Wolfram *Mathematica*® Tutorial Collection

SYSTEMS INTERFACES AND DEPLOYMENT

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The Main Loop

In any interactive session, *Mathematica* effectively operates in a loop. It waits for your input, processes the input, prints the result, then goes back to waiting for input again. As part of this "main loop", *Mathematica* maintains and uses various global objects. You will often find it useful to work with these objects.

You should realize, however, that if you use *Mathematica* through a special front end, your front end may set up its own main loop, and what is said here may not apply.

`In[n]`	the expression on the n^{th} input line
`InString[n]`	the textual form of the n^{th} input line
`%n` or `Out[n]`	the expression on the n^{th} output line
`Out[{n1,n2,...}]`	a list of output expressions
`%% ... %` (n times) or `Out[-n]`	the expression on the n^{th} previous output line
`MessageList[n]`	a list of messages produced while processing the n^{th} line
`$Line`	the current line number (resettable)

Input and output expressions.

In a standard interactive session, there is a sequence of input and output lines. *Mathematica* stores the values of the expressions on these lines in `In[n]` and `Out[n]`.

As indicated by the usual `In[n] :=` prompt, the input expressions are stored with delayed assignments. This means that whenever you ask for `In[n]`, the input expression will always be reevaluated in your current environment.

This assigns a value to x.

```
In[1]:= x = 7
Out[1]= 7
```

Now the value for x is used.

```
In[2]:= x - x^2 + 5 x - 1
Out[2]= -8
```

This removes the value assigned to x.

```
In[3]:= x =.
```

This is reevaluated in your current environment, where there is no value assigned to x.

```
In[4]:= In[2]
Out[4]= -1 + 6 x - x^2
```

This gives the textual form of the second input line, appropriate for editing or other textual manipulation.

```
In[5]:= InString[2] // InputForm
Out[5]//InputForm= "\\(x - \\(x^2\\) + \\(5 x\\) - 1\\)"
```

$HistoryLength	the number of previous lines of input and output to keep

Specifying the length of session history to keep.

Mathematica by default stores *all* your input and output lines for the duration of the session. In a very long session, this may take up a large amount of computer memory. You can nevertheless get rid of the input and output lines by explicitly clearing the values of In and Out, using Unprotect[In, Out], followed by Clear[In, Out]. You can also tell *Mathematica* to keep only a limited number of lines of history by setting the global variable $HistoryLength.

Note that at any point in a session, you can reset the line number counter $Line, so that, for example, new lines are numbered so as to overwrite previous ones.

$PreRead	a function applied to each input string before being fed to *Mathematica*
$Pre	a function applied to each input expression before evaluation
$Post	a function applied to each expression after evaluation
$PrePrint	a function applied after Out[*n*] is assigned, but before the result is printed
$SyntaxHandler	a function applied to any input line that yields a syntax error

Global functions used in the main loop.

Mathematica provides a variety of "hooks" that allow you to insert functions to be applied to expressions at various stages in the main loop. Thus, for example, any function you assign as the value of the global variable $Pre will automatically be applied before evaluation to any expression you give as input.

For a particular input line, the standard main loop begins by getting a text string of input. Particularly if you need to deal with special characters, you may want to modify this text string before it is further processed by *Mathematica*. You can do this by assigning a function as the value of the global variable $PreRead. This function will be applied to the text string, and the result will be used as the actual input string for the particular input line.

This tells *Mathematica* to replace listHead by {...} in every input string.

```
In[6]:= $PreRead = (ReplaceAll[#, "listHead" :> "List"] &)
Out[6]= #1 /. listHead :> List &
```

You can now enter lists as listHead expressions.

```
In[7]:= listHead[a, b, c]
Out[7]= {a, b, c}
```

You can remove the value for $PreRead like this, at least so long as your definition for $PreRead does not modify this very input string.

```
In[8]:= $PreRead =.
```

Once *Mathematica* has successfully read an input expression, it then evaluates this expression. Before doing the evaluation, *Mathematica* applies any function you have specified as the value

of $Pre, and after the evaluation, it applies any function specified as the value of $Post. Note that unless the $Pre function holds its arguments unevaluated, the function will have exactly the same effect as $Post.

$Post allows you to specify arbitrary "postprocessing" to be done on results obtained from *Mathematica*. Thus, for example, to make *Mathematica* get a numerical approximation to every result it generates, all you need do is to set $Post = N.

This tells *Mathematica* to apply N to every result it generates.

```
In[9]:= $Post = N
Out[9]= N
```

Now *Mathematica* gets a numerical approximation to anything you type in.

```
In[10]:= Sqrt[7]
Out[10]= 2.64575
```

This removes the postprocessing function you specified.

```
In[11]:= $Post =.
```

As soon as *Mathematica* has generated a result, and applied any $Post function you have specified, it takes the result, and assigns it as the value of Out[$Line]. The next step is for *Mathematica* to print the result. However, before doing this, it applies any function you have specified as the value of $PrePrint.

This tells *Mathematica* to shorten all output to two lines.

```
In[12]:= $PrePrint = Short[#, 2] &;
```

Only a two-line version of the output is now shown.

```
In[13]:= Expand[(x + y) ^ 40]
Out[13]= x^40 + 40 x^39 y + 780 x^38 y^2 + 9880 x^37 y^3 + 91 390 x^36 y^4 +
          658 008 x^35 y^5 + <<30>> + 91 390 x^4 y^36 + 9880 x^3 y^37 + 780 x^2 y^38 + 40 x y^39 + y^40
```

This removes the value you assigned to $PrePrint.

```
In[14]:= $PrePrint =.
```

There are various kinds of output generated in a typical *Mathematica* session. In general, each kind of output is sent to a definite *output channel*, as discussed in "Streams and Low-Level Input and Output". Associated with each output channel, there is a global variable which gives a list of the output streams to be included in that output channel.

`$Output`	standard output and text generated by `Print`
`$Echo`	an echo of each input line (as stored in `InString[`*n*`]`)
`$Urgent`	input prompts and other urgent output
`$Messages`	standard messages and output generated by `Message`

Output channels in a standard *Mathematica* session.

By modifying the list of streams in a given output channel, you can redirect or copy particular kinds of *Mathematica* output. Thus, for example, by opening an output stream to a file, and including that stream in the `$Echo` list, you can get each piece of input you give to *Mathematica* saved in a file.

`Streams[]`	list of all open streams
`Streams["`*name*`"]`	list of all open streams with the specified name
`$Input`	the name of the current input stream

Open streams in a *Mathematica* session.

The function `Streams` shows you all the input, output and other streams that are open at a particular point in a *Mathematica* session. The variable `$Input` gives the name of the current stream from which *Mathematica* input is being taken at a particular point. `$Input` is reset, for example, during the execution of a `Get` command.

`$MessagePrePrint`	a function to be applied to expressions that are given in messages
`$Language`	list of default languages to use for messages

Parameters for messages.

There are various global parameters which determine the form of messages generated by *Mathematica*.

As discussed in "Messages", typical messages include a sequence of expressions which are combined with the text of the message through `StringForm`. `$MessagePrePrint` gives a function to be applied to the expressions before they are printed. The default for `$MessagePrePrint` uses `Short` for text formatting and a combination of `Short` and `Shallow` for typesetting.

As discussed in "International Messages", *Mathematica* allows you to specify the language in which you want messages to be produced. In a particular *Mathematica* session, you can assign a list of language names as the value of `$Language`.

`Exit[]` or `Quit[]`	terminate your *Mathematica* session
`$Epilog`	a global variable to be evaluated before termination

Terminating *Mathematica* sessions.

Mathematica will continue in its main loop until you explicitly tell it to exit. Most *Mathematica* interfaces provide special ways to do this. Nevertheless, you can always do it by explicitly calling `Exit` or `Quit`.

Mathematica allows you to give a value to the global variable `$Epilog` to specify operations to perform just before *Mathematica* actually exits. In this way, you can for example make *Mathematica* always save certain objects before exiting.

