end{bmatrix}
\]

and the residual is close to zero.

\[
\text{sum(sum(Fval.*Fval))}
\]
\[
\text{ans} =
\begin{bmatrix}
4.8081e-020
\end{bmatrix}
\]

**Notes**

If the system of equations is linear, use \(\backslash\) (matrix left division) for better speed and accuracy. For example, to find the solution to the following linear system of equations:

\[
3x_1 + 11x_2 - 2x_3 = 7
\]
\[
x_1 + x_2 - 2x_3 = 4
\]
\[
x_1 - x_2 + x_3 = 19.
\]
Formulate and solve the problem as

\[
A = \begin{bmatrix}
3 & 11 & -2 \\
1 & 1 & -2 \\
1 & -1 & 1
\end{bmatrix};
\]

\[
b = \begin{bmatrix}
7 \\
4 \\
19
\end{bmatrix};
\]

\[
x = A\backslash b
\]

\[
x = \\
\quad 13.2188 \\
\quad -2.3438 \\
\quad 3.4375
\]

### Algorithms

The Levenberg-Marquardt and trust-region-reflective methods are based on the nonlinear least-squares algorithms also used in `lsqnonlin`. Use one of these methods if the system may not have a zero. The algorithm still returns a point where the residual is small. However, if the Jacobian of the system is singular, the algorithm might converge to a point that is not a solution of the system of equations (see “Limitations” on page 11-139 and “Diagnostics” on page 11-138 following).

- By default `fsolve` chooses the trust-region dogleg algorithm. The algorithm is a variant of the Powell dogleg method described in [8]. It is similar in nature to the algorithm implemented in [7]. It is described in the User's Guide in “Trust-Region Dogleg Method” on page 6-183.

- The trust-region-reflective algorithm is a subspace trust-region method and is based on the interior-reflective Newton method described in [1] and [2]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). See “Trust-Region Reflective `fsolve` Algorithm” on page 6-186.

- The Levenberg-Marquardt method is described in [4], [5], and [6]. It is described in the User’s Guide in “Levenberg-Marquardt Method” on page 6-189.

### Diagnostics

#### All Algorithms

`fsolve` may converge to a nonzero point and give this message:
Optimizer is stuck at a minimum that is not a root
Try again with a new starting guess

In this case, run `fsolve` again with other starting values.

**Trust-Region-Dogleg Algorithm**

For the trust-region dogleg method, `fsolve` stops if the step size becomes too small and it can make no more progress. `fsolve` gives this message:

```
The optimization algorithm can make no further progress:
Trust region radius less than 10*eps
```

In this case, run `fsolve` again with other starting values.

**Limitations**

The function to be solved must be continuous. When successful, `fsolve` only gives one root. `fsolve` may converge to a nonzero point, in which case, try other starting values.

`fsolve` only handles real variables. When x has complex variables, the variables must be split into real and imaginary parts.

**Trust-Region-Reflective Algorithm**

The preconditioner computation used in the preconditioned conjugate gradient part of the trust-region-reflective algorithm forms $J^TJ$ (where $J$ is the Jacobian matrix) before computing the preconditioner; therefore, a row of $J$ with many nonzeros, which results in a nearly dense product $J^TJ$, might lead to a costly solution process for large problems.

**Large-Scale Problem Coverage and Requirements**

<table>
<thead>
<tr>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provide sparsity structure of the Jacobian or compute the Jacobian in <code>fun</code>.</td>
</tr>
<tr>
<td>• The Jacobian should be sparse.</td>
</tr>
</tbody>
</table>
Number of Equations

The default trust-region dogleg method can only be used when the system of equations is square, i.e., the number of equations equals the number of unknowns. For the Levenberg-Marquardt method, the system of equations need not be square.

References


See Also

`lsqcurvefit` | `lsqnonlin` | `optimset` | `optimtool` | `fsolve`
How To

• @ (function_handle)
• \n
• “Anonymous Functions”
• “Equation Solving Algorithms” on page 6-183
• “Equation Solving Examples” on page 6-191
Purpose
Find root of continuous function of one variable

Syntax
x = fzero(fun,x0)
x = fzero(fun,x0,options)
x = fzero(problem)
[x,fval] = fzero(...)
[x,fval,exitflag] = fzero(...)
[x,fval,exitflag,output] = fzero(...)

Description
x = fzero(fun,x0) tries to find a zero of fun near x0, if x0 is a scalar. fun is a function handle for either a function file or an anonymous function. The value x returned by fzero is near a point where fun changes sign, or NaN if the search fails. In this case, the search terminates when the search interval is expanded until an Inf, NaN, or complex value is found.

Note “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to fun, if necessary.

If x0 is a vector of length two, fzero assumes x0 is an interval where the sign of fun(x0(1)) differs from the sign of fun(x0(2)). An error occurs if this is not true. Calling fzero with such an interval guarantees that fzero returns a value near a point where fun changes sign. An interval x0 must be finite; it cannot contain ±Inf.

Note Calling fzero with an interval (x0 with two elements) is often faster than calling it with a scalar x0.

x = fzero(fun,x0,options) solves the equation with the optimization options specified in the structure options. Use optimset to set these options.
x = fzero(problem) solves problem, where problem is a structure described in “Input Arguments” on page 11-143.

Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = fzero(...) returns the value of the objective function fun at the solution x.

[x,fval,exitflag] = fzero(...) returns a value exitflag that describes the exit condition.

[x,fval,exitflag,output] = fzero(...) returns a structure output that contains information about the optimization.

Note For the purposes of this command, zeros are considered to be points where the function actually crosses—not just touches—the x-axis.

Input Arguments

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into fzero. This section provides function-specific details for fun, options, and problem:

fun

The function whose zero is to be computed. fun is a function handle for a function that accepts a scalar x and returns a scalar, the objective function evaluated at x.

The function fun can be specified as a function handle for a function file:

x = fzero(@myfun,x0)

where myfun is a MATLAB function such as

function f = myfun(x)
f = ...               % Compute function value at x

fun can also be a function handle for an anonymous function.
x = fzero(@(x)sin(x*x),x0);

Options
Optimization options. You can set or change the values of these options using the optimset function. fzero uses these options structure fields:

Display
Level of display:

- 'off' displays no output.
- 'iter' displays output at each iteration.
- 'final' displays just the final output.
- 'notify' (default) displays output only if the function does not converge.

FunValCheck
Check whether objective function values are valid. 'on' displays an error when the objective function returns a value that is complex, Inf, or NaN. The default, 'off', displays no error.

OutputFcn
Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.
PlotFcns: Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([]).

- @optimplotx plots the current point
- @optimplotfval plots the function value

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

TolX: Termination tolerance on x, a positive scalar. The default is eps, 2.2204e-16.

Output Arguments

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by `fzero`. This section provides function-specific details for `exitflag` and `output`:

- `exitflag` Integer identifying the reason the algorithm terminated. The following lists the values of `exitflag` and the corresponding reasons the algorithm terminated.
  - 1 Function converged to a solution x.
-1 Algorithm was terminated by the output function.
-3 NaN or Inf function value was encountered during search for an interval containing a sign change.
-4 Complex function value was encountered during search for an interval containing a sign change.
-5 Algorithm might have converged to a singular point.

output Structure containing information about the optimization. The fields of the structure are
intervaliterations Number of iterations taken to find an interval containing a root
iterations Number of zero-finding iterations
funcCount Number of function evaluations
algorithm 'bisection, interpolation'
message Exit message

Examples Calculate $\pi$ by finding the zero of the sine function near 3.

```matlab
x = fzero(@sin,3)
x =
   3.1416
```

To find the zero of cosine between 1 and 2, enter
x = fzero(@cos,[1 2])
x =
  1.5708

Note that \( \cos(1) \) and \( \cos(2) \) differ in sign.

To find a zero of the function

\[
f(x) = x^3 - 2x - 5,
\]

write a file called f.m.

```matlab
function y = f(x)
y = x.^3-2*x-5;
```

To find the zero near 2, enter

```matlab
z = fzero(@f,2)
z =
  2.0946
```

Since this function is a polynomial, the statement

```matlab
roots([1 0 -2 -5])
```

finds the same real zero, and a complex conjugate pair of zeros:

```matlab
ans =
  2.0946
  -1.0473 + 1.1359i
  -1.0473 - 1.1359i
```

**Algorithms**

The `fzero` command is a function file. The algorithm, which was originated by T. Dekker, uses a combination of bisection, secant, and inverse quadratic interpolation methods. An Algol 60 version, with some improvements, is given in [1]. A Fortran version, upon which `fzero` is based, is in [2].
**Limitations**

The `fzero` command finds a point where the function changes sign. If the function is *continuous*, this is also a point where the function has a value near zero. If the function is not continuous, `fzero` may return values that are discontinuous points instead of zeros. For example, `fzero(@tan,1)` returns `1.5708`, a discontinuous point in tan.

Furthermore, the `fzero` command defines a *zero* as a point where the function crosses the x-axis. Points where the function touches, but does not cross, the x-axis are not valid zeros. For example, `y = x.^2` is a parabola that touches the x-axis at 0. Since the function never crosses the x-axis, however, no zero is found. For functions with no valid zeros, `fzero` executes until `Inf`, `NaN`, or a complex value is detected.

**References**


**See Also**

`fminbnd` | `fsolve` | `optimset` | `optimtool` | `roots`

**How To**

- `@ (function_handle)`
- `
- “Anonymous Functions”`
Fzmult

**Purpose**

Multiplication with fundamental nullspace basis

**Syntax**

- `W = fzmult(A,V)`
- `W = fzmult(A,V,'transpose')`
- `[W,L,U,pcol,P] = fzmult(A,V)`
- `W = fzmult(A,V,transpose,L,U,pcol,P)`

**Description**

`W = fzmult(A,V)` computes the product `W` of matrix `Z` with matrix `V`, that is, `W = Z * V`, where `Z` is a fundamental basis for the nullspace of matrix `A`. `A` must be a sparse `m`-by-`n` matrix where `m < n`, `rank(A) = m`, and `rank(A(1:m,1:m)) = m`. `V` must be `p`-by-`q`, where `p = n - m`. If `V` is sparse, `W` is sparse, else `W` is full.

`W = fzmult(A,V,'transpose')` computes the product of the transpose of the fundamental basis times `V`, that is, `W = Z' * V`. `V` must be `p`-by-`q`, where `q = n - m`. `fzmult(A,V)` is the same as `fzmult(A,V,[])`.

`[W,L,U,pcol,P] = fzmult(A,V)` returns the sparse LU-factorization of matrix `A(1:m,1:m)`, that is, `A1 = A(1:m,1:m)` and `P*A1(:,pcol) = L*U`.

`W = fzmult(A,V,transpose,L,U,pcol,P)` uses the precomputed sparse LU factorization of matrix `A(1:m,1:m)`, that is, `A1 = A(1:m,1:m)` and `P*A1(:,pcol) = L*U`. `transpose` is either 'transpose' or [].

The nullspace basis matrix `Z` is not formed explicitly. An implicit representation is used based on the sparse LU factorization of `A(1:m,1:m)`. 

11-149
Purpose
Zero out “small” entries subject to structural rank

Syntax
A = gangstr(M, tol)

Description
A = gangstr(M, tol) creates matrix A of full structural rank such that A is M except that elements of M that are relatively “small,” based on tol, are zeros in A. The algorithm decreases tol, if needed, until sprank(A) = sprank(M). M must have at least as many columns as rows. Default tol is 1e-2.

gangstr identifies elements of M that are relatively less than tol by first normalizing all the rows of M to have norm 1. It then examines nonzeros in M in a columnwise fashion, replacing with zeros those elements with values of magnitude less than tol times the maximum absolute value in that column.

See Also
sprank | spy
**Purpose**
Find minimum of constrained or unconstrained nonlinear multivariable function using KNITRO third-party libraries

**Equation**
Finds the minimum of a problem specified by

\[
\min_{x} f(x) \text{ such that } \begin{cases} 
    c(x) \leq 0 \\
    ceq(x) = 0 \\
    A \cdot x \leq b \\
    Aeq \cdot x = beq \\
    lb \leq x \leq ub,
\end{cases}
\]

where \( x, b, beq, lb, \) and \( ub \) are vectors, \( A \) and \( Aeq \) are matrices, \( c(x) \) and \( ceq(x) \) are functions that return vectors, and \( f(x) \) is a function that returns a scalar. \( f(x), c(x), \) and \( ceq(x) \) can be nonlinear functions. All constraints are optional; \text{ktrlink} \ can minimize unconstrained problems.

**Syntax**

\[
x = \text{ktrlink}(\text{fun},x0) \\
x = \text{ktrlink}(\text{fun},x0,A,b) \\
x = \text{ktrlink}(\text{fun},x0,A,b,Aeq,beq) \\
x = \text{ktrlink}(\text{fun},x0,A,b,Aeq,beq,lb,ub) \\
x = \text{ktrlink}(\text{fun},x0,A,b,Aeq,beq,lb,ub,\text{nonlcon}) \\
x = \text{ktrlink}(\text{fun},x0,A,b,Aeq,beq,lb,ub,\text{nonlcon},\text{options},\text{knitroOptions}) \\
[x,fval] = \text{ktrlink}(\ldots) \\
[x,fval,\text{exitflag}] = \text{ktrlink}(\ldots) \\
[x,fval,\text{exitflag},\text{output}] = \text{ktrlink}(\ldots) \\
[x,fval,\text{exitflag},\text{output},\text{lambda}] = \text{ktrlink}(\ldots)
\]

**Description**

\text{ktrlink} \ attempts to find a minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as \textit{constrained} or \textit{unconstrained nonlinear optimization}, or \textit{nonlinear programming}.
Note “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the objective function and nonlinear constraint functions, if necessary.

\[ x = \text{ktrlink}(\text{fun}, x_0) \]
starts at \( x_0 \) and attempts to find a minimizer \( x \) of the function described in \( \text{fun} \), subject to no constraints. \( x_0 \) can be a scalar, vector, or matrix.

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b) \]
minimizes \( \text{fun} \) subject to the linear inequalities \( A \cdot x \leq b \).

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b, \text{Aeq}, \text{beq}) \]
minimizes \( \text{fun} \) subject to the linear equalities \( \text{Aeq} \cdot x = \text{beq} \) as well as \( A \cdot x \leq b \). If no inequalities exist, set \( A = \text{[]} \) and \( b = \text{[]} \).

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}) \]
defines a set of lower and upper bounds on the design variables in \( x \), so that the solution is always in the range \( \text{lb} \leq x \leq \text{ub} \). If no equalities exist, set \( \text{Aeq} = \text{[]} \) and \( \text{beq} = \text{[]} \). If \( x(i) \) is unbounded below, set \( \text{lb}(i) = -\text{Inf} \), and if \( x(i) \) is unbounded above, set \( \text{ub}(i) = \text{Inf} \).