`$IgnoreEOF`	whether to ignore the end-of-file character

A global variable that determines the treatment of end-of-file characters.

As discussed in "Special Characters: Strings and Characters", *Mathematica* usually does not treat special characters in a special way. There is one potential exception, however. With the default setting `$IgnoreEOF = False`, *Mathematica* recognizes end-of-file characters. If *Mathematica* receives an end-of-file character as the only thing on a particular input line in a standard interactive *Mathematica* session, then it will exit the session.

Exactly how you enter an end-of-file character depends on the computer system you are using. Under Unix, for example, you typically press Ctrl+D.

Note that if you use *Mathematica* in a “batch mode”, with all its input coming from a file, then it will automatically exit when it reaches the end of the file, regardless of the value of `$IgnoreEOF`.

Dialogs

Within a standard interactive session, you can create "subsessions" or *dialogs* using the *Mathematica* command `Dialog`. Dialogs are often useful if you want to interact with *Mathematica* while it is in the middle of doing a calculation. As mentioned in "Tracing Evaluation", `TraceDialog` for example automatically calls `Dialog` at specified points in the evaluation of a particular expression. In addition, if you interrupt *Mathematica* during a computation, you can typically "inspect" its state using a dialog.

`Dialog[]`	initiate a *Mathematica* dialog
`Dialog[`*expr*`]`	initiate a dialog with *expr* as the current value of `%`
`Return[]`	return from a dialog, taking the current value of `%` as the return value
`Return[`*expr*`]`	return from a dialog, taking *expr* as the return value

Initiating and returning from dialogs.

This initiates a dialog.

```
In[1]:= Dialog[]
```

You can do computations in a dialog just as you would in any *Mathematica* session.

```
In[2]:= 2^41
Out[2]= 2 199 023 255 552
```

You can use `Return` to exit from a dialog.

```
In[3]:= Return[]
Out[3]= 2 199 023 255 552
```

When you exit a dialog, you can return a value for the dialog using `Return[`*expr*`]`. If you do not want to return a value, and you have set `$IgnoreEOF = False`, then you can also exit a dialog simply by giving an end-of-file character, at least on systems with text-based interfaces.

To evaluate this expression, *Mathematica* initiates a dialog.

```
In[4]:= 1 + Dialog[]^2
```

The value a + b returned from the dialog is now inserted in the original expression.

```
In[5]:= Return[a + b]
Out[5]= 1 + (a + b)^2
```

In starting a dialog, you will often find it useful to have some "initial expression". If you use `Dialog[`*expr*`]`, then *Mathematica* will start a dialog, using *expr* as the initial expression, accessible for example as the value of `%`.

This first starts a dialog with initial expression a^2.

```
In[6]:= Map[Dialog, {a^2, b + c}]
Out[6]= a^2
```

`%` is the initial expression in the dialog.

```
In[7]:= %^2 + 1
Out[7]= 1 + a^4
```

This returns a value from the first dialog, and starts the second dialog, with initial expression b + c.

```
In[8]:= Return[%]
Out[8]= b + c
```

This returns a value from the second dialog. The final result is the original expression, with values from the two dialogs inserted.

```
In[9]:= Return[444]
Out[9]= {1 + a^4, 444}
```

`Dialog` effectively works by running a subsidiary version of the standard *Mathematica* main loop. Each dialog you start effectively "inherits" various values from the overall main loop. Some of the values are, however, local to the dialog, so their original values are restored when you exit the dialog.

Thus, for example, dialogs inherit the current line number `$Line` when they start. This means that the lines in a dialog have numbers that follow the sequence used in the main loop. Nevertheless, the value of `$Line` is local to the dialog. As a result, when you exit the dialog, the value of `$Line` reverts to what it was in the main loop.

If you start a dialog on line `10` of your *Mathematica* session, then the first line of the dialog will be labeled `In[11]`. Successive lines of the dialog will be labeled `In[12]`, `In[13]` and so on. Then, when you exit the dialog, the next line in your main loop will be labeled `In[11]`. At this point, you can still refer to results generated within the dialog as `Out[11]`, `Out[12]` and so on. These results will be overwritten, however, when you reach lines `In[12]`, `In[13]`, and so on in the main loop.

In a standard *Mathematica* session, you can tell whether you are in a dialog by seeing whether your input and output lines are indented. If you call a dialog from within a dialog, you will get two levels of indentation. In general, the indentation you get inside d nested dialogs is determined by the output form of the object `DialogIndent[`d`]`. By defining the format for this object, you can specify how dialogs should be indicated in your *Mathematica* session.

`DialogSymbols:>`$\{x, y, \ldots\}$	symbols whose values should be treated as local to the dialog
`DialogSymbols:>`$\{x=x_0, y=y_0, \ldots\}$	symbols with initial values
`DialogProlog:>`*expr*	an expression to evaluate before starting the dialog

Options for `Dialog`.

Whatever setting you give for `DialogSymbols`, `Dialog` will always treat the values of `$Line`, `$Epilog` and `$MessageList` as local. Note that if you give a value for `$Epilog`, it will automatically be evaluated when you exit the dialog.

When you call `Dialog`, its first step is to localize the values of variables. Then it evaluates any expression you have set for the option `DialogProlog`. If you have given an explicit argument to the `Dialog` function, this is then evaluated next. Finally, the actual dialog is started.

When you exit the dialog, you can explicitly specify the return value using `Return[`*expr*`]`. If you do not do this, the return value will be taken to be the last value generated in the dialog.

Date and Time Functions

`DateList[]`	give the current local date and time in the form {*year*, *month*, *day*, *hour*, *minute*, *second*}
`DateList[TimeZone->z]`	give the current date and time in time zone *z*
`$TimeZone`	give the time zone assumed by your computer system

Finding the date and time.

This gives the current date and time.

```
In[1]:= DateList[]
Out[1]= {2005, 3, 31, 19, 21, 29.566769}
```

The *Mathematica* `DateList` function returns whatever your computer system gives as the current date and time. It assumes that any corrections for daylight saving time and so on have already been done by your computer system. In addition, it assumes that your computer system has been set for the appropriate time zone.

The variable `$TimeZone` returns the current time zone assumed by your computer system. The time zone is given as the number of hours which must be added to Greenwich Mean Time (GMT) to obtain the correct local time. Thus, for example, U.S. Eastern Standard Time (EST) corresponds to time zone -5. Note that daylight saving time corrections must be included in the time zone, so U.S. Eastern Daylight Time (EDT) corresponds to time zone -4.

This gives the current time zone assumed by your computer system.

```
In[2]:= $TimeZone
Out[2]= -6.
```

This gives the current date and time in time zone +9, the time zone for Japan.

```
In[3]:= DateList[TimeZone -> 9]
Out[3]= {2005, 4, 1, 10, 21, 29.579505}
```

`AbsoluteTime[]`	total number of seconds since the beginning of January 1, 1900
`SessionTime[]`	total number of seconds elapsed since the beginning of your current *Mathematica* session
`TimeUsed[]`	total number of seconds of CPU time used in your current *Mathematica* session
`$TimeUnit`	the minimum time interval recorded on your computer system

Time functions.

You should realize that on any computer system, there is a certain "granularity" in the times that can be measured. This granularity is given as the value of the global variable `$TimeUnit`. Typically it is either about $\frac{1}{100}$ or $\frac{1}{1000}$ of a second.

`Pause[`*n*`]`	pause for at least *n* seconds

Pausing during a calculation.

This gives various time functions.

```
In[4]:= {AbsoluteTime[], SessionTime[], TimeUsed[]}
Out[4]= {3.321285689607146×10^9, 6.125768, 2.24}
```

This pauses for 10 seconds, then reevaluates the time functions. Note that `TimeUsed[]` is not affected by the pause.

```
In[5]:= Pause[10]; {AbsoluteTime[], SessionTime[], TimeUsed[]}
Out[5]= {3.321285699616089×10^9, 16.134709, 2.24}
```

`AbsoluteTime[`*date*`]`	convert from date to absolute time
`DateList[`*time*`]`	convert from absolute time to date

Converting between dates and absolute times.