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}, \text{nonlcon}) \]
subjects the minimization to the nonlinear inequalities \( c(x) \) and the equalities \( \text{ceq}(x) \) defined in \( \text{nonlcon} \). \text{fmincon} optimizes such that \( c(x) \leq 0 \) and \( \text{ceq}(x) = 0 \). If no bounds exist, set \( \text{lb} = \text{[]} \) and/or \( \text{ub} = \text{[]} \).

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}, \text{nonlcon}, \text{options}) \]
minimizes with the optimization options specified in the structure \( \text{options} \). Use \text{optimset} to set these options. If there are no nonlinear inequality or equality constraints, set \( \text{nonlcon} = \text{[]} \).

\[ x = \text{ktrlink}(\text{fun}, x_0, A, b, \text{Aeq}, \text{beq}, \text{lb}, \text{ub}, \text{nonlcon}, \text{options}, \text{knitroOptions}) \]
minimizes with the KNITRO options specified in the text file \text{knitroOptions}. All options given in \text{options} are ignored except for \text{HessFcn}, \text{HessMult}, \text{HessPattern}, and \text{JacobPattern}.

\[ [x, fval] = \text{ktrlink}(\ldots) \]
returns the value of the objective function \( \text{fun} \) at the solution \( x \).
[\text{x}, \text{fval}, \text{exitflag}] = \text{ktrlink}(\ldots) \text{ returns } \text{exitflag}, \text{which describes the exit condition of the KNITRO solver.}

[\text{x}, \text{fval}, \text{exitflag}, \text{output}] = \text{ktrlink}(\ldots) \text{ returns a structure output with information about the optimization.}

[\text{x}, \text{fval}, \text{exitflag}, \text{output}, \text{lambda}] = \text{ktrlink}(\ldots) \text{ returns a structure lambda whose fields contain the Lagrange multipliers at the solution } \text{x}.

\textbf{Note} \text{ If the specified input bounds for a problem are inconsistent, the output } \text{x} \text{ is } \text{x0} \text{ and the output } \text{fval} \text{ is } \text{[].}

Components of \text{x0} \text{ that violate the bounds } \text{lb} \leq \text{x} \leq \text{ub} \text{ are reset to the interior of the box defined by the bounds. Components that respect the bounds are not changed.}

\textbf{Input Arguments} \text{ “Function Arguments” on page 9-2 contains descriptions of arguments passed to \text{ktrlink}. “Options” on page 11-49 provides the function-specific details for the options values. This section provides function-specific details for \text{fun} and \text{nonlcon}.}

\text{fun} \text{ The function to be minimized. } \text{fun} \text{ is a function that accepts a vector } \text{x} \text{ and returns a scalar } \text{f}, \text{ the objective function evaluated at } \text{x}. \text{fun} \text{ can be specified as a function handle for a function file:}

\text{x} = \text{ktrlink}(\text{@myfun}, \text{x0}, \text{A}, \text{b})

\text{where myfun is a MATLAB function such as}

\text{function } \text{f} = \text{myfun}(\text{x})
\text{f} = \ldots \quad \% \text{Compute function value at } \text{x}

\text{fun} \text{ can also be a function handle for an anonymous function.}

\text{x} = \text{ktrlink}(\text{@(x)norm(x)^2}, \text{x0}, \text{A}, \text{b});
If you can compute the gradient of \texttt{fun} and the \texttt{GradObj} option is 'on', as set by

\begin{verbatim}
options = optimset('GradObj','on')
\end{verbatim}

then \texttt{fun} must return the gradient vector \( g(x) \) in the second output argument.

If you can compute the Hessian matrix, there are several ways to pass the Hessian to \texttt{ktrlink}. See “Hessian” on page 11-156 for details.

The function that computes the nonlinear inequality constraints \( c(x) \leq 0 \) and the nonlinear equality constraints \( \text{ceq}(x) = 0 \). \texttt{nonlcon} accepts a vector \( x \) and returns the two vectors \( c \) and \( \text{ceq} \). \( c \) contains the nonlinear inequalities evaluated at \( x \), and \( \text{ceq} \) contains the nonlinear equalities evaluated at \( x \). The function \texttt{nonlcon} can be specified as a function handle.

\begin{verbatim}
x = ktrlink(@myfun,x0,A,b,Aeq,beq,lb,ub,@mycon)
\end{verbatim}

where \texttt{mycon} is a MATLAB function such as

\begin{verbatim}
function [c,ceq] = mycon(x)
c = ... % Compute nonlinear inequalities at x.
ceq = ... % Compute nonlinear equalities at x.
\end{verbatim}

If you can compute the gradients of the constraints and the \texttt{GradConstr} option is 'on', as set by

\begin{verbatim}
options = optimset('GradConstr','on')
\end{verbatim}

then \texttt{nonlcon} must also return \( GC \), the gradient of \( c(x) \), and \( G\text{ceq} \), the gradient of \( \text{ceq}(x) \), in the third and fourth output arguments respectively. See “Nonlinear Constraints” on page 2-33 for details.
“Passing Extra Parameters” on page 2-38 explains how to parameterize the nonlinear constraint function `nonlcon`, if necessary.

**Output Arguments**

“Function Arguments” on page 9-2 contains descriptions of arguments returned by `ktrlink`. This section provides function-specific details for `exitflag`, `lambda`, and `output`:

- **exitflag**: Integer identifying the reason the algorithm terminated. For more information, see the KNITRO documentation at `http://www.ziena.com/`.
- **lambda**: Structure containing the Lagrange multipliers at the solution `x` (separated by constraint type). The fields of the structure are:
  - `lower`: Lower bounds `lb`
  - `upper`: Upper bounds `ub`
  - `ineqlin`: Linear inequalities
  - `eqlin`: Linear equalities
  - `ineqnonlin`: Nonlinear inequalities
  - `eqnonlin`: Nonlinear equalities
- **output**: Structure containing information about the optimization. The fields of the structure are:
  - `iterations`: Number of iterations taken
  - `funcCount`: Number of function evaluations
Maximum of constraint violations (interior-point algorithm only)

Measure of first-order optimality

**Hessian**

`ktrlink` can optionally use a user-supplied Hessian, the matrix of second derivatives of the Lagrangian, namely,

\[ \nabla^2_{xx} L(x, \lambda) = \nabla^2 f(x) + \sum \lambda_i \nabla^2 c_i(x) + \sum \lambda_i \nabla^2 ceq_i(x). \]  \hspace{1cm} (11-2)

If you don’t supply a Hessian, KNITRO software estimates it.

To provide a Hessian, the syntax is

```matlab
hessian = hessianfcn(x, lambda)
```

`hessian` is an `n`-by-`n` matrix, sparse or dense, where `n` is the number of variables. `lambda` is a structure with the Lagrange multiplier vectors associated with the nonlinear constraints:

```matlab
lambda.ineqnonlin
lambda.eqnonlin
```

KNITRO software computes `lambda`. `hessianfcn` must calculate the sums in Equation 11-2. Indicate that you are supplying a Hessian by

```matlab
options = optimset('Hessian','user-supplied', 'HessFcn', @hessianfcn);
```

There are several more options for Hessians:

- ```matlab
    options = optimset('Hessian','bfgs');
    ```

The KNITRO solver calculates the Hessian by a dense quasi-Newton approximation.
• options = optimset('Hessian',...
   {'lbfgs',positive integer});

   The KNITRO solver calculates the Hessian by a limited-memory, large-scale quasi-Newton approximation. The positive integer specifies how many past iterations should be remembered.

• options = optimset('Hessian','fin-diff-grads',...
   'SubproblemAlgorithm','cg','GradObj','on',...
   'GradConstr','on');

   The KNITRO solver calculates a Hessian-times-vector product by finite differences of the gradient(s). You must supply the gradient of the objective function, and also gradients of any nonlinear constraint functions.

• options = optimset('Hessian','user-supplied',...
   'SubproblemAlgorithm','cg','HessMult',@HessMultFcn);

   The KNITRO solver uses a Hessian-times-vector product. You must supply the function HessMultFcn, which returns an n-by-1 vector. The HessMult option enables you to pass the result of multiplying the Hessian by a vector without calculating the Hessian.

   The syntax for the 'HessMult' option is:

   w = HessMultFcn(x,lambda,v);

   The result w should be the product H*v, where H is the Hessian at x, lambda is the Lagrange multiplier (computed by KNITRO software), and v is a vector.

   **Options**

   Optimization options used by ktrlink. Use optimset to set or change the values of fields in the options structure options. See “Optimization Options Reference” on page 9-7 for detailed information. For example:

   options=optimset('Algorithm','active-set');
<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>Choose a KNITRO optimization algorithm: 'interior-point' or 'active-set'.</td>
</tr>
<tr>
<td>AlwaysHonorConstraints</td>
<td>The default 'bounds' ensures that bound constraints are satisfied at every iteration. Disable by setting to 'none'.</td>
</tr>
<tr>
<td>Display</td>
<td>Level of display:</td>
</tr>
<tr>
<td></td>
<td>• 'off' displays no output.</td>
</tr>
<tr>
<td></td>
<td>• 'iter' displays output at each iteration.</td>
</tr>
<tr>
<td></td>
<td>• 'final' (default) displays just the final output.</td>
</tr>
<tr>
<td>FinDiffType</td>
<td>Finite differences, used to estimate gradients, are either 'forward' (the default), or 'central' (centered). 'central' takes twice as many function evaluations but should be more accurate. 'central' differences might violate bounds during their evaluation.</td>
</tr>
<tr>
<td>GradObj</td>
<td>Gradient for the objective function defined by the user. See the preceding description of fun to see how to define the gradient in fun. Set to 'on' to have KNITRO use a user-defined gradient of the objective function. The default 'off' causes KNITRO to estimate gradients using finite differences.</td>
</tr>
<tr>
<td>HessFcn</td>
<td>Function handle to a user-supplied Hessian (see “Hessian” on page 11-47).</td>
</tr>
<tr>
<td>Hessian</td>
<td>Chooses how ktrlink calculates the Hessian (see “Hessian” on page 11-47).</td>
</tr>
<tr>
<td>Option</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>HessMult</td>
<td>Handle to a user-supplied function that gives a Hessian-times-vector product (see “Hessian” on page 11-47).</td>
</tr>
<tr>
<td>InitBarrierParam</td>
<td>Initial barrier value. A value above the default 0.1 might help, especially if the objective or constraint functions are large.</td>
</tr>
<tr>
<td>InitTrustRegionRadius</td>
<td>Initial radius of the trust region. On badly-scaled problems choose a value smaller than the default, $\sqrt{n}$, where $n$ is the number of variables.</td>
</tr>
<tr>
<td>MaxIter</td>
<td>Maximum number of iterations allowed.</td>
</tr>
<tr>
<td>MaxProjCGIter</td>
<td>A tolerance (stopping criterion) for the number of projected conjugate gradient iterations; this is an inner iteration, not the number of iterations of the algorithm.</td>
</tr>
<tr>
<td>ObjectiveLimit</td>
<td>A tolerance (stopping criterion). If the objective function value goes below ObjectiveLimit and the iterate is feasible, the iterations halt, since the problem is presumably unbounded.</td>
</tr>
<tr>
<td>ScaleProblem</td>
<td>The default 'obj-and-constr' causes the algorithm to normalize all constraints and the objective function. Disable by setting to 'none'.</td>
</tr>
<tr>
<td>SubproblemAlgorithm</td>
<td>Determines how the iteration step is calculated. The default 'ldl-factorization' is usually faster than 'cg' (conjugate gradient), though 'cg' may be faster for large problems with dense Hessians.</td>
</tr>
</tbody>
</table>
**Option**  |  **Description**  
---|---  
TolFun  |  Termination tolerance on the function value.  
TolCon  |  Termination tolerance on the constraint violation.  
TolX  |  Termination tolerance on x.  

**KNITRO Options**  
You can set options for the KNITRO libraries and pass them in a text file. The text file should consist of lines of text with the name of an option followed by blank space and then the desired value of the option. For example, to select the maximum run time to be less than 100 seconds, and to use an adaptive algorithm for changing the multiplier \( \mu \), create a text file containing the following lines:

```
ms_maxtime_real 100
bar_murule adaptive
```

For full details about the structure of the file and all possible options, see the KNITRO documentation at http://www.ziena.com/.

**References**  

**See Also**  
fminbnd | fmincon | fminsearch | fminunc | optimset | ktrlink

**How To**  
- @ (function_handle)  
- “ktrlink: An Interface to KNITRO Libraries” on page 8-2
**Purpose**
Solve linear programming problems

**Equation**
Finds the minimum of a problem specified by

\[
\min_{x} f^{T}x \text{ such that } \begin{cases} 
A \cdot x \leq b, \\
A_{eq} \cdot x = beq, \\
lb \leq x \leq ub. 
\end{cases}
\]

\(f, x, b, beq, lb, \) and \(ub\) are vectors, and \(A\) and \(A_{eq}\) are matrices.

**Syntax**
\[
x = \text{linprog}(f,A,b)
\]
\[
x = \text{linprog}(f,A,b,A_{eq},beq)
\]
\[
x = \text{linprog}(f,A,b,A_{eq},beq,lb,ub)
\]
\[
x = \text{linprog}(f,A,b,A_{eq},beq,lb,ub,x0)
\]
\[
x = \text{linprog}(f,A,b,A_{eq},beq,lb,ub,x0,options)
\]
\[
x = \text{linprog}(\text{problem})
\]
\[
[x,fval] = \text{linprog}(...)
\]
\[
[x,fval,exitflag] = \text{linprog}(...)
\]
\[
[x,fval,exitflag,output] = \text{linprog}(...)
\]
\[
[x,fval,exitflag,output,lambda] = \text{linprog}(...)
\]

**Description**
linprog solves linear programming problems.

\(x = \text{linprog}(f,A,b)\) solves \(\min f^{T}x\) such that \(A\cdot x \leq b\).

\(x = \text{linprog}(f,A,b,A_{eq},beq)\) solves the problem above while additionally satisfying the equality constraints \(A_{eq}\cdot x = beq\). Set \(A = []\) and \(b = []\) if no inequalities exist.

\(x = \text{linprog}(f,A,b,A_{eq},beq,lb,ub)\) defines a set of lower and upper bounds on the design variables, \(x\), so that the solution is always in the range \(lb \leq x \leq ub\). Set \(A_{eq} = []\) and \(beq = []\) if no equalities exist.

\(x = \text{linprog}(f,A,b,A_{eq},beq,lb,ub,x0)\) sets the starting point to \(x0\). This option is only available with the medium-scale algorithm (the LargeScale option is set to 'off' using optimset). The default large-scale algorithm and the simplex algorithm ignore any starting point.
x = linprog(f,A,b,Aeq,beq,lb,ub,x0,options) minimizes with the optimization options specified in the structure options. Use optimset to set these options.

x = linprog(problem) finds the minimum for problem, where problem is a structure described in “Input Arguments” on page 11-162.

Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,fval] = linprog(...) returns the value of the objective function fun at the solution x: fval = f'*x.

[x,fval,exitflag] = linprog(...) returns a value exitflag that describes the exit condition.

[x,fval,exitflag,output] = linprog(...) returns a structure output that contains information about the optimization.

[x,fval,exitflag,output,lambda] = linprog(...) returns a structure lambda whose fields contain the Lagrange multipliers at the solution x.

**Note** If the specified input bounds for a problem are inconsistent, the output x is x0 and the output fval is [].

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into linprog. “Options” on page 11-164 provides the function-specific details for the options values.
**linprog**

- **problem f**  
  Linear objective function vector \( f \)

- **Aineq**  
  Matrix for linear inequality constraints

- **bineq**  
  Vector for linear inequality constraints

- **Aeq**  
  Matrix for linear equality constraints

- **beq**  
  Vector for linear equality constraints

- **lb**  
  Vector of lower bounds

- **ub**  
  Vector of upper bounds

- **x0**  
  Initial point for \( x \), active set algorithm only

- **solver**  
  'linprog'

- **options**  
  Options structure created with `optimset`

---

**Output Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by `linprog`. This section provides function-specific details for `exitflag`, `lambda`, and `output`:

- **exitflag**  
  Integer identifying the reason the algorithm terminated. The following lists the values of `exitflag` and the corresponding reasons the algorithm terminated.

  1  
  Function converged to a solution \( x \).

  0  
  Number of iterations exceeded `options.MaxIter`.

  -2  
  No feasible point was found.

  -3  
  Problem is unbounded.

  -4  
  NaN value was encountered during execution of the algorithm.

  -5  
  Both primal and dual problems are infeasible.
Search direction became too small. No further progress could be made.

**lambda** Structure containing the Lagrange multipliers at the solution \( x \) (separated by constraint type). The fields of the structure are:

- `lower`  Lower bounds \( lb \)
- `upper`  Upper bounds \( ub \)
- `ineqlin` Linear inequalities
- `eqlin` Linear equalities

**output** Structure containing information about the optimization. The fields of the structure are:

- `iterations`  Number of iterations
- `algorithm`  Optimization algorithm used
- `cgiterations`  0 (large-scale algorithm only, included for backward compatibility)
- `message`  Exit message
- `constrviolation` Maximum of constraint functions
- `firstorderopt` First-order optimality measure

### Options

Optimization options used by `linprog`. Some options apply to all algorithms, and others are only relevant when using the large-scale algorithm. You can use `optimset` to set or change the values of these fields in the options structure, `options`. See “Optimization Options Reference” on page 9-7 for detailed information.

### Medium-Scale and Large-Scale Algorithms

Both the medium-scale and large-scale algorithms use the following options:
Diagnostics
Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.

Display
Level of display.

- 'off' displays no output.
- 'iter' displays output at each iteration. The 'iter' option only works with the large-scale and medium-scale simplex algorithms.
- 'final' (default) displays just the final output.

LargeScale
Use large-scale algorithm when set to 'on' (default). Use a medium-scale algorithm when set to 'off' (see Simplex in “Medium-Scale Algorithm Only” on page 11-166). For information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

MaxIter
Maximum number of iterations allowed, a positive integer. The default is:

- 85 for the large-scale algorithm
- 10*numberOfVariables for the simplex algorithm
- 10*max(numberOfVariables, numberOfInequalities + numberOfBounds) for the medium-scale active-set algorithm

TolFun
Termination tolerance on the function value, a positive scalar. The default is:

- 1e-8 for the large-scale algorithm
- 1e-6 for the simplex algorithm
• The option is not used for the medium-scale active-set algorithm

**Medium-Scale Algorithm Only**

The medium-scale algorithms use the following option:

Simplex  
If 'on', **linprog** uses the simplex algorithm. The simplex algorithm uses a built-in starting point, ignoring the starting point \( x_0 \) if supplied. The default is 'off', meaning **linprog** uses an active-set algorithm. See “Medium-Scale Optimization” on page 11-168 for more information and an example.

**Examples**

Find \( x \) that minimizes

\[
f(x) = -5x_1 - 4x_2 - 6x_3,
\]

subject to

\[
x_1 - x_2 + x_3 \leq 20
\]
\[
3x_1 + 2x_2 + 4x_3 \leq 42
\]
\[
3x_1 + 2x_2 \leq 30
\]
\[
0 \leq x_1, 0 \leq x_2, 0 \leq x_3.
\]

First, enter the coefficients

\[
f = [-5; -4; -6];
\]
\[
A = 
\begin{bmatrix}
1 & -1 & 1 \\
3 & 2 & 4 \\
3 & 2 & 0
\end{bmatrix};
\]
\[
b = [20; 42; 30];
\]
\[
lb = zeros(3,1);
\]

Next, call a linear programming routine.
[x, fval, exitflag, output, lambda] = linprog(f, A, b, [], [], lb);

Examine the solution and Lagrange multipliers:

\[ x, \lambda_{ineqlin}, \lambda_{lower} \]

\[
\begin{align*}
x &= \\
0.0000 & 15.0000 & 3.0000 \\
\text{ans} &= \\
0.0000 & 1.5000 & 0.5000 \\
\text{ans} &= \\
1.0000 & 0.0000 & 0.0000 \\
\end{align*}
\]

Nonzero elements of the vectors in the fields of lambda indicate active constraints at the solution. In this case, the second and third inequality constraints (in lambda.ineqlin) and the first lower bound constraint (in lambda.lower) are active constraints (i.e., the solution is on their constraint boundaries).

**Algorithms**

**Large-Scale Optimization**

The large-scale method is based on LIPSOL (Linear Interior Point Solver, [3]), which is a variant of Mehrotra’s predictor-corrector algorithm ([2]), a primal-dual interior-point method. A number of preprocessing steps occur before the algorithm begins to iterate. See “Large Scale Linear Programming” on page 6-94.
Medium-Scale Optimization

`linprog` uses a projection method as used in the `quadprog` algorithm. `linprog` is an active set method and is thus a variation of the well-known `simplex` method for linear programming [1]. The algorithm finds an initial feasible solution by first solving another linear programming problem.

Alternatively, you can use the simplex algorithm, described in “Medium-Scale `linprog` Simplex Algorithm” on page 6-102, by entering

```matlab
options = optimset('LargeScale', 'off', 'Simplex', 'on')
```

and passing `options` as an input argument to `linprog`. The simplex algorithm returns a vertex optimal solution.

**Note** You cannot supply an initial point `x0` for `linprog` with either the large-scale method or the medium-scale method using the simplex algorithm. In either case, if you pass in `x0` as an input argument, `linprog` ignores `x0` and computes its own initial point for the algorithm.

Diagnostics

Large-Scale Optimization

The first stage of the algorithm might involve some preprocessing of the constraints (see “Large Scale Linear Programming” on page 6-94). Several possible conditions might occur that cause `linprog` to exit with an infeasibility message. In each case, the `exitflag` argument returned by `linprog` is set to a negative value to indicate failure.

If a row of all zeros is detected in `Aeq` but the corresponding element of `beq` is not zero, the exit message is

```
Exiting due to infeasibility: An all-zero row in the constraint matrix does not have a zero in corresponding right-hand-side entry.
```

If one of the elements of `x` is found not to be bounded below, the exit message is
Exiting due to infeasibility: Objective $f^*x$ is unbounded below.

If one of the rows of $A_{eq}$ has only one nonzero element, the associated value in $x$ is called a singleton variable. In this case, the value of that component of $x$ can be computed from $A_{eq}$ and $b_{eq}$. If the value computed violates another constraint, the exit message is

Exiting due to infeasibility: Singleton variables in equality constraints are not feasible.

If the singleton variable can be solved for but the solution violates the upper or lower bounds, the exit message is

Exiting due to infeasibility: Singleton variables in the equality constraints are not within bounds.

**Note** The preprocessing steps are cumulative. For example, even if your constraint matrix does not have a row of all zeros to begin with, other preprocessing steps may cause such a row to occur.

Once the preprocessing has finished, the iterative part of the algorithm begins until the stopping criteria are met. (See “Large Scale Linear Programming” on page 6-94 for more information about residuals, the primal problem, the dual problem, and the related stopping criteria.) If the residuals are growing instead of getting smaller, or the residuals are neither growing nor shrinking, one of the two following termination messages is displayed, respectively,

One or more of the residuals, duality gap, or total relative error has grown 100000 times greater than its minimum value so far:

or

One or more of the residuals, duality gap, or total relative error has stalled:
After one of these messages is displayed, it is followed by one of the following six messages indicating that the dual, the primal, or both appear to be infeasible. The messages differ according to how the infeasibility or unboundedness was measured.

The dual appears to be infeasible (and the primal unbounded). (The primal residual < TolFun.)
The primal appears to be infeasible (and the dual unbounded). (The dual residual < TolFun.)
The dual appears to be infeasible (and the primal unbounded) since the dual residual > sqrt(TolFun). (The primal residual < 10*TolFun.)
The primal appears to be infeasible (and the dual unbounded) since the primal residual > sqrt(TolFun). (The dual residual < 10*TolFun.)
The dual appears to be infeasible and the primal unbounded since the primal objective < -1e+10 and the dual objective < 1e+6.
The primal appears to be infeasible and the dual unbounded since the dual objective > 1e+10 and the primal objective > -1e+6.
Both the primal and the dual appear to be infeasible.

Note that, for example, the primal (objective) can be unbounded and the primal residual, which is a measure of primal constraint satisfaction, can be small.

**Medium-Scale Optimization**

`linprog` gives a warning when the problem is infeasible.

**Warning:** The constraints are overly stringent; there is no feasible solution.

In this case, `linprog` produces a result that minimizes the worst case constraint violation.

When the equality constraints are inconsistent, `linprog` gives

**Warning:** The equality constraints are overly stringent; there is no feasible solution.
Unbounded solutions result in the warning

Warning: The solution is unbounded and at infinity; the constraints are not restrictive enough.

In this case, linprog returns a value of x that satisfies the constraints.

**Limitations**

**Medium-Scale Optimization**

At this time, the only levels of display, using the `Display` option in `options`, are 'off' and 'final'; iterative output using 'iter' is not available.

**Large-Scale Optimization**

**Large-Scale Problem Coverage and Requirements**

<table>
<thead>
<tr>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A and Aeq should be sparse.</td>
</tr>
</tbody>
</table>

**References**


**See Also**

quadprog | optimtool | linprog

**How To**

- “Linear Programming Algorithms” on page 6-94
• “Linear Programming Examples” on page 6-107
**Purpose**
Solve nonlinear curve-fitting (data-fitting) problems in least-squares sense

**Equation**
Find coefficients $x$ that solve the problem

$$\min_x \| F(x,xdata) - ydata \|_2^2 = \min_x \sum_i (F(x,xdata_i) - ydata_i)^2,$$

given input data $xdata$, and the observed output $ydata$, where $xdata$ and $ydata$ are matrices or vectors, and $F(x,xdata)$ is a matrix-valued or vector-valued function of the same size as $ydata$.

The `lsqcurvefit` function uses the same algorithm as `lsqnonlin`. `lsqcurvefit` simply provides a convenient interface for data-fitting problems.

**Syntax**

```matlab
x = lsqcurvefit(fun,x0,xdata,ydata)
x = lsqcurvefit(fun,x0,xdata,ydata,lb,ub)
x = lsqcurvefit(fun,x0,xdata,ydata,lb,ub,options)
x = lsqcurvefit(problem)
[x,resnorm] = lsqcurvefit(...)  
[x,resnorm,residual] = lsqcurvefit(...)  
[x,resnorm,residual,exitflag] = lsqcurvefit(...)  
[x,resnorm,residual,exitflag,output] = lsqcurvefit(...)  
[x,resnorm,residual,exitflag,output,lambda] = lsqcurvefit(...)  
[x,resnorm,residual,exitflag,output,lambda,jacobian] = lsqcurvefit(...)  
```

**Description**
`x = lsqcurvefit(fun,x0,xdata,ydata)` starts at $x0$ and finds coefficients $x$ to best fit the nonlinear function $fun(x,xdata)$ to the data $ydata$ (in the least-squares sense). $ydata$ must be the same size as the vector (or matrix) $F$ returned by $fun$. 

Note: “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to fun, if necessary.

fun should return fun(x,xdata), and not the sum-of-squares sum((fun(x,xdata)-ydata).^2). lsqcurvefit implicitly squares and sums fun(x,xdata)-ydata.

\[
\begin{align*}
x &= \text{lsqcurvefit}(\text{fun}, x_0, xdata, ydata, lb, ub) \text{ defines a set of lower and upper bounds on the design variables in } x \text{ so that the solution is always in the range } lb \leq x \leq ub. \\
x &= \text{lsqcurvefit}(\text{fun}, x_0, xdata, ydata, lb, ub, \text{options}) \text{ minimizes with the optimization options specified in the structure options. Use \text{optimset} to set these options. Pass empty matrices for } lb \text{ and } ub \text{ if no bounds exist.} \\
x &= \text{lsqcurvefit}(\text{problem}) \text{ finds the minimum for problem, where } \text{problem} \text{ is a structure described in “Input Arguments” on page 11-175.} \\
\end{align*}
\]

Create the problem structure by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

\[
\begin{align*}
[x,\text{resnorm}] &= \text{lsqcurvefit}(\ldots) \text{ returns the value of the squared 2-norm of the residual at } x: \text{sum}((\text{fun}(x,xdata)-ydata)^2). \\
[x,\text{resnorm},\text{residual}] &= \text{lsqcurvefit}(\ldots) \text{ returns the value of the residual } \text{fun}(x,xdata)-ydata \text{ at the solution } x. \\
[x,\text{resnorm},\text{residual},\text{exitflag}] &= \text{lsqcurvefit}(\ldots) \text{ returns a value } \text{exitflag} \text{ that describes the exit condition.} \\
[x,\text{resnorm},\text{residual},\text{exitflag},\text{output}] &= \text{lsqcurvefit}(\ldots) \text{ returns a structure } \text{output} \text{ that contains information about the optimization.} \\
[x,\text{resnorm},\text{residual},\text{exitflag},\text{output},\text{lambda}] &= \text{lsqcurvefit}(\ldots) \text{ returns a structure } \text{lambda} \text{ whose fields contain the Lagrange multipliers at the solution } x.
\end{align*}
\]
[x, resnorm, residual, exitflag, output, lambda, jacobian] = lsqcurvefit(...) returns the Jacobian of fun at the solution x.

Note If the specified input bounds for a problem are inconsistent, the output x is x0 and the outputs resnorm and residual are [].

Components of x0 that violate the bounds lb, x, ub are reset to the interior of the box defined by the bounds. Components that respect the bounds are not changed.

Input Arguments

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into lsqcurvefit. This section provides function-specific details for fun, options, and problem:

fun

The function you want to fit. fun is a function that takes two inputs: a vector or matrix x, and a vector or matrix xdata. fun returns a vector or matrix F, the objective function evaluated at x and xdata. The function fun can be specified as a function handle for a function file:

\[ x = \text{lsqcurvefit}(@myfun, x0, xdata, ydata) \]

where myfun is a MATLAB function such as

\begin{verbatim}
function F = myfun(x, xdata)
F = ... % Compute function values at x, xdata
\end{verbatim}

fun can also be a function handle for an anonymous function.

\[ f = @(x, xdata)x(1)*xdata.^2+x(2)*\sin(xdata); \]
\[ x = \text{lsqcurvefit}(f, x0, xdata, ydata); \]

lsqcurvefit internally converts matrix x or F to vectors using linear indexing.
**Note** fun should return \( \text{fun}(x,xdata) \), and not the sum-of-squares \( \text{sum}((\text{fun}(x,xdata)-ydata).^2) \). \text{lsqcurvefit} implicitly squares and sums \( \text{fun}(x,xdata)-ydata \).

If the Jacobian can also be computed *and* the Jacobian option is 'on', set by

```matlab
options = optimset('Jacobian','on')
```

then the function fun must return, in a second output argument, the Jacobian value \( J \), a matrix, at \( x \). By checking the value of nargout, the function can avoid computing \( J \) when fun is called with only one output argument (in the case where the optimization algorithm only needs the value of \( F \) but not \( J \)).