This sets `d` to be the current date.

```
In[6]:= d = DateList[]
Out[6]= {2005, 3, 31, 19, 21, 39.625914}
```

This adds one month to the current date.

```
In[7]:= DateList[] + {0, 1, 0, 0, 0, 0}
Out[7]= {2005, 4, 31, 19, 21, 39.629234}
```

This gives the number of seconds in the additional month.

```
In[8]:= AbsoluteTime[%] - AbsoluteTime[d]
Out[8]= 2.678400003320×10^6
```

`DateList["string"]`	convert a date string to a date list
`DateList[{"string",{"e1","e2",...}}]`	give the date list obtained by extracting elements "e_i" from "*string*"

Converting from different date formats.

You can use `DateList["string"]` to convert a date string into a date list, as long as the date format is sufficiently unambiguous.

This attempts to interpret the string as a date.

```
In[9]:= DateList["June 23, 1988 - 3:55 pm"]
Out[9]= {1988, 6, 23, 15, 55, 0.}
```

For more control of the conversion, you can specify the order and type of date elements appearing in the string. The elements can be strings like `"Year"`, `"Quarter"`, `"Month"`, `"MonthName"`, `"Day"`, `"DayName"`, `"Hour"`, `"AMPM"`, `"Minute"`, or `"Second"`.

This extracts a date using the specified elements.

```
In[10]:= DateList[{"3/5/2001", {"Month", "Day", "Year"}}]
Out[10]= {2001, 3, 5, 0, 0, 0}
```

If the date element delimiters contain letters or digits, these must also be specified as part of the date elements.

This extracts a date containing a letter as a separator.

```
In[11]:= DateList[{"Jun Y1988", {"MonthName", " Y", "Year"}}]
Out[11]= {1988, 6, 1, 0, 0, 0}
```

DateString[]	give a string representing current local date and time
DateString[*datespec*, *elems*]	give elements *elems* of date and time given by *datespec*

Converting to different date formats.

DateString is used to give a nice string representation of a date and time. The exact output format can be specified from a long list of date elements, such as "DateTime", "DayName", "HourShort", etc.

This gives the current date and time in the default format.

```
In[12]:= DateString[]
Out[12]= Fri 15 Dec 2006 13:27:47
```

This specifies a format for the given date.

```
In[13]:= DateString[{1988, 6, 23, 15, 55, 0}, {"MonthName", " ", "DayShort", ", ",
           "Year", " - ", "Hour12Short", ":", "Minute", " ", "AMPMLowerCase"}]
Out[13]= June 23, 1988 - 3:55 pm
```

DatePattern[*elems*]	string pattern matching a date with the given elements

Extracting dates from a string.

You can use DatePattern[*elems*] as a string pattern in string matching functions. The date elements are the same as used in DateList, although the default date element delimiters are restricted to the /, -, : or . characters. Other delimiters can be given explicitly in the list of date elements.

This extracts dates of the given format from a string.

```
In[14]:= StringCases["abc 12/5/2005 def 1/15/2002 ghi",
          x : DatePattern[{"Month", "Day", "Year"}] :> DateList[x]]

DateList::ambig : Warning: the interpretation of the string 12/5/2005 as a date is ambiguous. >>

Out[14]= {{2005, 12, 5, 0, 0, 0.}, {2002, 1, 15, 0, 0, 0.}}
```

This extracts dates with explicit delimiters.

```
In[15]:= StringCases["abc Mar 2002 def Aug 2005 ghi",
          x : DatePattern[{"MonthName", " ", "Year"}] :> DateList[x]]
Out[15]= {{2002, 3, 1, 0, 0, 0.}, {2005, 8, 1, 0, 0, 0.}}
```

DateListPlot[*list*]	generate a plot from a list of data with date coordinates
DateListPlot[*list*,*datespec*]	generate a plot from a list of data with dates specified by *datespec*
DateListLogPlot[*list*]	generate a linear-log plot from a list of data with date coordinates
DateListLogPlot[*list*,*datespec*]	generate a linear-log plot from a list of data with dates specified by *datespec*

Plotting data with date coordinates.

DateListPlot can be used to plot data with date or time horizontal coordinates. Dates can be lists, strings, or absolute times as with DateList, DateString, and AbsoluteTime. A date specification *datespec* can be given to associate dates with data given as $\{y_1, y_2, \ldots\}$. DateListLogPlot allows you to plot the data with a logarithmic vertical scale.

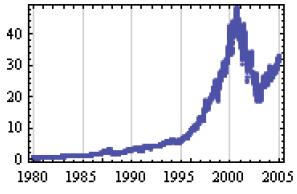
This gathers some financial time series data.

In[16]:=
```
fd = FinancialData["GE", {{1980}, {2005}}];
```

This plots the financial data.

In[17]:=
```
DateListPlot[fd]
```

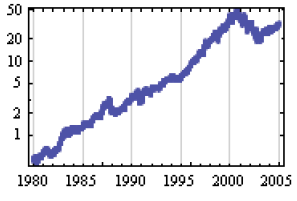
Out[17]=



This plots the same data on a logarithmic scale.

In[18]:=
```
DateListLogPlot[fd]
```

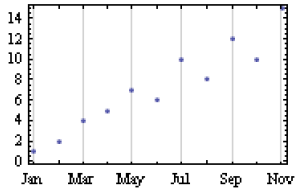
Out[18]=



This plots monthly data which does not contain explicit dates.

```
In[19]:= DateListPlot[{1, 2, 4, 5, 7, 6, 10, 8, 12, 10, 15}, {{2008}, Automatic, "Month"}]
```

Out[19]=



`Timing`[*expr*]	evaluate *expr*, and return a list of the CPU time needed, together with the result obtained
`AbsoluteTiming`[*expr*]	evaluate *expr*, giving the absolute time taken

Timing *Mathematica* operations.

`Timing` allows you to measure the CPU time associated with the evaluation of a single *Mathematica* expression. `Timing` corresponds to the increase in `TimeUsed`. Note that only CPU time associated with the actual evaluation of the expression within the *Mathematica* kernel is included. The time needed to format the expression for output, and any time associated with external programs, is not included.

`AbsoluteTiming` allows you to measure absolute total elapsed time. You should realize, however, that the time reported for a particular calculation by both `AbsoluteTiming` and `Timing` depends on many factors.

First, the time depends in detail on the computer system you are using. It depends not only on instruction times, but also on memory caching, as well as on the details of the optimization done in compiling the parts of the internal code of *Mathematica* used in the calculation.

The time also depends on the precise state of your *Mathematica* session when the calculation was done. Many of the internal optimizations used by *Mathematica* depend on details of preceding calculations. For example, *Mathematica* often uses previous results it has obtained, and avoids unnecessarily reevaluating expressions. In addition, some *Mathematica* functions build internal tables when they are first called in a particular way, so that if they are called in that way again, they run much faster. For all of these kinds of reasons, it is often the case that a particular calculation may not take the same amount of time if you run it at different points in the same *Mathematica* session.

This gives the CPU time needed for the calculation. The semicolon causes the result of the calculation to be given as `Null`.

```
In[20]:= Timing[100 000 !;]
Out[20]= {0.49 Second, Null}
```

Now *Mathematica* has built internal tables for factorial functions, and the calculation takes no measurable CPU time.

```
In[21]:= Timing[100 000 !;]
Out[21]= {0. Second, Null}
```

However, some absolute time does elapse.

```
In[22]:= AbsoluteTiming[100 000 !;]
Out[22]= {0.000102 Second, Null}
```

Note that the results you get from `Timing` are only accurate to the timing granularity `$TimeUnit` of your computer system. Thus, for example, a timing reported as `0` could in fact be as much as `$TimeUnit`.

`TimeConstrained[`*expr*`,`*t*`]`	try to evaluate *expr*, aborting the calculation after *t* seconds
`TimeConstrained[`*expr*`,`*t*`,`*failexpr*`]`	return *failexpr* if the time constraint is not met

Time-constrained calculation.