```matlab
function [F,J] = myfun(x,xdata)
F = ... % objective function values at x
if nargout > 1 % two output arguments
    J = ... % Jacobian of the function evaluated at x
end
```

If fun returns a vector (matrix) of \( m \) components and \( x \) has length \( n \), where \( n \) is the length of \( x0 \), then the Jacobian \( J \) is an \( m \)-by-\( n \) matrix where \( J(i,j) \) is the partial derivative of \( F(i) \) with respect to \( x(j) \). (The Jacobian \( J \) is the transpose of the gradient of \( F \).) For more information, see “Writing Vector and Matrix Objective Functions” on page 2-23.

```matlab
options = optimset('Jacobian','on')
```

“Options” on page 11-179 provides the function-specific details for the options values.
lsqcurvefit

<table>
<thead>
<tr>
<th>problem</th>
<th>objective</th>
<th>Objective function of x and xdata</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>Initial point for x, active set algorithm only</td>
<td></td>
</tr>
<tr>
<td>xdata</td>
<td>Input data for objective function</td>
<td></td>
</tr>
<tr>
<td>ydata</td>
<td>Output data to be matched by objective function</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
<tr>
<td>ub</td>
<td>Vector of upper bounds</td>
<td></td>
</tr>
<tr>
<td>solver</td>
<td>'lsqcurvefit'</td>
<td></td>
</tr>
<tr>
<td>options</td>
<td>Options structure created with optimset</td>
<td></td>
</tr>
</tbody>
</table>

**Output Arguments**

"Function Arguments" on page 9-2 contains general descriptions of arguments returned by lsqcurvefit. This section provides function-specific details for exitflag, lambda, and output:

<table>
<thead>
<tr>
<th>exitflag</th>
<th>Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Function converged to a solution x.</td>
</tr>
<tr>
<td>2</td>
<td>Change in x was less than the specified tolerance.</td>
</tr>
<tr>
<td>3</td>
<td>Change in the residual was less than the specified tolerance.</td>
</tr>
<tr>
<td>4</td>
<td>Magnitude of search direction smaller than the specified tolerance.</td>
</tr>
<tr>
<td>0</td>
<td>Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.</td>
</tr>
</tbody>
</table>
lsqcurvefit

-1 Output function terminated the algorithm.

-2 Problem is infeasible: the bounds lb and ub are inconsistent.

-3 Regularization parameter became too large (levenberg-marquardt algorithm).

-4 Optimization could not make further progress.

**lambda** Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields of the structure are

- **lower** Lower bounds lb
- **upper** Upper bounds ub

**output** Structure containing information about the optimization. The fields of the structure are

- **firstorderopt** Measure of first-order optimality (trust-region-reflective algorithm, [] for others).
- **iterations** Number of iterations taken
- **funcCount** Number of function evaluations
- **cgiterations** Total number of PCG iterations (trust-region-reflective algorithm, [] for others)
- **algorithm** Optimization algorithm used
- **stepsize** Final displacement in x (Levenberg-Marquardt algorithm)
- **message** Exit message
**Note** The sum of squares should not be formed explicitly. Instead, your function should return a vector of function values. See the examples below.

**Options**

Optimization options used by `lsqcurvefit`. Some options apply to all algorithms, some are only relevant when using the trust-region-reflective algorithm, and others are only relevant when you are using the Levenberg-Marquardt algorithm. Use `optimset` to set or change the values of these fields in the options structure `options`. See “Algorithm Options” on page 11-179 for detailed information.

The `Algorithm` option specifies a preference for which algorithm to use. It is only a preference, because certain conditions must be met to use the trust-region-reflective or Levenberg-Marquardt algorithm. For the trust-region-reflective algorithm, the nonlinear system of equations cannot be underdetermined; that is, the number of elements of `F` returned by `fun` must be at least as many as the length of `x`. Furthermore, only the trust-region-reflective algorithm handles bound constraints.

**Algorithm Options**

Both algorithms use the following option:

**Algorithm**

Choose between `'trust-region-reflective'` (default) and `'levenberg-marquardt'`. Set the initial Levenberg-Marquardt parameter $\lambda$ by setting `Algorithm` to a cell array such as `{'levenberg-marquardt', .005}`. The default $\lambda = 0.01$.

The `Algorithm` option specifies a preference for which algorithm to use. It is only a preference, because certain conditions must be met to use each algorithm. For the trust-region-reflective algorithm, the nonlinear system of equations cannot be underdetermined; that is, the number of
equations (the number of elements of \( F \) returned by \( \text{fun} \)) must be at least as many as the length of \( x \). The Levenberg-Marquardt algorithm does not handle bound constraints. For more information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

**DerivativeCheck** Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default 'off'.

**Diagnostics** Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.

**DiffMaxChange** Maximum change in variables for finite-difference gradients (a positive scalar). The default is \( \text{Inf} \).

**DiffMinChange** Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.

**Display** Level of display. 'off' displays no output, and 'final' (default) displays just the final output.

**FinDiffRelStep** Scalar or vector step size factor. When you set FinDiffRelStep to a vector \( v \), forward finite differences \( \Delta \) are

\[
\Delta = v .* \text{sign}(x) .* \text{max}(\text{abs}(x), \text{TypicalX});
\]

and central finite differences are

\[
\Delta = v .* \text{max}(\text{abs}(x), \text{TypicalX});
\]

Scalar FinDiffRelStep expands to a vector. The default is \( \sqrt{\text{eps}} \) for forward finite differences, and \( \text{eps}^{(1/3)} \) for central finite differences.
**FinDiffType**

Finite differences, used to estimate gradients, are either 'forward' (default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.

The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.

**FunValCheck**

Check whether function values are valid. 'on' displays an error when the function returns a value that is complex, Inf, or NaN. The default 'off' displays no error.

**Jacobian**

If 'on', lsqcurvefit uses a user-defined Jacobian (defined in fun), or Jacobian information (when using JacobMult), for the objective function. If 'off' (default), lsqcurvefit approximates the Jacobian using finite differences.

**MaxFunEvals**

Maximum number of function evaluations allowed, a positive integer. The default is 100*numberOfVariables.

**MaxIter**

Maximum number of iterations allowed, a positive integer. The default is 400.

**OutputFcn**

Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([]). See “Output Function” on page 9-18.
PlotFcns

Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]) :

- @optimplotx plots the current point.
- @optimplotfunccount plots the function count.
- @optimplotfval plots the function value.
- @optimplotresnorm plots the norm of the residuals.
- @optimplotstepsize plots the step size.
- @optimplotfirstorderopt plots the first-order optimality measure.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.

TolFun

Termination tolerance on the function value, a positive scalar. The default is 1e-6.

TolX

Termination tolerance on x, a positive scalar. The default is 1e-6.

TypicalX

Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). lsqcurvefit uses TypicalX for scaling finite differences for gradient estimation.

Trust-Region-Reflective Algorithm Only

The trust-region-reflective algorithm uses the following options:
**JacobMult**

Function handle for Jacobian multiply function. For large-scale structured problems, this function computes the Jacobian matrix product $J*Y$, $J'*Y$, or $J'*(J*Y)$ without actually forming $J$. The function is of the form

$$W = jmfun(Jinfo,Y,flag)$$

where $Jinfo$ contains the matrix used to compute $J*Y$ (or $J'*Y$, or $J'*(J*Y)$). The first argument $Jinfo$ must be the same as the second argument returned by the objective function $fun$, for example, in

$$[F,Jinfo] = fun(x)$$

$Y$ is a matrix that has the same number of rows as there are dimensions in the problem. $flag$ determines which product to compute:

- If $flag == 0$ then $W = J'*(J*Y)$.
- If $flag > 0$ then $W = J*Y$.
- If $flag < 0$ then $W = J'*Y$.

In each case, $J$ is not formed explicitly. `lsqcurvefit` uses $Jinfo$ to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply values for any additional parameters $jmfun$ needs.

**Note** 'Jacobian' must be set to 'on' for `lsqcurvefit` to pass $Jinfo$ from $fun$ to $jmfun.
See “Example: Nonlinear Minimization with a Dense but Structured Hessian and Equality Constraints” on page 6-68 and “Example: Jacobian Multiply Function with Linear Least Squares” on page 6-162 for similar examples.

**JacobPattern**

Sparsity pattern of the Jacobian for finite differencing. If it is not convenient to compute the Jacobian matrix $J$ in `fun`, `lsqcurvefit` can approximate $J$ via sparse finite differences, provided the structure of $J$, i.e., locations of the nonzeros, is supplied as the value for `JacobPattern`. In the worst case, if the structure is unknown, you can set `JacobPattern` to be a dense matrix and a full finite-difference approximation is computed in each iteration (this is the default if `JacobPattern` is not set). This can be very expensive for large problems, so it is usually worth the effort to determine the sparsity structure.

**MaxPCGIter**

Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is $\max(1,\text{floor}(\text{numberOfVariables}/2))$. For more information, see “Algorithms” on page 11-186.
**PrecondBandWidth**  
Upper bandwidth of preconditioner for PCG, a nonnegative integer. The default \( \text{PrecondBandWidth} \) is \( \text{Inf} \), which means a direct factorization (Cholesky) is used rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution. Set \( \text{PrecondBandWidth} \) to 0 for diagonal preconditioning (upper bandwidth of 0). For some problems, an intermediate bandwidth reduces the number of PCG iterations.

**TolPCG**  
Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.

**Levenberg-Marquardt Algorithm Only**

The Levenberg-Marquardt algorithm uses the following options:

**ScaleProblem**  
'Jacobian' can sometimes improve the convergence of a poorly-scaled problem; the default is 'none'.

**Examples**

Given vectors of data \( xdata \) and \( ydata \), suppose you want to find coefficients \( x \) to find the best fit to the exponential decay equation

\[
ydata(i) = x(1)e^{x(2)xdata(i)}
\]

That is, you want to minimize

\[
\min_x \sum_i (F(x,xdata_i) - ydata_i)^2,
\]

where \( m \) is the length of \( xdata \) and \( ydata \), the function \( F \) is defined by

\[
F(x,xdata) = x(1)\exp(x(2)*xdata);
\]
and the starting point is \( x_0 = [100; -1] \).

First, write a file to return the value of \( F \) (\( F \) has \( n \) components).

\[
\text{function } F = \text{myfun}(x,\text{xdata})
\]
\[
F = x(1) \times \exp(x(2) \times \text{xdata});
\]

Next, invoke an optimization routine:

\[
\text{function } F = \text{myfun}(x,\text{xdata})
\]
\[
F = x(1) \times \exp(x(2) \times \text{xdata});
\]

\[
\text{next, invoke an optimization routine:}
\]
\[
\text{% Assume you determined xdata and ydata experimentally}
\]
\[
\text{xdata} = \ldots
\]
\[
[0.9 \ 1.5 \ 13.8 \ 19.8 \ 24.1 \ 28.2 \ 35.2 \ 60.3 \ 74.6 \ 81.3];
\]
\[
ydata = \ldots
\]
\[
[455.2 \ 428.6 \ 124.1 \ 67.3 \ 43.2 \ 28.1 \ 13.1 \ -0.4 \ -1.3 \ -1.5];
\]
\[
x0 = [100; -1] \ % \text{Starting guess}
\]
\[
[x,\text{resnorm}] = \text{lsqcurvefit}(@\text{myfun},x0,\text{xdata},\text{ydata});
\]

At the time that \text{lsqcurvefit} is called, \text{xdata} and \text{ydata} are assumed to exist and are vectors of the same size. They must be the same size because the value \( F \) returned by \text{fun} must be the same size as \( \text{ydata} \).

After 27 function evaluations, this example gives the solution

\[
x,\text{resnorm}
\]
\[
x =
\]
\[
498.8309 \ -0.1013
\]
\[
\text{resnorm} =
\]
\[
9.5049
\]

There may be a slight variation in the number of iterations and the value of the returned \( x \), depending on the platform and release.

\textbf{Algorithms}

\textbf{Trust-Region-Reflective Optimization}

By default \text{lsqcurvefit} chooses the trust-region-reflective algorithm. This algorithm is a subspace trust-region method and is based on the interior-reflective Newton method described in [1] and [2]. Each iteration involves the approximate solution of a large linear system.
using the method of preconditioned conjugate gradients (PCG). See “Large-Scale Least Squares” on page 6-146, and in particular, “Large Scale Nonlinear Least Squares” on page 6-148.

**Levenberg-Marquardt Optimization**

If you set the `Algorithm` option to `'levenberg-marquardt'` with `optimset`, `lsqcurvrelu` uses the Levenberg-Marquardt method [4], [5], and [6]. See “Levenberg-Marquardt Method” on page 6-150.

**Diagnostics**

**Trust-Region-Reflective Optimization**

The trust-region-reflective method does not allow equal upper and lower bounds. For example, if `lb(2)==ub(2)`, `lsqcurvrelu` gives the error

```
Equal upper and lower bounds not permitted.
```

`lsqcurvrelu` does not handle equality constraints, which is another way to formulate equal bounds. If equality constraints are present, use `fmincon`, `fminimax`, or `fgoalattain` for alternative formulations where equality constraints can be included.

**Limitations**

The function to be minimized must be continuous. `lsqcurvrelu` might only give local solutions.

`lsqcurvrelu` only handles real variables (the user-defined function must only return real values). When `x` has complex variables, the variables must be split into real and imaginary parts.

**Note** The Statistics Toolbox function `nlinfit` has more statistics-oriented outputs that are useful, for example, in finding confidence intervals for the coefficients. It also comes with the `nlintool` GUI for visualizing the fitted function.

The `lsqnonlin` function has more outputs related to how well the optimization performed. It can put bounds on the parameters, and it accepts many options to control the optimization algorithm.
Trust-Region-Reflective Optimization

The trust-region-reflective algorithm for `lsqcurvefit` does not solve underdetermined systems; it requires that the number of equations, i.e., the row dimension of $F$, be at least as great as the number of variables. In the underdetermined case, the Levenberg-Marquardt algorithm is used instead.

The preconditioner computation used in the preconditioned conjugate gradient part of the trust-region-reflective method forms $J^TJ$ (where $J$ is the Jacobian matrix) before computing the preconditioner; therefore, a row of $J$ with many nonzeros, which results in a nearly dense product $J^TJ$, can lead to a costly solution process for large problems.

If components of $x$ have no upper (or lower) bounds, then `lsqcurvefit` prefers that the corresponding components of $ub$ (or $lb$) be set to $\text{inf}$ (or $-\text{inf}$ for lower bounds) as opposed to an arbitrary but very large positive (or negative for lower bounds) number.

Trust-Region-Reflective Problem Coverage and Requirements

<table>
<thead>
<tr>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provide sparsity structure of the Jacobian or compute the Jacobian in <code>fun</code>.</td>
</tr>
<tr>
<td>• The Jacobian should be sparse.</td>
</tr>
</tbody>
</table>

Levenberg-Marquardt Optimization

The Levenberg-Marquardt algorithm does not handle bound constraints.

Since the trust-region-reflective algorithm does not handle underdetermined systems and the Levenberg-Marquardt does not handle bound constraints, problems with both these characteristics cannot be solved by `lsqcurvefit`.

References


See Also
lsqlin | lsqnonlin | lsqnonneg | optimset | optimtool | nlinfit | lsqcurvefit | lsqcurvefit

How To
• @(function_handle)
• \n
• “Least Squares (Model Fitting) Algorithms” on page 6-145
• “Example: Nonlinear Curve Fitting with lsqcurvefit” on page 6-167
**Purpose**
Solve constrained linear least-squares problems

**Equation**
Solves least-squares curve fitting problems of the form

\[
\min_{x} \frac{1}{2} \|Cx - d\|_2^2 \quad \text{such that} \quad \begin{cases} 
A \cdot x \leq b, \\
A_{eq} \cdot x = beq, \\
lb \leq x \leq ub.
\end{cases}
\]

**Syntax**
- `x = lsqlin(C,d,A,b)` solves the linear system \( C \cdot x = d \) in the least-squares sense subject to \( A \cdot x \leq b \), where \( C \) is \( m \)-by-\( n \).
- `x = lsqlin(C,d,A,b,Aeq,beq)` solves the preceding problem while additionally satisfying the equality constraints \( A_{eq} \cdot x = beq \). Set \( A = [] \) and \( b = [] \) if no inequalities exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub)` defines a set of lower and upper bounds on the design variables in \( x \) so that the solution is always in the range \( lb \leq x \leq ub \). Set \( A_{eq} = [] \) and \( beq = [] \) if no equalities exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub,x0)` sets the starting point to \( x0 \). Set \( lb = [] \) and \( b = [] \) if no bounds exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub,x0,options)` minimizes with the optimization options specified in the structure `options`. Use `optimset` to set these options.

**Description**
- `x = lsqlin(C,d,A,b)` solves the linear system \( C \cdot x = d \) in the least-squares sense subject to \( A \cdot x \leq b \), where \( C \) is \( m \)-by-\( n \).
- `x = lsqlin(C,d,A,b,Aeq,beq)` solves the preceding problem while additionally satisfying the equality constraints \( A_{eq} \cdot x = beq \). Set \( A = [] \) and \( b = [] \) if no inequalities exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub)` defines a set of lower and upper bounds on the design variables in \( x \) so that the solution is always in the range \( lb \leq x \leq ub \). Set \( A_{eq} = [] \) and \( beq = [] \) if no equalities exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub,x0)` sets the starting point to \( x0 \). Set \( lb = [] \) and \( b = [] \) if no bounds exist.
- `x = lsqlin(C,d,A,b,Aeq,beq,lb,ub,x0,options)` minimizes with the optimization options specified in the structure `options`. Use `optimset` to set these options.
x = lsqlin(problem) finds the minimum for problem, where problem
is a structure described in “Input Arguments” on page 11-192.

Create the structure problem by exporting a problem from Optimization
Tool, as described in “Exporting Your Work” on page 5-17.

[x,resnorm] = lsqlin(...) returns the value of the squared 2-norm
of the residual, norm(C*x-d)^2.

[x,resnorm,residual] = lsqlin(...) returns the residual C*x-d.

[x,resnorm,residual,exitflag] = lsqlin(...) returns a value
exitflag that describes the exit condition.

[x,resnorm,residual,exitflag,output] = lsqlin(...) returns a
structure output that contains information about the optimization.

[x,resnorm,residual,exitflag,output,lambda] = lsqlin(...) returns a structure lambda whose fields contain the Lagrange
multipliers at the solution x.
**Note** If the specified input bounds for a problem are inconsistent, the output $x$ is $x_0$ and the outputs `resnorm` and `residual` are $[]$.

Components of $x_0$ that violate the bounds $lb\leq x\leq ub$ are reset to the interior of the box defined by the bounds. Components that respect the bounds are not changed.

If no $x_0$ is provided, $x_0$ is set to the zero vector. If any component of this zero vector $x_0$ violates the bounds, $x_0$ is set to a point in the interior of the box defined by the bounds.

The factor $\frac{1}{2}$ in the definition of the problem affects the values in the `lambda` structure.

You can solve some large structured problems, including those where the $C$ matrix is too large to fit in memory, using the large-scale algorithm with a Jacobian multiply function. For information, see “Large-Scale Algorithm Only” on page 11-195.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into `lsqlin`. “Options” on page 11-194 provides the options values specific to `lsqlin`.

<table>
<thead>
<tr>
<th><code>problem</code></th>
<th>C</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>d</code></td>
<td>Vector</td>
<td></td>
</tr>
<tr>
<td><code>Aineq</code></td>
<td>Matrix for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td><code>bineq</code></td>
<td>Vector for linear inequality constraints</td>
<td></td>
</tr>
<tr>
<td><code>Aeq</code></td>
<td>Matrix for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td><code>beq</code></td>
<td>Vector for linear equality constraints</td>
<td></td>
</tr>
<tr>
<td><code>lb</code></td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
<tr>
<td><code>ub</code></td>
<td>Vector of upper bounds</td>
<td></td>
</tr>
</tbody>
</table>
x0  Initial point for x
solver  'lsqlin'
options  Options structure created with optimset

Output Arguments

"Function Arguments" on page 9-2 contains general descriptions of arguments returned by lsqmin. This section provides function-specific details for exitflag, lambda, and output:

exitflag  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated:

1  Function converged to a solution x.
3  Change in the residual was smaller than the specified tolerance.
0  Number of iterations exceeded options.MaxIter.
-2  The problem is infeasible.
-4  Ill-conditioning prevents further optimization.
-7  Magnitude of search direction became too small. No further progress could be made.

lambda  Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields are

lower  Lower bounds lb
upper  Upper bounds ub
**Ineqlin**

Structure containing information about the optimization. The fields are:

- **iterations**: Number of iterations taken
- **algorithm**: Optimization algorithm used
- **cgiterations**: Total number of PCG iterations (large-scale algorithm, [] for medium-scale)
- **firstorderopt**: Measure of first-order optimality (large-scale algorithm, [] for medium-scale)
- **message**: Exit message

**Options**

Optimization options used by `Ineqlin`. You can set or change the values of these options using the `optimset` function. Some options apply to all algorithms, some are only relevant when you are using the large-scale algorithm, and others are only relevant when using the medium-scale algorithm. See “Optimization Options Reference” on page 9-7 for detailed information.

**Medium-Scale and Large-Scale Algorithms**

Both the medium-scale and large-scale algorithms use the following options:

- **Diagnostics**: Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.
- **Display**: Level of display. 'off' displays no output; 'final' (default) displays just the final output.
LargeScale  Use the large-scale algorithm if possible when set to 'on' (default). Use the medium-scale algorithm when set to 'off'.

The large-scale algorithm requires only upper and lower bounds, meaning no linear inequalities or equalities. Otherwise, lsqlin uses the medium-scale algorithm. For more information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

MaxIter  Maximum number of iterations allowed, a positive integer. The default value is 200.

Large-Scale Algorithm Only

The large-scale algorithm uses the following options:

JacobMult  Function handle for Jacobian multiply function. For large-scale structured problems, this function should compute the Jacobian matrix product \( C*Y \), \( C'*Y \), or \( C'*(C*Y) \) without actually forming \( C \). Write the function in the form

\[
W = \text{jmfun}(\text{Jinfo},Y,\text{flag})
\]

where \( \text{Jinfo} \) contains a matrix used to compute \( C*Y \) (or \( C'*Y \), or \( C'*(C*Y) \)).

\text{jmfun} must compute one of three different products, depending on the value of \text{flag} that \text{lsqlin} passes:

- If \text{flag} == 0 then \( W = C'*(C*Y) \).
- If \text{flag} > 0 then \( W = C*Y \).
- If \text{flag} < 0 then \( W = C'*Y \).
In each case, `jmfun` need not form `C` explicitly. `lsqlin` uses `Jinfo` to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply extra parameters if necessary.

See “Example: Jacobian Multiply Function with Linear Least Squares” on page 6-162 for an example.

**MaxPCGIter**

Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is `max(1,floor(numberOfVariables/2))`. For more information, see “Algorithms” on page 11-199.

**PrecondBandWidth**

Upper bandwidth of preconditioner for PCG. By default, diagonal preconditioning is used (upper bandwidth of 0). For some problems, increasing the bandwidth reduces the number of PCG iterations. Setting `PrecondBandWidth` to `Inf` uses a direct factorization (Cholesky) rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution.

**TolFun**

Termination tolerance on the function value, a positive scalar. The default is `100*eps`, about `2.2204e-14`. 

11-196
Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.

Typical \( x \) values. The number of elements in Typical\( x \) is equal to the number of elements in \( x_0 \), the starting point. The default value is \texttt{ones(numberofvariables,1)}. \texttt{lsqnonlin} uses Typical\( x \) internally for scaling. Typical\( x \) has an effect only when \( x \) has unbounded components, and when a Typical\( x \) value for an unbounded component is larger than 1.

**Examples**

Find the least-squares solution to the overdetermined system \( C x = d \), subject to \( A x \leq b \) and \( l b \leq x \leq u b \).

First, enter the coefficient matrices and the lower and upper bounds.

\[
C = \begin{bmatrix}
0.9501 & 0.7620 & 0.6153 & 0.4057 \\
0.2311 & 0.4564 & 0.7919 & 0.9354 \\
0.6068 & 0.0185 & 0.9218 & 0.9169 \\
0.4859 & 0.8214 & 0.7382 & 0.4102 \\
0.8912 & 0.4447 & 0.1762 & 0.8936 \\
\end{bmatrix};
\]

\[
d = \begin{bmatrix}
0.0578 \\
0.3528 \\
0.8131 \\
0.0098 \\
0.1388 \\
\end{bmatrix};
\]

\[
A = \begin{bmatrix}
0.2027 & 0.2721 & 0.7467 & 0.4659 \\
0.1987 & 0.1988 & 0.4450 & 0.4186 \\
0.6037 & 0.0152 & 0.9318 & 0.8462 \\
\end{bmatrix};
\]

\[
b = \begin{bmatrix}
0.5251 \\
0.2026 \\
0.6721 \\
\end{bmatrix};
\]
lb = -0.1*ones(4,1);
ub = 2*ones(4,1);

Next, call the constrained linear least-squares routine.

\[
\begin{align*}
[x,\text{resnorm},\text{residual}, \text{exitflag}, \text{output}, \text{lambda}] &= \ldots \\
lsqlin(C,d,A,b,\text{[ ]},\text{[ ]},lb,ub);
\end{align*}
\]

Examine \( x \), \( \text{lambda.ineqlin} \), \( \text{lambda.lower} \), and \( \text{lambda.upper} \):

\[
\begin{align*}
x &= \\
-0.1000 \\
-0.1000 \\
0.2152 \\
0.3502
\end{align*}
\]

\[
\begin{align*}
\text{lambda.ineqlin} &= \ldots \\
\text{ans} &= \\
0 \\
0.2392 \\
0
\end{align*}
\]

\[
\begin{align*}
\text{lambda.lower} &= \ldots \\
\text{ans} &= \\
0.0409 \\
0.2784 \\
0 \\
0
\end{align*}
\]

\[
\begin{align*}
\text{lambda.upper} &= \ldots \\
\text{ans} &= \\
0 \\
0 \\
0 \\
0
\end{align*}
\]
Nonzero elements of the vectors in the fields of \texttt{lambda} indicate active constraints at the solution. In this case, the second inequality constraint (in \texttt{lambda.ineqlin}) and the first lower and second lower bound constraints (in \texttt{lambda.lower}) are active constraints (i.e., the solution is on their constraint boundaries).

**Notes**

For problems with no constraints, use \( \backslash \) (matrix left division). For example, \( x = A\backslash b \).

Because the problem being solved is always convex, \texttt{lsqlin} will find a global, although not necessarily unique, solution.

Better numerical results are likely if you specify equalities explicitly, using \texttt{Aeq} and \texttt{beq}, instead of implicitly, using \texttt{lb} and \texttt{ub}.

**Large-Scale Optimization**

If \( x_0 \) is not strictly feasible, \texttt{lsqlin} chooses a new strictly feasible (centered) starting point.

If components of \( x \) have no upper (or lower) bounds, set the corresponding components of \texttt{ub} (or \texttt{lb}) to \( \text{Inf} \) (or \( -\text{Inf} \) for \texttt{lb}) as opposed to an arbitrary but very large positive (or negative in the case of lower bounds) number.

**Algorithms**

**Large-Scale Optimization**

When the problem given to \texttt{lsqlin} has only upper and lower bounds; i.e., no linear inequalities or equalities are specified, and the matrix \( C \) has at least as many rows as columns, the default algorithm is the large-scale method. This method is a subspace trust-region method based on the interior-reflective Newton method described in [1]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). See “Trust-Region Methods for Nonlinear Minimization” on page 6-3 and “Preconditioned Conjugate Gradient Method” on page 6-24.

**Medium-Scale Optimization**

\texttt{lsqlin}, with the \texttt{LargeScale} option set to ‘off’ with \texttt{optimset}, or when linear inequalities or equalities are given, is based on \texttt{quadprog},
lsqnonlin

which uses an active set method similar to that described in [2]. It finds an initial feasible solution by first solving a linear programming problem. See “trust-region-reflective quadprog Algorithm” on page 6-115.

Diagnostics

Large-Scale Optimization

The large-scale method does not allow equal upper and lower bounds. For example, if \(lb(2) == ub(2)\), then \texttt{lsqnonlin} gives the following error:

```
Equal upper and lower bounds not permitted
in this large-scale method.
Use equality constraints and the medium-scale
method instead.
```

At this time, you must use the medium-scale algorithm to solve equality constrained problems.

Medium-Scale Optimization

If the matrices \(C\), \(A\), or \(Aeq\) are sparse, and the problem formulation is not solvable using the large-scale method, \texttt{lsqnonlin} warns that the matrices are converted to full.