When you use *Mathematica* interactively, it is quite common to try doing a calculation, but to abort the calculation if it seems to be taking too long. You can emulate this behavior inside a program by using `TimeConstrained`. `TimeConstrained` tries to evaluate a particular expression for a specified amount of time. If it does not succeed, then it aborts the evaluation, and returns either `$Aborted`, or an expression you specify.

You can use `TimeConstrained`, for example, to have *Mathematica* try a particular approach to a problem for a certain amount of time, and then to switch to another approach if the first one has not yet succeeded. You should realize however that `TimeConstrained` may overrun the time you specify if *Mathematica* cannot be interrupted during a particular part of a calculation. In addition, you should realize that because different computer systems run at different speeds, programs that use `TimeConstrained` will often give different results on different systems.

Memory Management

`MemoryInUse[]`	number of bytes of memory currently being used by *Mathematica*
`MaxMemoryUsed[]`	maximum number of bytes of memory used by *Mathematica* in this session

Finding memory usage.

Particularly for symbolic computations, memory is usually the primary resource which limits the size of computations you can do. If a computation runs slowly, you can always potentially let it run longer. But if the computation generates intermediate expressions which simply cannot fit in the memory of your computer system, then you cannot proceed with the computation.

Mathematica is careful about the way it uses memory. Every time an intermediate expression you have generated is no longer needed, *Mathematica* immediately reclaims the memory allocated to it. This means that at any point in a session, *Mathematica* stores only those expressions that are actually needed; it does not keep unnecessary objects which have to be "garbage collected" later.

This gives the number of bytes of memory currently being used by *Mathematica*.

```
In[1]:= MemoryInUse[]
Out[1]= 947 712
```

This generates a 10000-element list.

```
In[2]:= Range[10 000] // Short
Out[2]= {1, 2, 3, 4, 5, 6, 7, 8, <<9985>>, 9994, 9995, 9996, 9997, 9998, 9999, 10 000}
```

Additional memory is needed to store the list.

```
In[3]:= MemoryInUse[]
Out[3]= 989 616
```

This list is kept because it is the value of `Out[2]`. If you clear `Out[2]`, the list is no longer needed.

```
In[4]:= Unprotect[Out]; Out[2] =.
```

The memory in use goes down again.

```
In[5]:= MemoryInUse[]
Out[5]= 954 408
```

This shows the maximum memory needed at any point in the session.

```
In[6]:= MaxMemoryUsed[]
Out[6]= 1 467 536
```

One issue that often comes up is exactly how much memory *Mathematica* can actually use on a particular computer system. Usually there is a certain amount of memory available for *all* processes running on the computer at a particular time. Sometimes this amount of memory is equal to the physical number of bytes of RAM in the computer. Often, it includes a certain amount of "virtual memory", obtained by swapping data on and off a mass storage device.

When *Mathematica* runs, it needs space both for data and for code. The complete code of *Mathematica* is typically several megabytes in size. For any particular calculation, only a small fraction of this code is usually used. However, in trying to work out the total amount of space available for *Mathematica* data, you should not forget what is needed for *Mathematica* code. In addition, you must include the space that is taken up by other processes running in the computer. If there are fewer jobs running, you will usually find that your job can use more memory.

It is also worth realizing that the time needed to do a calculation can depend very greatly on how much physical memory you have. Although virtual memory allows you in principle to use large amounts of memory space, it is usually hundreds or even thousands of times slower to access than physical memory. As a result, if your calculation becomes so large that it needs to make use of virtual memory, it may run *much* more slowly.

`MemoryConstrained[`*expr*`,`*b*`]`	try to evaluate *expr*, aborting if more than *b* additional bytes of memory are requested
`MemoryConstrained[`*expr*`,`*b*`,`*failexpr*`]`	return *failexpr* if the memory constraint is not met

Memory-constrained computation.

`MemoryConstrained` works much like `TimeConstrained`. If more than the specified amount of memory is requested, `MemoryConstrained` attempts to abort your computation. As with `TimeConstrained`, there may be some overshoot in the actual amount of memory used before the computation is aborted.

ByteCount[*expr*]	the maximum number of bytes of memory needed to store *expr*
LeafCount[*expr*]	the number of terminal nodes in the expression tree for *expr*

Finding the size of expressions.

Although you may find ByteCount useful in estimating how large an expression of a particular kind you can handle, you should realize that the specific results given by ByteCount can differ substantially from one version of *Mathematica* to another.

Another important point is that ByteCount always gives you the *maximum* amount of memory needed to store a particular expression. Often *Mathematica* will actually use a much smaller amount of memory to store the expression. The main issue is how many of the subexpressions in the expression can be *shared*.

In an expression like f[1 + x, 1 + x], the two subexpressions 1 + x are identical, but they may or may not actually be stored in the same piece of computer memory. ByteCount gives you the number of bytes needed to store expressions with the assumption that no subexpressions are shared. You should realize that the sharing of subexpressions is often destroyed as soon as you use an operation like the /. operator.

Nevertheless, you can explicitly tell *Mathematica* to share subexpressions using the function Share. In this way, you can significantly reduce the actual amount of memory needed to store a particular expression.

Share[*expr*]	share common subexpressions in the storage of *expr*
Share[]	share common subexpressions throughout memory

Optimizing memory usage.

On most computer systems, the memory used by a running program is divided into two parts: memory explicitly allocated by the program, and "stack space". Every time an internal routine is called in the program, a certain amount of stack space is used to store parameters associated with the call. On many computer systems, the maximum amount of stack space that can be used by a program must be specified in advance. If the specified stack space limit is exceeded, the program usually just exits.

In *Mathematica*, one of the primary uses of stack space is in handling the calling of one *Mathematica* function by another. All such calls are explicitly recorded in the *Mathematica* `Stack` discussed in "The Evaluation Stack". You can control the size of this stack by setting the global parameter `$RecursionLimit`. You should be sure that this parameter is set small enough that you do not run out of stack space on your particular computer system.

Global System Information

In order to write the most general *Mathematica* programs you will sometimes need to find out global information about the setup under which your program is being run.

Thus, for example, to tell whether your program should be calling functions like `NotebookWrite`, you need to find out whether the program is being run in a *Mathematica* session that is using the notebook front end. You can do this by testing the global variable `$Notebooks`.

`$Notebooks`	whether a notebook front end is being used

Determining whether a notebook front end is being used.

Mathematica is usually used interactively, but it can also operate in a batch mode—say taking input from a file and writing output to a file. In such a case, a program cannot for example expect to get interactive input from the user.

`$BatchInput`	whether input is being given in batch mode
`$BatchOutput`	whether output should be given in batch mode, without labeling, etc.

Variables specifying batch mode operation.

The *Mathematica* kernel is a process that runs under the operating system on your computer. Within *Mathematica* there are several global variables that allow you to find the characteristics of this process and its environment.

`$CommandLine`	the original command line used to invoke the *Mathematica* kernel
`$ParentLink`	the *MathLink* `LinkObject` specifying the program that invoked the kernel (or `Null` if the kernel was invoked directly)
`$ProcessID`	the ID assigned to the *Mathematica* kernel process by the operating system
`$ParentProcessID`	the ID of the process that invoked the *Mathematica* kernel
`$UserName`	the login name of the user running the *Mathematica* kernel
`Environment["`*var*`"]`	the value of a variable defined by the operating system

Variables associated with the *Mathematica* kernel process.

If you have a variable such as x in a particular *Mathematica* session, you may or may not want that variable to be the same as an x in another *Mathematica* session. In order to make it possible to maintain distinct objects in different sessions, *Mathematica* supports the variable `$SessionID`, which uses information such as starting time, process ID and machine ID to try to give a different value for every single *Mathematica* session, whether it is run on the same computer or a different one.

`$SessionID`	a number set up to be different for every *Mathematica* session

A unique number different for every *Mathematica* session.

Mathematica provides various global variables that allow you to tell which version of the kernel you are running. This is important if you write programs that make use of features that are, say, new in Version 6. You can then check `$VersionNumber` to find out if these features will be available.