```
Warning: This problem formulation not yet available
for sparse matrices.
Converting to full to solve.
```

When a problem is infeasible, \texttt{lsqnonlin} gives a warning:

```
Warning: The constraints are overly stringent;
there is no feasible solution.
```

In this case, \texttt{lsqnonlin} produces a result that minimizes the worst case constraint violation.

When the equality constraints are inconsistent, \texttt{lsqnonlin} gives

```
Warning: The equality constraints are overly stringent;
there is no feasible solution.
```
Limitations
At this time, the only levels of display, using the Display option in options, are 'off' and 'final'; iterative output using 'iter' is not available.

Large-Scale Problem Coverage and Requirements

<table>
<thead>
<tr>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>C should be sparse.</td>
</tr>
</tbody>
</table>

References


See Also
lsqnonneg | quadprog | optimtool | lsqlin

How To
• \n• “Least Squares (Model Fitting) Algorithms” on page 6-145
• “Least Squares (Model Fitting) Examples” on page 6-154
**Purpose**
Solve nonlinear least-squares (nonlinear data-fitting) problems

**Equation**
Solves nonlinear least-squares curve fitting problems of the form

\[
\min_x \left\| f(x) \right\|^2 = \min_x \left( f_1(x)^2 + f_2(x)^2 + \ldots + f_n(x)^2 \right)
\]

**Syntax**
- \( x = \text{lsqnonlin}(\text{fun},x0) \)
- \( x = \text{lsqnonlin}(\text{fun},x0,lb,ub) \)
- \( x = \text{lsqnonlin}(\text{fun},x0,lb,ub,\text{options}) \)
- \( x = \text{lsqnonlin}(\text{problem}) \)
- \([x,\text{resnorm}] = \text{lsqnonlin}(...)\)
- \([x,\text{resnorm},\text{residual}] = \text{lsqnonlin}(...)\)
- \([x,\text{resnorm},\text{residual},\text{exitflag}] = \text{lsqnonlin}(...)\)
- \([x,\text{resnorm},\text{residual},\text{exitflag},\text{output}] = \text{lsqnonlin}(...)\)
- \([x,\text{resnorm},\text{residual},\text{exitflag},\text{output},\lambda,\text{jacobian}] = \text{lsqnonlin}(...)\)

**Description**
lsqnonlin solves nonlinear least-squares problems, including nonlinear data-fitting problems.

Rather than compute the value \( \| f(x) \|^2 \) (the sum of squares), lsqnonlin requires the user-defined function to compute the vector-valued function

\[
f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix}
\]

Then, in vector terms, you can restate this optimization problem as

\[
\min_x \left\| f(x) \right\|^2 = \min_x \left( f_1(x)^2 + f_2(x)^2 + \ldots + f_n(x)^2 \right)
\]

where \( x \) is a vector and \( f(x) \) is a function that returns a vector value.
x = lsqnonlin(fun,x0) starts at the point x0 and finds a minimum of the sum of squares of the functions described in fun. fun should return a vector of values and not the sum of squares of the values. (The algorithm implicitly sums and squares fun(x).)

**Note** “Passing Extra Parameters” on page 2-38 explains how to pass extra parameters to the vector function f, if necessary.

x = lsqnonlin(fun,x0,lb,ub) defines a set of lower and upper bounds on the design variables in x, so that the solution is always in the range lb ≤ x ≤ ub.

x = lsqnonlin(fun,x0,lb,ub,options) minimizes with the optimization options specified in the structure options. Use optimset to set these options. Pass empty matrices for lb and ub if no bounds exist.

x = lsqnonlin(problem) finds the minimum for problem, where problem is a structure described in “Input Arguments” on page 11-204.

Create the structure problem by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

[x,resnorm] = lsqnonlin(...) returns the value of the squared 2-norm of the residual at x: sum(fun(x).^2).

[x,resnorm,residual] = lsqnonlin(...) returns the value of the residual fun(x) at the solution x.

[x,resnorm,residual,exitflag] = lsqnonlin(...) returns a value exitflag that describes the exit condition.

[x,resnorm,residual,exitflag,output] = lsqnonlin(...) returns a structure output that contains information about the optimization.

[x,resnorm,residual,exitflag,output,lambda] = lsqnonlin(...) returns a structure lambda whose fields contain the Lagrange multipliers at the solution x.
[x,resnorm,residual,exitflag,output,lambda,jacobian] = 
lsqnonlin(...) returns the Jacobian of fun at the solution x.

**Note** If the specified input bounds for a problem are inconsistent, the 
output x is x0 and the outputs resnorm and residual are [].

Components of x0 that violate the bounds lb x ub are reset to the 
interior of the box defined by the bounds. Components that respect the 
bounds are not changed.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions 
of arguments passed into lsqnonlin. This section provides 
function-specific details for fun, options, and problem:

fun

The function whose sum of squares is minimized. fun is 
a function that accepts a vector x and returns a vector F, 
the objective functions evaluated at x. The function fun 
can be specified as a function handle to a file:

```matlab
x = lsqnonlin(@myfun,x0)
```

where myfun is a MATLAB function such as

```matlab
function F = myfun(x)
    F = ... % Compute function values at x
```

fun can also be a function handle for an anonymous 
function.

```matlab
x = lsqnonlin(@(x)sin(x.*x),x0);
```

If the user-defined values for x and F are matrices, they 
are converted to a vector using linear indexing.
**Note** The sum of squares should not be formed explicitly. Instead, your function should return a vector of function values. See “Examples” on page 11-213.

If the Jacobian can also be computed *and* the Jacobian option is ‘on’, set by

```matlab
options = optimset('Jacobian', 'on')
```

the function `fun` must return, in a second output argument, the Jacobian value `J`, a matrix, at `x`. By checking the value of `nargout`, the function can avoid computing `J` when `fun` is called with only one output argument (in the case where the optimization algorithm only needs the value of `F` but not `J`).

```matlab
function [F,J] = myfun(x)
F = ... % Objective function values at x
if nargout > 1 % Two output arguments
    J = ... % Jacobian of the function evaluated at x
end
```

If `fun` returns a vector (matrix) of `m` components and `x` has length `n`, where `n` is the length of `x0`, the Jacobian `J` is an `m`-by-`n` matrix where `J(i,j)` is the partial derivative of `F(i)` with respect to `x(j)`. (The Jacobian `J` is the transpose of the gradient of `F").

“Options” on page 11-208 provides the function-specific details for the `options` values.
**lsqnonlin**

<table>
<thead>
<tr>
<th>problem</th>
<th>objective</th>
<th>Objective function</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>Initial point for x</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>Vector of lower bounds</td>
<td></td>
</tr>
<tr>
<td>ub</td>
<td>Vector of upper bounds</td>
<td></td>
</tr>
<tr>
<td>solver</td>
<td>'lsqnonlin'</td>
<td></td>
</tr>
<tr>
<td>options</td>
<td>Options structure created with optimset</td>
<td></td>
</tr>
</tbody>
</table>

**Output Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by lsqnonlin. This section provides function-specific details for exitflag, lambda, and output:

- **exitflag**
  
  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated:

  1. Function converged to a solution $x$.
  2. Change in $x$ was less than the specified tolerance.
  3. Change in the residual was less than the specified tolerance.
  4. Magnitude of search direction was smaller than the specified tolerance.
  0. Number of iterations exceeded options.MaxIter or number of function evaluations exceeded options.FunEvals.
  -1. Output function terminated the algorithm.
-2 Problem is infeasible: the bounds lb and ub are inconsistent.

-3 Regularization parameter became too large (levenberg-marquardt algorithm).

-4 Line search could not sufficiently decrease the residual along the current search direction.

**lambda** Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields are

- lower Lower bounds lb
- upper Upper bounds ub

**output** Structure containing information about the optimization. The fields of the structure are

- firstorderopt Measure of first-order optimality (trust-region-reflective algorithm, [ ] for others)
- iterations Number of iterations taken
- funcCount The number of function evaluations
- cgiterations Total number of PCG iterations (trust-region-reflective algorithm, [ ] for others)
- stepsizes Final displacement in x (Levenberg-Marquardt algorithm)
- algorithm Optimization algorithm used
- message Exit message
Options

Optimization options. You can set or change the values of these options using the `optimset` function. Some options apply to all algorithms, some are only relevant when you are using the trust-region-reflective algorithm, and others are only relevant when you are using the Levenberg-Marquardt algorithm. See “Optimization Options Reference” on page 9-7 for detailed information.

Algorithm Options

Both algorithms use the following options:

- **Algorithm** Choose between 'trust-region-reflective' (default) and 'levenberg-marquardt'. Set the initial Levenberg-Marquardt parameter $\lambda$ by setting `Algorithm` to a cell array such as `{'levenberg-marquardt',.005}`. The default $\lambda = 0.01$.

  The `Algorithm` option specifies a preference for which algorithm to use. It is only a preference, because certain conditions must be met to use each algorithm. For the trust-region-reflective algorithm, the nonlinear system of equations cannot be underdetermined; that is, the number of equations (the number of elements of $F$ returned by `fun`) must be at least as many as the length of $x$. The Levenberg-Marquardt algorithm does not handle bound constraints. For more information on choosing the algorithm, see “Choosing the Algorithm” on page 2-7.

- **DerivativeCheck** Compare user-supplied derivatives (gradients of objective or constraints) to finite-differencing derivatives. The choices are 'on' or the default 'off'.

- **Diagnostics** Display diagnostic information about the function to be minimized or solved. The choices are 'on' or the default 'off'.
DiffMaxChange

Maximum change in variables for finite-difference gradients (a positive scalar). The default is Inf.

DiffMinChange

Minimum change in variables for finite-difference gradients (a positive scalar). The default is 0.

Display

Level of display. 'off' displays no output, and 'final' (default) displays just the final output.

FinDiffRelStep

Scalar or vector step size factor. When you set FinDiffRelStep to a vector v, forward finite differences \( \Delta \) are

\[
\Delta = v \cdot \text{sign}(x) \cdot \max(\text{abs}(x), \text{TypicalX});
\]

and central finite differences are

\[
\Delta = v \cdot \max(\text{abs}(x), \text{TypicalX});
\]

Scalar FinDiffRelStep expands to a vector. The default is \( \sqrt{\text{eps}} \) for forward finite differences, and \( \text{eps}^{(1/3)} \) for central finite differences.

FinDiffType

Finite differences, used to estimate gradients, are either 'forward' (default), or 'central' (centered). 'central' takes twice as many function evaluations, but should be more accurate.

The algorithm is careful to obey bounds when estimating both types of finite differences. So, for example, it could take a backward, rather than a forward, difference to avoid evaluating at a point outside bounds.

FunValCheck

Check whether function values are valid. 'on' displays an error when the function returns a value that is complex, Inf, or NaN. The default 'off' displays no error.
lsqnonlin uses a user-defined Jacobian (defined in `fun`), or Jacobian information (when using `JacobMult`), for the objective function. If 'off' (default), `lsqnonlin` approximates the Jacobian using finite differences.

### MaxFunEvals
Maximum number of function evaluations allowed, a positive integer. The default is $100 \times \text{numberOfVariables}$.

### MaxIter
Maximum number of iterations allowed, a positive integer. The default is 400.

### OutputFcn
Specify one or more user-defined functions that an optimization function calls at each iteration, either as a function handle or as a cell array of function handles. The default is none ([ ]). See “Output Function” on page 9-18.

### PlotFcns
Plots various measures of progress while the algorithm executes, select from predefined plots or write your own. Pass a function handle or a cell array of function handles. The default is none ([ ]):

- `@optimplotx` plots the current point.
- `@optimplotfval` plots the function value.
- `@optimplotresnorm` plots the norm of the residuals.
- `@optimplotstepsize` plots the step size.
- `@optimplotfirstorderopt` plots the first-order optimality measure.

For information on writing a custom plot function, see “Plot Functions” on page 9-27.
**TolFun**  
Termination tolerance on the function value, a positive scalar. The default is 1e-6.

**TolX**  
Termination tolerance on x, a positive scalar. The default is 1e-6.

**TypicalX**  
Typical x values. The number of elements in TypicalX is equal to the number of elements in x0, the starting point. The default value is ones(numberOfVariables,1). lsqnonlin uses TypicalX for scaling finite differences for gradient estimation.

---

**Trust-Region-Reflective Algorithm Only**

The trust-region-reflective algorithm uses the following options:

**JacobMult**  
Function handle for Jacobian multiply function. For large-scale structured problems, this function computes the Jacobian matrix product J*Y, J'*Y, or J'* (J*Y) without actually forming J. The function is of the form

\[ W = jmfun(Jinfo,Y,flag) \]

where Jinfo contains the matrix used to compute J*Y (or J'*Y, or J'* (J*Y)). The first argument Jinfo must be the same as the second argument returned by the objective function fun, for example, by

\[ [F,Jinfo] = \text{fun}(x) \]

Y is a matrix that has the same number of rows as there are dimensions in the problem. flag determines which product to compute:

- If flag == 0 then \( W = J'* (J*Y) \).
• If flag > 0 then \( W = J \cdot Y \).
• If flag < 0 then \( W = J' \cdot Y \).

In each case, \( J \) is not formed explicitly. \texttt{lsqnonlin} uses \texttt{Jinfo} to compute the preconditioner. See “Passing Extra Parameters” on page 2-38 for information on how to supply values for any additional parameters \texttt{jmfun} needs.

\textbf{Note} 'Jacobian' must be set to 'on' for \texttt{lsqnonlin} to pass \texttt{Jinfo} from \texttt{fun} to \texttt{jmfun}.

\texttt{JacobPattern}

Sparsity pattern of the Jacobian for finite differencing. If it is not convenient to compute the Jacobian matrix \( J \) in \texttt{fun}, \texttt{lsqnonlin} can approximate \( J \) via sparse finite differences, provided you supply the structure of \( J \) (locations of the nonzeros) as the value for \texttt{JacobPattern}. In the worst case, if the structure is unknown, you can set \texttt{JacobPattern} to be a dense matrix and a full finite-difference approximation is computed in each iteration. This is the default if \texttt{JacobPattern} is not set. This can be very expensive for large problems, so it is usually worth the effort to determine the sparsity structure.
MaxPCGIter  Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is \( \max(1, \text{numberOfVariables}/2) \). For more information, see “Algorithms” on page 11-186.

PrecondBandWidth  Upper bandwidth of preconditioner for PCG, a nonnegative integer. The default \( \text{PrecondBandWidth} \) is \( \text{Inf} \), which means a direct factorization (Cholesky) is used rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step towards the solution. Set \( \text{PrecondBandWidth} \) to 0 for diagonal preconditioning (upper bandwidth of 0). For some problems, an intermediate bandwidth reduces the number of PCG iterations.

TolPCG  Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.

**Levenberg-Marquardt Algorithm Only**

The Levenberg-Marquardt algorithm uses the following options:

ScaleProblem  'Jacobian' can sometimes improve the convergence of a poorly scaled problem; the default is 'none'.

**Examples**

Find \( x \) that minimizes

\[
\sum_{k=1}^{10} \left( 2 + 2k - e^{kx_1} - e^{kx_2} \right)^2,
\]

starting at the point \( x = [0.3, 0.4] \).
Because `lsqnonlin` assumes that the sum of squares is *not* explicitly formed in the user-defined function, the function passed to `lsqnonlin` should instead compute the vector-valued function

\[
F_k(x) = 2 + 2k - e^{kx_1} - e^{kx_2},
\]

for \(k = 1\) to 10 (that is, \(F\) should have \(k\) components).

First, write a file to compute the \(k\)-component vector \(F\).

```matlab
function F = myfun(x)
k = 1:10;
F = 2 + 2*k-exp(k*x(1))-exp(k*x(2));
```

Next, invoke an optimization routine.

```matlab
x0 = [0.3 0.4] % Starting guess
[x,resnorm] = lsqnonlin(@myfun,x0); % Invoke optimizer
```

After about 24 function evaluations, this example gives the solution

```matlab
x,resnorm
x =
    0.2578    0.2578

resnorm =
    124.3622
```

### Algorithms

**Trust-Region-Reflective Optimization**

By default, `lsqnonlin` chooses the trust-region-reflective algorithm. This algorithm is a subspace trust-region method and is based on the interior-reflective Newton method described in [1] and [2]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). See “Large-Scale Least Squares” on page 6-146, and in particular “Large Scale Nonlinear Least Squares” on page 6-148.
**Levenberg-Marquardt Optimization**

If you set the `Algorithm` option to `'levenberg-marquardt'` using `optimset`, `lsqnonlin` uses the Levenberg-Marquardt method [4], [5], and [6]. See “Levenberg-Marquardt Method” on page 6-150.

**Diagnostics**

**Trust-Region-Reflective Optimization**

The trust-region-reflective method does not allow equal upper and lower bounds. For example, if `lb(2)==ub(2)`, `lsqlin` gives the error

```
Equal upper and lower bounds not permitted.
```

(`lsqnonlin` does not handle equality constraints, which is another way to formulate equal bounds. If equality constraints are present, use `fmincon`, `fminimax`, or `fgoalattain` for alternative formulations where equality constraints can be included.)

**Limitations**

The function to be minimized must be continuous. `lsqnonlin` might only give local solutions.

`lsqnonlin` only handles real variables (the user-defined function must only return real values). When `x` has complex variables, the variables must be split into real and imaginary parts.

**Trust-Region-Reflective Optimization**

The trust-region-reflective algorithm for `lsqnonlin` does not solve underdetermined systems; it requires that the number of equations, i.e., the row dimension of `F`, be at least as great as the number of variables. In the underdetermined case, the Levenberg-Marquardt algorithm is used instead.

The preconditioner computation used in the preconditioned conjugate gradient part of the trust-region-reflective method forms $J^TJ$ (where $J$ is the Jacobian matrix) before computing the preconditioner; therefore, a row of $J$ with many nonzeros, which results in a nearly dense product $J^TJ$, can lead to a costly solution process for large problems.

If components of `x` have no upper (or lower) bounds, `lsqnonlin` prefers that the corresponding components of `ub` (or `lb`) be set to `inf` (or `-inf`
for lower bounds) as opposed to an arbitrary but very large positive (or negative for lower bounds) number.

**Trust-Region-Reflective Problem Coverage and Requirements**

<table>
<thead>
<tr>
<th>For Large Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provide sparsity structure of the Jacobian or compute the Jacobian in <code>fun</code>.</td>
</tr>
<tr>
<td>• The Jacobian should be sparse.</td>
</tr>
</tbody>
</table>

**Levenberg-Marquardt Optimization**

The Levenberg-Marquardt algorithm does not handle bound constraints. Since the trust-region-reflective algorithm does not handle underdetermined systems and the Levenberg-Marquardt does not handle bound constraints, problems with both these characteristics cannot be solved by `lsqnonlin`.

**References**


**See Also**

lsqcurvefit | lsqlin | optimset | optimtool | lsqnonlin

**How To**

- @ (function_handle)
- “Least Squares (Model Fitting) Algorithms” on page 6-145
- “Least Squares (Model Fitting) Examples” on page 6-154
lsqnonneg

**Purpose**
Solve nonnegative least-squares constraint problem

**Equation**
Solves nonnegative least-squares curve fitting problems of the form

\[ \min_{x} \| C \cdot x - d \|_2^2, \text{ where } x \geq 0. \]

**Syntax**

```matlab
x = lsqnonneg(C,d)
```

```matlab
x = lsqnonneg(C,d,options)
```

```matlab
x = lsqnonneg(problem)
```

```matlab
[x,resnorm] = lsqnonneg(...)
```

```matlab
[x,resnorm,residual] = lsqnonneg(...)
```

```matlab
[x,resnorm,residual,exitflag] = lsqnonneg(...)
```

```matlab
[x,resnorm,residual,exitflag,output] = lsqnonneg(...)
```

```matlab
[x,resnorm,residual,exitflag,output,lambda] = lsqnonneg(...)
```

**Description**

- `x = lsqnonneg(C,d)` returns the vector `x` that minimizes \( \| C \cdot x - d \|_2 \) subject to \( x \geq 0 \). \( C \) and \( d \) must be real.

- `x = lsqnonneg(C,d,options)` minimizes with the optimization options specified in the structure `options`. Use `optimset` to set these options.

- `x = lsqnonneg(problem)` finds the minimum for `problem`, where `problem` is a structure described in “Input Arguments” on page 11-219.

Create the structure `problem` by exporting a problem from Optimization Tool, as described in “Exporting Your Work” on page 5-17.

- `[x,resnorm] = lsqnonneg(...)` returns the value of the squared 2-norm of the residual, \( \| C \cdot x - d \|_2^2 \).

- `[x,resnorm,residual] = lsqnonneg(...)` returns the residual \( d - C \cdot x \).

- `[x,resnorm,residual,exitflag] = lsqnonneg(...)` returns a value `exitflag` that describes the exit condition of `lsqnonneg`.

- `[x,resnorm,residual,exitflag,output] = lsqnonneg(...)` returns a structure `output` that contains information about the optimization.
lsqnonneg

[x,resnorm,residual,exitflag,output,lambda] = lsqnonneg(...) returns the Lagrange multipliers in the vector lambda.

**Input Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments passed into lsqnonneg. This section provides function-specific details for options and problem:

**options**

Use optimset to set or change the values of these fields in the options structure, options. See “Optimization Options Reference” on page 9-7 for detailed information.

**Display**

Level of display:

- ‘off’ displays no output.
- ‘final’ displays just the final output.
- ‘notify’ (default) displays output only if the function does not converge.

**TolX**

Termination tolerance on x, a positive scalar. The default is \(10*\text{eps}*\text{norm}(C,1)*\text{length}(C)\).

**Output Arguments**

“Function Arguments” on page 9-2 contains general descriptions of arguments returned by lsqnonneg. This section provides function-specific details for exitflag, lambda, and output:

<table>
<thead>
<tr>
<th>C</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>Vector</td>
</tr>
<tr>
<td>x0</td>
<td>Initial point for x</td>
</tr>
<tr>
<td>solver</td>
<td>'lsqnonneg'</td>
</tr>
<tr>
<td>options</td>
<td>Options structure created with optimset</td>
</tr>
</tbody>
</table>
exitflag  Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.

1  Function converged to a solution x.
0  Number of iterations exceeded options.MaxIter.

lambda  Vector containing the Lagrange multipliers: lambda(i) 0 when x(i) is (approximately) 0, and lambda(i) is (approximately) 0 when x(i)>0.

output  Structure containing information about the optimization. The fields are

iterations  Number of iterations taken
algorithm  'active-set'
message  Exit message

Examples  Compare the unconstrained least-squares solution to the lsqnonneg solution for a 4-by-2 problem.

C = [
  0.0372  0.2869
  0.6861  0.7071
  0.6233  0.6245
  0.6344  0.6170];
d = [
  0.8587
  0.1781
  0.0747
  0.8405];

[C\d, lsqnonneg(C,d)]
The solution from lsqnonneg does not fit as well as the least-squares solution. However, the nonnegative least-squares solution has no negative components.

**Algorithms**

lsqnonneg uses the algorithm described in [1]. The algorithm starts with a set of possible basis vectors and computes the associated dual vector \( \lambda \). It then selects the basis vector corresponding to the maximum value in \( \lambda \) in order to swap it out of the basis in exchange for another possible candidate. This continues until \( \lambda = 0 \).

**Notes**

The nonnegative least-squares problem is a subset of the constrained linear least-squares problem. Thus, when \( C \) has more rows than columns (i.e., the system is overdetermined),

\[
[x,\text{resnorm},\text{residual},\text{exitflag},\text{output},\lambda] = ... \\text{lsqnonneg}(C,d)
\]

is equivalent to

\[
[m,n] = \text{size}(C);
[x,\text{resnorm},\text{residual},\text{exitflag},\text{output},\lambda_{\text{lsqlin}}] = ... \\text{lsqlin}(C,d,-\text{eye}(n,n),\text{zeros}(n,1));
\]

except that \( \lambda = -\lambda_{\text{lsqlin}}.\text{ineqlin} \).

For problems greater than order 20, lsqlin might be faster than lsqnonneg; otherwise lsqnonneg is generally more efficient.
References


See Also

lsqnonneg | lsqnonneg | optimset | optimtool

How To

· \
Purpose
Optimization options values

Syntax
val = optimget(options,'param')
val = optimget(options,'param',default)

Description
val = optimget(options,'param') returns the value of the specified option in the optimization options structure options. You need to type only enough leading characters to define the option name uniquely. Case is ignored for option names.

val = optimget(options,'param',default) returns default if the specified option is not defined in the optimization options structure options. Note that this form of the function is used primarily by other optimization functions.

Examples
This statement returns the value of the Display option in the structure called my_options.

    val = optimget(my_options,'Display')

This statement returns the value of the Display option in the structure called my_options (as in the previous example) except that if the Display option is not defined, it returns the value 'final'.

    optnew = optimget(my_options,'Display','final');

See Also
optimset
Purpose
Create or edit optimization options structure

Syntax
options = optimset('param1',value1,'param2',value2,...)
optimset
options = optimset
options = optimset(optimfun)
options = optimset(oldopts,'param1',value1,...)
options = optimset(oldopts,newopts)

Description
options = optimset('param1',value1,'param2',value2,...) creates an optimization options structure called options, in which the specified options (param) have specified values. Any unspecified options are set to [] (options with value [] indicate to use the default value for that option when you pass options to the optimization function). It is sufficient to type only enough leading characters to define the option name uniquely. Case is ignored for option names.

optimset with no input or output arguments displays a complete list of options with their valid values.

options = optimset (with no input arguments) creates an options structure options where all fields are set to [].

options = optimset(optimfun) creates an options structure options with all option names and default values relevant to the optimization function optimfun.

options = optimset(oldopts,'param1',value1,...) creates a copy of oldopts, modifying the specified options with the specified values.

options = optimset(oldopts,newopts) combines an existing options structure, oldopts, with a new options structure, newopts. Any options in newopts with nonempty values overwrite the corresponding old options in oldopts.

Options
For more information about individual options, including their default values, see the reference pages for the optimization functions. “Optimization Options Reference” on page 9-7 provides descriptions of optimization options and which functions use them.
Use the command `optimset(@solver)` or the equivalent `optimset solver` to see the default values of relevant optimization options for a solver. Some solvers do not have a default value, since the default depends on the algorithm. For example, the default value of the `maxIter` option in the `fmincon` solver is 400 for the trust-region-reflective algorithm, but is 1000 for the interior-point algorithm.

You can also see the default values of all relevant options in the Optimization Tool. To see the options:

1. Start the Optimization Tool, e.g., with the `optimtool` command.
2. Choose the solver from the **Solver** menu.
3. Choose the algorithm, if applicable, from the **Algorithm** menu.
4. Read off the default values within the **Options** pane.

### Examples

This statement creates an optimization options structure called `options` in which the `Display` option is set to `'iter'` and the `TolFun` option is set to `1e-8`.

```
options = optimset('Display','iter','TolFun',1e-8)
```

This statement makes a copy of the options structure called `options`, changing the value of the `TolX` option and storing new values in `optnew`.

```
optnew = optimset(options,'TolX',1e-4);
```

This statement returns an optimization options structure `options` that contains all the option names and default values relevant to the function `fminbnd`.