`$Version`	a string giving the complete version of *Mathematica* in use
`$VersionNumber`	the *Mathematica* kernel version number (e.g. `6.0`)
`$ReleaseNumber`	the release number for your version of the *Mathematica* kernel on your particular computer system
`$CreationDate`	the date, in `DateList` format, on which your particular *Mathematica* release was created

Variables specifying the version of *Mathematica* used.

Mathematica itself is set up to be as independent of the details of the particular computer system on which it is run as possible. However, if you want to access external aspects of your computer system, then you will often need to find out its characteristics.

`$System`	a full string describing the computer system in use
`$SystemID`	a short string specifying the computer system in use
`$ProcessorType`	the architecture of the processor in your computer system
`$MachineType`	the general type of your computer system
`$ByteOrdering`	the native byte ordering convention on your computer system
`$OperatingSystem`	the basic operating system in use
`$SystemCharacterEncoding`	the default raw character encoding used by your operating system

Variables specifying the characteristics of your computer system.

Mathematica uses the values of `$SystemID` to label directories that contain versions of files for different computer systems, as discussed in "Reading and Writing *Mathematica* Files: Files and Streams" and "Portability of *MathLink* Programs". Computer systems for which `$SystemID` is the same will normally be binary compatible.

`$OperatingSystem` has values such as `"Windows"` or `"Unix"`. By testing `$OperatingSystem` you can determine whether a particular external program is likely to be available on your computer system.

This gives some characteristics of the computer system on which the input is evaluated.

```
In[1]:= {$System, $ProcessorType, $OperatingSystem}
Out[1]= {Linux x86 (32-bit), x86, Unix}
```

`$MachineAddresses`	the list of current IP addresses
`$MachineName`	the name of the computer on which *Mathematica* is running
`$MachineDomains`	the current network domains for the computer
`$MachineID`	the unique ID assigned by *Mathematica* to the computer

Variables identifying the computer on which *Mathematica* is running.

$LicenseID	the ID for the license under which *Mathematica* is running
$LicenseExpirationDate	the date on which the license expires
$NetworkLicense	whether this is a network license
$LicenseServer	the full name of the machine serving the license
$LicenseProcesses	the number of *Mathematica* processes currently being run under the license
$MaxLicenseProcesses	the maximum number of processes provided by the license
$PasswordFile	password file used when the kernel was started

Variables associated with license management.

Mathematica Sessions

Command-Line Options and Environment Variables

-pwfile	*Mathematica* password file
-pwpath	path to search for a *Mathematica* password file
-run	*Mathematica* input to run (kernel only)
-initfile	*Mathematica* initialization file
-initpath	path to search for initialization files
-noinit	do not run initialization files
-mathlink	communicate only via *MathLink*

Typical command-line options for *Mathematica* executables.

If the *Mathematica* front end is called with a notebook file as a command-line argument, then this notebook will be made the initial selected notebook. Otherwise, a new notebook will be created for this purpose.

Mathematica kernels and front ends can also take additional command-line options specific to particular window environments.

MATHINIT	command-line environment for the *Mathematica* front end
MATHKERNELINIT	command-line environment for the *Mathematica* kernel
MATHEMATICA_BASE	setting for $BaseDirectory
MATHEMATICA_USERBASE	setting for $UserBaseDirectory

Environment variables.

Mathematica will read the values of operating system environment variables, and will use these values in addition to any command-line options explicitly given.

Initialization

On startup, the *Mathematica* kernel does the following:

- Performs license management operations.
- Runs *Mathematica* commands specified in any -run options passed to the kernel executable.
- Runs the *Mathematica* commands in the systemwide initialization file $BaseDirectory / Kernel / init.m.
- Runs the *Mathematica* commands in the user-specific initialization file $UserBaseDirectory / Kernel / init.m.
- Loads init.m and Kernel / init.m files in Autoload directories.
- Begins running the main loop.

The Main Loop

All *Mathematica* sessions repeatedly execute the following main loop:

- Read in input.
- Apply $PreRead function, if defined, to the input string.
- Print syntax warnings if necessary.

- Apply `$SyntaxHandler` function if there is a syntax error.
- Assign `InString[`*n*`]`.
- Apply `$Pre` function, if defined, to the input expression.
- Assign `In[`*n*`]`.
- Evaluate expression.
- Apply `$Post` function, if defined.
- Assign `Out[`*n*`]`, stripping off any formatting wrappers.
- Apply `$PrePrint` function, if defined.
- Assign `MessageList[`*n*`]` and clear `$MessageList`.
- Print expression, if it is not `Null`.
- Increment `$Line`.
- Clear any pending aborts.

Note that if you call *Mathematica* via *MathLink* from within an external program, then you must effectively create your own main loop, which will usually differ from the one described above.

Messages

During a *Mathematica* session messages can be generated either by explicit calls to `Message`, or in the course of executing other built-in functions.

f`::`*name*`::`*lang*	a message in a specific language
f`::`*name*	a message in a default language
`General::`*name*	a general message with a given name

Message names.

If no language is specified for a particular message, text for the message is sought in each of the languages specified by `$Language`. If *f*`::`*name* is not defined, a definition for `General::`*name* is sought. If still no message is found, any value defined for `$NewMessage` is applied to *f* and "*name*".

`Quiet[`*expr*`]` evaluates *expr* while preventing messages from being printed during the evaluation. `Off[`*message*`]` prevents a specified message from ever being printed. `Check` allows you to determine whether particular messages were generated during the evaluation of an expression. `$MessageList` and `MessageList[`*n*`]` record all the messages that were generated during the evaluation of a particular line in a *Mathematica* session.

Messages are specified as strings to be used as the first argument of `StringForm`. `$MessagePrePrint` is applied to each expression to be spliced into the string.

Termination

`Exit[] or Quit[]`	terminate *Mathematica*
`$Epilog`	symbol to evaluate before *Mathematica* exits
`$IgnoreEOF`	whether to exit an interactive *Mathematica* session when an end-of-file character is received
`end.m`	file to read when *Mathematica* terminates

Mathematica termination.

There are several ways to end a *Mathematica* session. If you are using *Mathematica* interactively, typing `Exit[]` or `Quit[]` on an input line will always terminate *Mathematica*.

If you are taking input for *Mathematica* from a file, *Mathematica* will exit when it reaches the end of the file. If you are using *Mathematica* interactively, it will still exit if it receives an end-of-file character (typically Ctrl+d). You can stop *Mathematica* from doing this by setting `$IgnoreEOF = True`.

Network License Management

single-machine license	a process must always run on a specific machine
network license	a process can run on any machine on a network

Single-machine and network licenses.

Copies of *Mathematica* can be set up with either single-machine or network licenses. A network license is indicated by a line in the `mathpass` file starting with `! name`, where *name* is the name of the server machine for the network license.

Network licenses are controlled by the *Mathematica* license management program `mathlm`, which is run on the server machine. This program must be running whenever a *Mathematica* with a network license is being used. Typically you will want to set up your system so that `mathlm` is started whenever the system boots.

- Type `. \ mathlm` directly on the command line
- Add `mathlm` as a Windows service

Ways to start the network license manager under Microsoft Windows.

- Type `. / mathlm` directly on the Unix command line
- Add a line to start `mathlm` in your central system startup script

Ways to start the network license manager on Macintosh and Unix systems.

When `mathlm` is not started directly from a command line, it normally sets itself up as a background process, and continues running until it is explicitly terminated. Note that if one `mathlm` process is running, any other `mathlm` processes you try to start will automatically exit immediately.

`-logfile` *file*	write a log of license server actions to *file*
`-loglevel` *n*	how verbose to make log entries (1 to 4)
`-logformat` *string*	use a log format specified by *string*
`-language` *name*	language to use for messages (default `English`)
`-pwfile` *file*	use the specified `mathpass` file (default `./mathpass`)
`-timeout` *n*	suspend authorization on stopped *Mathematica* jobs after *n* hours
`-restrict` *file*	use the specified restriction file
`-mathid`	print the MathID for the license server, and exit
`-foreground`	run `mathlm` in the foreground, logging to `stdout`
`-install`	install `mathlm` as a Windows service (Microsoft Windows only)
`-uninstall`	uninstall `mathlm` as a Windows service (Microsoft Windows only)

Some command-line options for `mathlm`.