```
options = optimset('fminbnd')
```

If you only want to see the default values for `fminbnd`, you can simply type

```
optimset fminbnd
```
or equivalently

```matlab
optimset('fminbnd')
```

**See Also**

optimget | optimtool
Purpose

Tool to select solver, optimization options, and run problems

Syntax

optimtool
optimtool(optstruct)
optimtool('solver')

Description

optimtool opens the Optimization tool, a graphical user interface (GUI) for selecting a solver, the optimization options, and running problems. See Chapter 5, “Graphical Optimization Tool” for a complete description of the tool.

optimtool can be used to run any Optimization Toolbox solver, and any Global Optimization Toolbox solver. Results can be exported to a file or to the MATLAB workspace as a structure.

optimtool(optstruct) starts the Optimization Tool and loads optstruct. The optstruct structure can be either an optimization options structure or an optimization problem structure. Create an options structure with the optimset function, or by using the export option from the Optimization Tool. Create a problem structure by exporting the problem from the Optimization Tool to the MATLAB workspace. If you have Global Optimization Toolbox, you can create a problem structure with the createOptimProblem function.

optimtool('solver') starts the Optimization Tool with the specified solver, identified as a string, and the corresponding default options and problem fields. All Optimization Toolbox and Global Optimization Toolbox solvers are valid inputs to the optimtool function.
See Also

optimset

How To

• Chapter 5, “Graphical Optimization Tool”
Purpose

Quadratic programming

Syntax

\[
x = \text{quadprog}(H,f)
\]
\[
x = \text{quadprog}(H,f,A,b)
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq)
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub)
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub,x0)
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub,x0,options)
\]
\[
x = \text{quadprog}(\text{problem})
\]
\[
[x,fval] = \text{quadprog}(H,f,...)
\]
\[
[x,fval,exitflag] = \text{quadprog}(H,f,...)
\]
\[
[x,fval,exitflag,output] = \text{quadprog}(H,f,...)
\]
\[
[x,fval,exitflag,output,lambda] = \text{quadprog}(H,f,...)
\]

Description

\[
x = \text{quadprog}(H,f) \text{ returns a vector } x \text{ that minimizes}
\]
\[
1/2*x'*H*x + f'*x. H \text{ must be positive definite for the problem to have a finite minimum.}
\]
\[
x = \text{quadprog}(H,f,A,b) \text{ minimizes } 1/2*x'*H*x + f'*x \text{ subject to the restrictions } A*x \leq b. A \text{ is a matrix of doubles, and } b \text{ is a vector of doubles.}
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq) \text{ solves the preceding problem subject to the additional restrictions } Aeq*x = beq. Aeq \text{ is a matrix of doubles, and } beq \text{ is a vector of doubles. If no inequalities exist, set } A = [ ] \text{ and } b = [ ].
\]
\[
x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub) \text{ solves the preceding problem subject to the additional restrictions } lb \leq x \leq ub. lb \text{ and } ub \text{ are vectors of doubles, and the restrictions hold for each } x \text{ component. If no equalities exist, set } Aeq = [ ] \text{ and } beq = [ ].
\]
quadprog

Note If the specified input bounds for a problem are inconsistent, the output x is x0 and the output fval is [].

quadprog resets components of x0 that violate the bounds lb ≤ x ≤ ub to the interior of the box defined by the bounds. quadprog does not change components that respect the bounds.

\[ x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub,x0) \] solves the preceding problem starting from the vector x0. If no bounds exist, set lb = [] and ub = []. Some quadprog algorithms ignore x0. If you do not give x0, all components of x0 are set to a point in the interior of the box defined by the bounds.

\[ x = \text{quadprog}(H,f,A,b,Aeq,beq,lb,ub,x0,options) \] solves the preceding problem using the optimization options specified in the structure options. Use optimset to create options. If you do not want to give an initial point, set x0 = [].

\[ x = \text{quadprog}(\text{problem}) \] returns the minimum for problem, where problem is a structure described in “Input Arguments” on page 11-231. Create problem by exporting a problem using the Optimization Tool; see “Exporting Your Work” on page 5-17.

\[ [x,fval] = \text{quadprog}(H,f,\ldots) \] returns the value of the objective function at x:

\[ fval = 0.5*x'*H*x + f'*x \]

\[ [x,fval,exitflag] = \text{quadprog}(H,f,\ldots) \] exitflag, a scalar that describes the exit condition of quadprog.

\[ [x,fval,exitflag,output] = \text{quadprog}(H,f,\ldots) \] output, a structure that contains information about the optimization.

\[ [x,fval,exitflag,output,lambda] = \text{quadprog}(H,f,\ldots) \] lambda, a structure whose fields contain the Lagrange multipliers at the solution x.
**Input Arguments**

**H**
Symmetric matrix of doubles. Represents the quadratic in the expression \(1/2 x' * H * x + f' * x\).

**f**
Vector of doubles. Represents the linear term in the expression \(1/2 x' * H * x + f' * x\).

**A**
Matrix of doubles. Represents the linear coefficients in the constraints \(A * x \leq b\).

**b**
Vector of doubles. Represents the constant vector in the constraints \(A * x \leq b\).

**Aeq**
Matrix of doubles. Represents the linear coefficients in the constraints \(Aeq * x = beq\).

**beq**
Vector of doubles. Represents the constant vector in the constraints \(Aeq * x = beq\).

**lb**
Vector of doubles. Represents the lower bounds elementwise in \(lb \leq x \leq ub\).

**ub**
Vector of doubles. Represents the upper bounds elementwise in \(lb \leq x \leq ub\).

**x0**
Vector of doubles. Optional. The initial point for some \texttt{quadprog} algorithms.

\texttt{options}

Options structure created using \texttt{optimset} or the Optimization Tool.

\textbf{All Algorithms}

\begin{itemize}
  \item \texttt{Algorithm}
  \begin{itemize}
    \item \texttt{trust-region-reflective} (default)
    \item \texttt{interior-point-convex}
    \item \texttt{active-set}
  \end{itemize}
  For details, see “Choosing the Algorithm” on page 2-7.
  \item \texttt{Diagnostics}
  Display diagnostic information about the function to be minimized or solved. The choices are 'on' or 'off' (default).
  \item \texttt{Display}
  Level of display returned to the command line.
  \begin{itemize}
    \item 'off' displays no output.
    \item 'final' displays just the final output (default).
  \end{itemize}
  The interior-point algorithm allows additional values:
  \begin{itemize}
    \item 'iter' gives iterative display.
    \item 'iter-detailed' gives iterative display with a detailed exit message.
  \end{itemize}
\end{itemize}
All Algorithms (Continued)

- 'final-detailed' displays just the final output, with a detailed exit message.

MaxIter
Maximum number of iterations allowed, a positive integer.

- For a trust-region-reflective equality-constrained problem, the default value is $2 \times (\text{numberOfVariables} - \text{numberOfEqualities})$.
- For all other algorithms and problems, the default value is 200.

All Algorithms Except active-set

TolFun
Termination tolerance on the function value, a positive scalar.

- For a trust-region-reflective equality-constrained problem, the default value is $1e-6$.
- For a trust-region-reflective bound-constrained problem, the default value is $100 \times \text{eps}$, about $2.2204e-14$.
- For interior-point-convex, the default value is $1e-8$.

TolX
Termination tolerance on $x$, a positive scalar.

- For trust-region-reflective, the default value is $100 \times \text{eps}$, about $2.2204e-14$. 
All Algorithms Except active-set (Continued)

- For interior-point-convex, the default value is $1e^{-8}$.

**trust-region-reflective Algorithm Only**

**HessMult**

Function handle for a Hessian multiply function. For large-scale structured problems, this function computes the Hessian matrix product $H*Y$ without actually forming $H$. The function has the form

$$W = hmfun(Hinfo,Y)$$

where $Hinfo$ and possibly some additional parameters contain the matrices used to compute $H*Y$.

See “Example: Quadratic Minimization with a Dense but Structured Hessian” on page 6-127 for an example that uses this option.

**MaxPCGIter**

Maximum number of PCG (preconditioned conjugate gradient) iterations, a positive scalar. The default is $\max(1,\text{floor}(\text{numberOfVariables}/2))$. For more information, see “Preconditioned Conjugate Gradient Method” on page 6-117.
trust-region-reflective Algorithm Only (Continued)

PrecondBandWidth Upper bandwidth of the preconditioner for PCG, a nonnegative integer. By default, quadprog uses diagonal preconditioning (upper bandwidth 0). For some problems, increasing the bandwidth reduces the number of PCG iterations. Setting PrecondBandWidth to Inf uses a direct factorization (Cholesky) rather than the conjugate gradients (CG). The direct factorization is computationally more expensive than CG, but produces a better quality step toward the solution.

TolPCG Termination tolerance on the PCG iteration, a positive scalar. The default is 0.1.

TypicalX Typical x values. The number of elements in TypicalX equals the number of elements in x0, the starting point. The default value is ones(numberofvariables,1). quadprog uses TypicalX internally for scaling. TypicalX has an effect only when x has unbounded components, and when a TypicalX value for an unbounded component exceeds 1.

interior-point-convex Algorithm Only

TolCon Tolerance on the constraint violation, a positive scalar. The default is 1e-8.

problem

Structure encapsulating the quadprog inputs and options:
quadprog

H  Symmetric matrix in 1/2*x'*H*x
f  Vector in linear term f'*x
Aineq Matrix in linear inequality constraints
     Aineq*x ≤ bineq
bineq Vector in linear inequality constraints
     Aineq*x ≤ bineq
Aeq  Matrix in linear equality constraints
     Aeq*x = beq
beq  Vector in linear equality constraints
     Aeq*x = beq
lb  Vector of lower bounds
ub  Vector of upper bounds
x0  Initial point for x
solver 'quadprog'
options Options structure created using optimset
          or the Optimization Tool

Output Arguments

x
Vector that minimizes 1/2*x'*H*x + f'*x subject to all bounds
and linear constraints. x can be a local minimum for nonconvex
problems. For convex problems, x is a global minimum. For more
information, see “Local vs. Global Optima” on page 4-26.

fval
Value of 1/2*x'*H*x + f'*x at the solution x, a double.

exitflag
Integer identifying the reason the algorithm terminated. The
following lists the values of exitflag and the corresponding
reasons the algorithm terminated:
All Algorithms

1  Function converged to the solution $x$.
0  Number of iterations exceeded `options.MaxIter`.
-2  Problem is infeasible.
-3  Problem is unbounded.

**interior-point-convex Algorithm**

-6  Nonconvex problem detected.

**trust-region-reflective Algorithm**

3  Change in the objective function value was smaller than `options.TolFun`.
-4  Current search direction was not a direction of descent. No further progress could be made.

**active-set Algorithm**

4  Local minimizer was found.
-7  Magnitude of search direction became too small. No further progress could be made. The problem is ill-posed or badly conditioned.

**output**

Structure containing information about the optimization. The fields are:

- `iterations`: Number of iterations taken
- `algorithm`: Optimization algorithm used
- `cgiterations`: Total number of PCG iterations (large-scale algorithm only)
quadprog

constrieviolation Maximum of constraint functions
firstorderopt Measure of first-order optimality
message Exit message

lambda

Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields are:

lower Lower bounds lb
upper Upper bounds ub
ineqlin Linear inequalities
eqlin Linear equalities

For details, see “Lagrange Multiplier Structures” on page 3-26.

Examples

Solve a simple quadratic programming problem: find values of x that minimize

\[ f(x) = \frac{1}{2} x_1^2 + x_2^2 - x_1 x_2 - 2x_1 - 6x_2, \]

subject to

\[ x_1 + x_2 \leq 2 \]
\[ -x_1 + 2x_2 \leq 2 \]
\[ 2x_1 + x_2 \leq 3 \]
\[ 0 \leq x_1, 0 \leq x_2. \]

In matrix notation this is

\[ f(x) = \frac{1}{2} x^T H x + f^T x, \]

where
\[
H = \begin{bmatrix} 1 & -1 \\ -1 & 2 \end{bmatrix}, \quad f = \begin{bmatrix} -2 \\ -6 \end{bmatrix}, \quad x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.
\]

1. Enter the coefficient matrices:

\[
\begin{align*}
H &= \begin{bmatrix} 1 & -1 \\ -1 & 2 \end{bmatrix}; \\
f &= \begin{bmatrix} -2 \\ -6 \end{bmatrix}; \\
A &= \begin{bmatrix} 1 & 1; & -1 & 2; & 2 & 1 \end{bmatrix}; \\
b &= \begin{bmatrix} 2; & 2; & 3 \end{bmatrix}; \\
lb &= \text{zeros}(2,1);
\end{align*}
\]

2. Set the options to use the active-set algorithm with no display:

\[
\text{opts} = \text{optimset}('\text{Algorithm}', 'active-set', '\text{Display}', 'off');
\]

3. Call quadprog:

\[
[x, fval, exitflag, output, lambda] = ... \\
\text{quadprog}(H, f, A, b, [], [], lb, [], [], opts);
\]

4. Examine the final point, function value, and exit flag:

\[
x, fval, exitflag
\]

\[
x = \\
\begin{align*}
0.6667 \\
1.3333
\end{align*}
\]

\[
fval = \\
\begin{align*}
-8.2222
\end{align*}
\]

\[
exitflag = \\
1
\]

5. An exit flag of 1 means the result is a local minimum. Because \( H \) is a positive definite matrix, this problem is convex, so the minimum
is a global minimum. You can see $H$ is positive definite by noting all its eigenvalues are positive:

```matlab
eig(H)
ans =
   0.3820
   2.6180
```

Use the `interior-point-convex` algorithm to solve a sparse quadratic program.

1 Generate a sparse symmetric matrix for the quadratic form:

```matlab
v = sparse([1,-.25,0,0,0,0,0,-.25]);
H = gallery('circul',v);
```

2 Include the linear term for the problem:

```matlab
f = -4:3;
```

3 Include the constraint that the sum of the terms in the solution $x$ must be less than -2:

```matlab
A = ones(1,8);b = -2;
```

4 Set options to use the `interior-point-convex` algorithm and iterative display:

```matlab
opts = optimset('Algorithm','interior-point-convex','Display','iter');
```

5 Run the `quadprog` solver and observe the iterations:


```matlab
[x fval eflag output lambda] = quadprog(H,f,A,b,[],[],[],[],[],opts);
```

<table>
<thead>
<tr>
<th>Iter</th>
<th>f(x)</th>
<th>Feasibility</th>
<th>optimality</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2.000000e+000</td>
<td>1.000e+001</td>
<td>4.500e+000</td>
<td>1.200e+001</td>
</tr>
<tr>
<td>1</td>
<td>-2.630486e+001</td>
<td>0.000e+000</td>
<td>9.465e-002</td>
<td>9.465e-002</td>
</tr>
<tr>
<td>2</td>
<td>-2.639877e+001</td>
<td>0.000e+000</td>
<td>3.914e-005</td>
<td>3.914e-005</td>
</tr>
<tr>
<td>3</td>
<td>-2.639881e+001</td>
<td>0.000e+000</td>
<td>3.069e-015</td>
<td>6.883e-015</td>
</tr>
</tbody>
</table>

Minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

6 Examine the solution:

```matlab
fval,eflag
```

```matlab
fval =
-26.3988
```

```matlab
eflag =
1
```

For the interior-point-convex algorithm, an exit flag of 1 means the result is a global minimum.

**Algorithms  trust-region-reflective**

The trust-region-reflective algorithm is a subspace trust-region method based on the interior-reflective Newton method described in [1]. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG).
For more information, see “trust-region-reflective quadprog Algorithm” on page 6-115.

**active-set**

quadprog uses an active set method, which is also a projection method, similar to that described in [2]. It finds an initial feasible solution by first solving a linear programming problem. For more information, see “active-set quadprog Algorithm” on page 6-120.

**interior-point-convex**

The interior-point-convex algorithm attempts to follow a path that is strictly inside the constraints. It uses a presolve module to remove redundancies, and to simplify the problem by solving for components that are straightforward. For more information, see “interior-point-convex quadprog Algorithm” on page 6-111.

**References**


**Alternatives**

You can use the Optimization Tool for quadratic programming. Enter `optimtool` at the MATLAB command line, and choose the `quadprog` - Quadratic programming solver. For more information, see Chapter 5, “Graphical Optimization Tool”.

**See Also**

`linprog` | `lsqnonlin`

**Tutorials**

- “Quadratic Programming Examples” on page 6-125
How To

• Chapter 2, “Setting Up an Optimization”
• Chapter 3, “Examining Results”
• Chapter 4, “Steps to Take After Running a Solver”
• Chapter 5, “Graphical Optimization Tool”
• “Quadratic Programming Algorithms” on page 6-111
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“Example: Checking Derivatives of Objective and Constraint Functions” on page 2-52
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