For more detailed information on `mathlm`, see "System Administration for Network Licenses".

`monitorlm`	a program to monitor network license activity
`monitorlm` *name*	monitor activity for license server *name*

Monitoring network license activity.

If `monitorlm` is run in an environment where a web browser can be started, it will automatically generate HTML output in the browser. Otherwise it will generate plain text.

`-file` *file*	write output to a file
`-format` *spec*	use the specified format (`text`, `html` or `cgi`)
`-template` *file*	use the specified file as a template for the output

Some command-line options for `monitorlm`.

The Internals of *Mathematica*

Why You Do Not Usually Need to Know about Internals

Most of the documentation provided for *Mathematica* is concerned with explaining *what Mathematica* does, not *how* it does it. But the purpose of this is to say at least a little about how *Mathematica* does what it does. "Some Notes on Internal Implementation" gives more details.

You should realize at the outset that while knowing about the internals of *Mathematica* may be of intellectual interest, it is usually much less important in practice than you might at first suppose.

Indeed, one of the main points of *Mathematica* is that it provides an environment where you can perform mathematical and other operations without having to think in detail about how these operations are actually carried out inside your computer.

Thus, for example, if you want to factor the polynomial $x^{15} - 1$, you can do this just by giving *Mathematica* the command `Factor[x^15 - 1]`; you do not have to know the fairly complicated details of how such a factorization is actually carried out by the internal code of *Mathematica*.

Indeed, in almost all practical uses of *Mathematica*, issues about how *Mathematica* works inside turn out to be largely irrelevant. For most purposes it suffices to view *Mathematica* simply as an abstract system which performs certain specified mathematical and other operations.

You might think that knowing how *Mathematica* works inside would be necessary in determining what answers it will give. But this is only very rarely the case. For the vast majority of the computations that *Mathematica* does are completely specified by the definitions of mathematical or other operations.

Thus, for example, `3^40` will always be `12 157 665 459 056 928 801`, regardless of how *Mathematica* internally computes this result.

There are some situations, however, where several different answers are all equally consistent with the formal mathematical definitions. Thus, for example, in computing symbolic integrals, there are often several different expressions which all yield the same derivative. Which of these expressions is actually generated by `Integrate` can then depend on how `Integrate` works inside.

Here is the answer generated by `Integrate`.

```
In[1]:= Integrate[1 / x + 1 / x^2, x]
```

$$\text{Out[1]}= -\frac{1}{x} + \text{Log}[x]$$

This is an equivalent expression that might have been generated if `Integrate` worked differently inside.

```
In[2]:= Together[%]
```

$$\text{Out[2]}= \frac{-1 + x\,\text{Log}[x]}{x}$$

In numerical computations, a similar phenomenon occurs. Thus, for example, `FindRoot` gives you a root of a function. But if there are several roots, which root is actually returned depends on the details of how `FindRoot` works inside.

This finds a particular root of $\cos(x) + \sin(x)$.

```
In[3]:= FindRoot[Cos[x] + Sin[x], {x, 10.5}]
Out[3]= {x → 14.9226}
```

With a different starting point, a different root is found. Which root is found with each starting point depends in detail on the internal algorithm used.

```
In[4]:= FindRoot[Cos[x] + Sin[x], {x, 10.8}]
Out[4]= {x → 11.781}
```

The dependence on the details of internal algorithms can be more significant if you push approximate numerical computations to the limits of their validity.

Thus, for example, if you give `NIntegrate` a pathological integrand, whether it yields a meaningful answer or not can depend on the details of the internal algorithm that it uses.

`NIntegrate` knows that this result is unreliable, and can depend on the details of the internal algorithm, so it prints warning messages.

```
In[5]:= NIntegrate[Sin[1 / x], {x, 0, 1}]

NIntegrate::slwcon :
  Numerical integration converging too slowly; suspect one of the following: singularity, value
    of the integration is 0, highly oscillatory integrand, or WorkingPrecision too small. ≫

NIntegrate::ncvb :
  NIntegrate failed to converge to prescribed accuracy after 9 recursive bisections in x near
    {x} = {0.0053386}. NIntegrate obtained 0.5038782627066661` and
    0.0011134563535424439` for the integral and error estimates. ≫

Out[5]= 0.503878
```

Traditional numerical computation systems have tended to follow the idea that all computations should yield results that at least nominally have the same precision. A consequence of this idea is that it is not sufficient just to look at a result to know whether it is accurate; you typically also have to analyze the internal algorithm by which the result was found. This fact has tended to make people believe that it is always important to know internal algorithms for numerical computations.

But with the approach that *Mathematica* takes, this is rarely the case. For *Mathematica* can usually use its arbitrary-precision numerical computation capabilities to give results where every digit that is generated follows the exact mathematical specification of the operation being performed.

Even though this is an approximate numerical computation, every digit is determined by the mathematical definition for π.

```
In[6]:= N[Pi, 30]
Out[6]= 3.14159265358979323846264338328
```

Once again, every digit here is determined by the mathematical definition for $\sin(x)$.

```
In[7]:= N[Sin[10^50], 20]
Out[7]= -0.78967249342931008271
```

If you use machine-precision numbers, *Mathematica* cannot give a reliable result, and the answer depends on the details of the internal algorithm used.

```
In[8]:= Sin[10.^50]
Out[8]= 0.669369
```

It is a general characteristic that whenever the results you get can be affected by the details of internal algorithms, you should not depend on these results. For if nothing else, different versions of *Mathematica* may exhibit differences in these results, either because the algorithms operate slightly differently on different computer systems, or because fundamentally different algorithms are used in versions released at different times.

This is the result for $\sin\left(10^{50}\right)$ on one type of computer.

```
In[9]:= Sin[10.^50]
Out[9]= 0.669369
```

Here is the same calculation on another type of computer.

```
In[10]:= Sin[10.^50]
Out[10]= 0.669369
```

And here is the result obtained in *Mathematica* Version 1.

```
In[11]:= Sin[10.^50]
Out[11]= 0.669369
```

Particularly in more advanced applications of *Mathematica*, it may sometimes seem worthwhile to try to analyze internal algorithms in order to predict which way of doing a given computation will be the most efficient. And there are indeed occasionally major improvements that you will be able to make in specific computations as a result of such analyses.

But most often the analyses will not be worthwhile. For the internals of *Mathematica* are quite complicated, and even given a basic description of the algorithm used for a particular purpose, it is usually extremely difficult to reach a reliable conclusion about how the detailed implementation of this algorithm will actually behave in particular circumstances.

A typical problem is that *Mathematica* has many internal optimizations, and the efficiency of a computation can be greatly affected by whether the details of the computation do or do not allow a given internal optimization to be used.

Basic Internal Architecture

numbers	sequences of binary digits
strings	sequences of character code bytes or byte pairs
symbols	pointers to the central table of symbols
general expressions	sequences of pointers to the head and elements

Internal representations used by *Mathematica*.

When you type input into *Mathematica*, a data structure is created in the memory of your computer to represent the expression you have entered.

In general, different pieces of your expression will be stored at different places in memory. Thus, for example, for a list such as `{2, x, y + z}` the "backbone" of the list will be stored at one place, while each of the actual elements will be stored at a different place.

The backbone of the list then consists just of three "pointers" that specify the addresses in computer memory at which the actual expressions that form the elements of the list are to be found. These expressions then in turn contain pointers to their subexpressions. The chain of pointers ends when one reaches an object such as a number or a string, which is stored directly as a pattern of bits in computer memory.

Crucial to the operation of *Mathematica* is the notion of symbols such as `x`. Whenever `x` appears in an expression, *Mathematica* represents it by a pointer. But the pointer is always to the same place in computer memory—an entry in a central table of all symbols defined in your *Mathematica* session.

This table is a repository of all information about each symbol. It contains a pointer to a string giving the symbol's name, as well as pointers to expressions which give rules for evaluating the symbol.

- Recycle memory as soon as the data in it is no longer referenced.

The basic principle of *Mathematica* memory management.

Every piece of memory used by *Mathematica* maintains a count of how many pointers currently point to it. When this count drops to zero, *Mathematica* knows that the piece of memory is no longer being referenced, and immediately makes the piece of memory available for something new.

This strategy essentially ensures that no memory is ever wasted, and that any piece of memory that *Mathematica* uses is actually storing data that you need to access in your *Mathematica* session.

- Create an expression corresponding to the input you have given.
- Process the expression using all rules known for the objects in it.
- Generate output corresponding to the resulting expression.

The basic actions of *Mathematica*.

At the heart of *Mathematica* is a conceptually simple procedure known as the *evaluator* which takes every function that appears in an expression and evaluates that function.

When the function is one of the thousand or so that are built into *Mathematica*, what the evaluator does is to execute directly internal code in the *Mathematica* system. This code is set up to perform the operations corresponding to the function, and then to build a new expression representing the result.

- The built-in functions of *Mathematica* support universal computation.

The basic feature that makes *Mathematica* a self-contained system.

A crucial feature of the built-in functions in *Mathematica* is that they support *universal computation*. What this means is that out of these functions you can construct programs that perform absolutely any kinds of operations that are possible for a computer.

As it turns out, small subsets of *Mathematica*'s built-in functions would be quite sufficient to support universal computation. But having the whole collection of functions makes it in practice easier to construct the programs one needs.

The underlying point, however, is that because *Mathematica* supports universal computation you never have to modify its built-in functions: all you have to do to perform a particular task is to combine these functions in an appropriate way.

Universal computation is the basis for all standard computer languages. But many of these languages rely on the idea of *compilation*. If you use C or Fortran, for example, you first write your program, then you compile it to generate machine code that can actually be executed on your computer.

Mathematica does not require you to go through the compilation step: once you have input an expression, the functions in the expression can immediately be executed.

Often *Mathematica* will preprocess expressions that you enter, arranging things so that subsequent execution will be as efficient as possible. But such preprocessing never affects the results that are generated, and can rarely be seen explicitly.

The Algorithms of *Mathematica*

The built-in functions of *Mathematica* implement a very large number of algorithms from computer science and mathematics. Some of these algorithms are fairly old, but the vast majority had to be created or at least modified specifically for *Mathematica*. Most of the more mathematical algorithms in *Mathematica* ultimately carry out operations which at least at some time in the past were performed by hand. In almost all cases, however, the algorithms use methods very different from those common in hand calculation.

Symbolic integration provides an example. In hand calculation, symbolic integration is typically done by a large number of tricks involving changes of variables and the like.

But in *Mathematica* symbolic integration is performed by a fairly small number of very systematic procedures. For indefinite integration, the idea of these procedures is to find the most general form of the integral, then to differentiate this and try to match up undetermined coefficients.

Often this procedure produces at an intermediate stage immensely complicated algebraic expressions, and sometimes very sophisticated kinds of mathematical functions. But the great advantage of the procedure is that it is completely systematic, and its operation requires no special cleverness of the kind that only a human could be expected to provide.

In having *Mathematica* do integrals, therefore, one can be confident that it will systematically get results, but one cannot expect that the way these results are derived will have much at all to do with the way they would be derived by hand.

The same is true with most of the mathematical algorithms in *Mathematica*. One striking feature is that even for operations that are simple to describe, the systematic algorithms to perform these operations in *Mathematica* involve fairly advanced mathematical or computational ideas.

Thus, for example, factoring a polynomial in x is first done modulo a prime such as 17 by finding the null space of a matrix obtained by reducing high powers of x modulo the prime and the original polynomial. Then factorization over the integers is achieved by "lifting" modulo successive powers of the prime using a collection of intricate theorems in algebra and analysis.

The use of powerful systematic algorithms is important in making the built-in functions in *Mathematica* able to handle difficult and general cases. But for easy cases that may be fairly common in practice it is often possible to use simpler and more efficient algorithms.

As a result, built-in functions in *Mathematica* often have large numbers of extra pieces that handle various kinds of special cases. These extra pieces can contribute greatly to the complexity of the internal code, often taking what would otherwise be a five-page algorithm and making it hundreds of pages long.

Most of the algorithms in *Mathematica*, including all their special cases, were explicitly constructed by hand. But some algorithms were instead effectively created automatically by computer.

Many of the algorithms used for machine-precision numerical evaluation of mathematical functions are examples. The main parts of such algorithms are formulas which are as short as possible but which yield the best numerical approximations.

Most such formulas used in *Mathematica* were actually derived by *Mathematica* itself. Often many months of computation were required, but the result was a short formula that can be used to evaluate functions in an optimal way.

The Software Engineering of *Mathematica*

Mathematica is one of the more complex software systems ever constructed. It is built from several million lines of source code, written in C/C++, Java and *Mathematica*.

The C code in *Mathematica* is actually written in a custom extension of C which supports certain memory management and object-oriented features. The *Mathematica* code is optimized using `Share` and `DumpSave`.

In the *Mathematica* kernel the breakdown of different parts of the code is roughly as follows: language and system: 30%; numerical computation: 20%; algebraic computation: 20%; graphics and kernel output: 30%.

Most of this code is fairly dense and algorithmic: those parts that are in effect simple procedures or tables use minimal code since they tend to be written at a higher level—often directly in *Mathematica*.

The source code for the kernel, save a fraction of a percent, is identical for all computer systems on which *Mathematica* runs.

For the front end, however, a significant amount of specialized code is needed to support each different type of user interface environment. The front end contains about 700,000 lines of system-independent C++ source code, of which roughly 200,000 lines are concerned with expression formatting. Then there are between 50,000 and 100,000 lines of specific code customized for each user interface environment.

Mathematica uses a client-server model of computing. The front end and kernel are connected via *MathLink*—the same system as is used to communicate with other programs. *MathLink* supports multiple transport layers, including one based upon TCP/IP and one using shared memory.

The front end and kernel are connected via three independent *MathLink* connections. One is used for user-initiated evaluations. A second is used by the front end to resolve the values of `Dynamic` expressions. The third is used by the kernel to notify the front end of `Dynamic` objects which should be invalidated.

Within the C code portion of the *Mathematica* kernel, modularity and consistency are achieved by having different parts communicate primarily by exchanging complete *Mathematica* expressions.

But it should be noted that even though different parts of the system are quite independent at the level of source code, they have many algorithmic interdependencies. Thus, for example, it is common for numerical functions to make extensive use of algebraic algorithms, or for graphics code to use fairly advanced mathematical algorithms embodied in quite different *Mathematica* functions.

Since the beginning of its development in 1986, the effort spent directly on creating the source code for *Mathematica* is about a thousand developer-years. In addition, a comparable or somewhat larger effort has been spent on testing and verification.

The source code of *Mathematica* has changed greatly since Version 1 was released. The total number of lines of code in the kernel grew from 150,000 in Version 1 to 350,000 in Version 2, 600,000 in Version 3, 800,000 in Version 4, 1.5 million in Version 5 and 2.5 million in Version 6. In addition, at every stage existing code has been revised—so that Version 6 has only a few percent of its code in common with Version 1.

Despite these changes in internal code, however, the user-level design of *Mathematica* has remained compatible from Version 1 on. Much functionality has been added, but programs created for *Mathematica* Version 1 will almost always run absolutely unchanged under Version 6.

Testing and Verification

Every version of *Mathematica* is subjected to a large amount of testing before it is released. The vast majority of this testing is done by an automated system that is written in *Mathematica*.

The automated system feeds millions of pieces of input to *Mathematica*, and checks that the output obtained from them is correct. Often there is some subtlety in doing such checking: one must account for different behavior of randomized algorithms and for such issues as differences in machine-precision arithmetic on different computers.

The test inputs used by the automated system are obtained in several ways:

- For every *Mathematica* function, inputs are devised that exercise both common and extreme cases.
- Inputs are devised to exercise each feature of the internal code.
- All the examples in *Mathematica*'s documentation system are used, as well as those from many books about *Mathematica.*
- Tests are constructed from mathematical benchmarks and test sets from numerous websites.
- Standard numerical tables are optically scanned for test inputs.
- Formulas from standard mathematical tables are entered.
- Exercises from textbooks are entered.
- For pairs of functions such as `Integrate` and `D` or `Factor` and `Expand`, random expressions are generated and tested.

When tests are run, the automated testing system checks not only the results, but also side effects such as messages, as well as memory usage and speed.

There is also a special instrumented version of *Mathematica* which is set up to perform internal consistency tests. This version of *Mathematica* runs at a small fraction of the speed of the real *Mathematica*, but at every step it checks internal memory consistency, interruptibility, and so on.

The instrumented version of *Mathematica* also records which pieces of *Mathematica* source code have been accessed, allowing one to confirm that all of the various internal functions in *Mathematica* have been exercised by the tests given.

All standard *Mathematica* tests are routinely run on current versions of *Mathematica*, on each different computer system. Depending on the speed of the computer system, these tests take from a few hours to a few days of computer time.

Even with all this testing, however, it is inevitable in a system as complex as *Mathematica* that errors will remain.

The standards of correctness for *Mathematica* are certainly much higher than for typical mathematical proofs. But just as long proofs will inevitably contain errors that go undetected for many years, so also a complex software system such as *Mathematica* will contain errors that go undetected even after millions of people have used it.

Nevertheless, particularly after all the testing that has been done on it, the probability that you will actually discover an error in *Mathematica* in the course of your work is extremely low.

Doubtless there will be times when *Mathematica* does things you do not expect. But you should realize that the probabilities are such that it is vastly more likely that there is something wrong with your input to *Mathematica* or your understanding of what is happening than with the internal code of the *Mathematica* system itself.

If you do believe that you have found a genuine error in *Mathematica*, then you should contact Wolfram Research Technical Support, so that the error can be corrected in future versions.

Security and Connectivity

Mathematica Internet Connectivity

Introduction

Mathematica provides important functionality through accessing the internet. Most *Mathematica* functions that provide computable data operate by loading data over the internet. Some functions require real-time access to the internet; others update a local data repository by accessing the internet when required. *Mathematica* also requires internet access when you explicitly use `Import` to read from a URL, or when you use web services. The *Mathematica* documentation system also supports automatic updating via the internet.

When you call a data function like `FinancialData`, *Mathematica* gets the data it needs from the internet. When you click a link to a documentation notebook or call a data function like `CountryData`, *Mathematica* knows whether a newer version of the information is available on a Wolfram Research Paclet Server, and if so it will download and install the update automatically. In the case of smaller paclets like documentation notebooks, this is often so fast that you will not even notice it happening.

Mathematica acts like a web browser when it accesses the internet, so if you can browse the web from your computer, you should be able to use *Mathematica*'s internet connectivity features, although in some cases additional configuration may be required.

Internet Connectivity Dialog

The **Internet Connectivity** dialog, accessed from the **Help** menu, allows you to configure a number of settings related to the paclet system, and *Mathematica*'s use of the internet in general.

The **Allow *Mathematica* to access the Internet** checkbox can be turned off to prevent *Mathematica* from even attempting to use the internet. You will not be able to get load-on-demand updates to documentation, and some data collection functions will not operate.

The **Test Internet Connectivity** button is useful to see if *Mathematica* is properly configured for internet use. After clicking the button, you should see a dialog within a few seconds (perhaps slightly longer if it fails) reporting success or failure. If the test succeeds, then *Mathematica*'s internet functionality should work properly. If it fails, consult "Troubleshooting Connectivity Problems".

The **Proxy Settings** section allows you to specify a proxy server if necessary. In many cases, *Mathematica* is able to inherit the proxy settings configured globally for your system or browser. This is the default setting, and most users will leave it as is. If you know that you do not need to go through a proxy server to access the internet, you can click the **Direct connection to the Internet** checkbox. You can also manually configure proxy settings if necessary. Contact your system administrator for the values to use. Most users will only need to set the HTTP proxy.

The **Automatically check for documentation updates** checkbox and the **Automatically check for data updates** checkbox can be turned off to disable load-on-demand updates to documentation and data files. This will not interfere with the operation of *Mathematica,* except that you will not receive updates to the documentation or data paclets as they become available.

The **Update Local Indices from the Wolfram Research Server** button will cause *Mathematica* to read information from the Wolfram Research Paclet Server that describes the versions of the paclets that are available. *Mathematica* uses this information to decide whether an update is available to a given resource when you access that resource. *Mathematica* reads this information on a weekly basis automatically, but you can force an update using this button. You might want to do this to be sure you will get the absolute latest data from data collection functions like `CountryData`, `ChemicalData`, `AstronomicalData`, etc.

Troubleshooting Connectivity Problems

If you get error messages or dialogs that report internet connectivity problems while running *Mathematica*, the first thing to do is try the **Test Internet Connectivity** button in the **Internet Connectivity** dialog, accessible from the **Help** menu. If the test succeeds, then *Mathematica* is correctly configured for general internet use, and the problem probably lies elsewhere (such as trying to access an incorrect URL). If the test fails, try the following steps:

1. Test network connectivity by seeing if other programs on your computer can access the internet. For example, launch a web browser and see if it works. If it fails, then the network might be unavailable, or you might have connectivity problems beyond what can be configured in *Mathematica*.
2. Check proxy settings, as in "Proxy Settings".
3. Check firewall settings, as in "Firewall Settings".

Proxy Settings

Incorrect proxy settings are a common cause of problems with internet connectivity. Many users on a company network cannot directly access the internet, but instead must pass through a proxy server, which acts like a gateway to the internet. By default, *Mathematica* will attempt to use systemwide proxy settings, if your operating system has such settings. For example, on Windows, *Mathematica* will use the proxy settings configured for Internet Explorer. On Mac OS X, proxy settings are configured in the **Network Preferences** panel.

Mathematica's proxy settings are configured in the **Internet Connectivity** dialog. The default setting, described in "Internet Connectivity Dialog", is **Use proxy settings from my system or browser**. If this does not work for you, try the **Direct connection to the Internet** choice. If that does not work, then contact your system administrator for proxy settings to enter into the text fields. If you can successfully surf the web with a web browser, you can find its proxy settings dialog and read the values it is using. Many users will only need to set the HTTP proxy.

If your system or browser is configured to get proxy settings from a configuration script, then *Mathematica* will not be able to use these settings, and you will have to manually configure its proxy settings.

If *Mathematica* is configured to **Use proxy settings from your system or browser**, and your browser functions but *Mathematica* cannot connect, see if your system proxy settings have a **Use same proxy server for all protocols** checkbox and try unchecking it. *Mathematica* will attempt to use a SOCKS proxy if one is set, and if your HTTP proxy does not also handle SOCKS traffic, **Use same proxy server for all protocols** is not a correct setting for your system. An incorrectly configured SOCKS proxy can cause very long timeouts, so if the **Test Network Connectivity** button fails after a minutes-long delay, an incorrect SOCKS proxy configuration is likely the problem. *Mathematica* does not require a SOCKS proxy, so the SOCKS **Host** field can be left blank, but if you supply a value, either manually or via the system setting **Use the same proxy server for all protocols**, it must be correct.

Firewall Settings

Because *Mathematica* acts like a web browser when it accesses the internet, most company firewalls will not interfere with it. Some users, however, have so-called "personal" firewalls on their machines (ZoneAlarm, Norton, etc., or the one built into Microsoft Windows). If configured with strict settings, these firewalls might interfere with *Mathematica*'s attempts to use the internet.

These types of firewalls will generally display a dialog box warning you that a program is trying to use the internet and allow you to accept or reject it. If you see such a dialog, it might report that the program is the *Mathematica* kernel or the Java Runtime Environment that is bundled in the *Mathematica* layout. Configure the firewall to always allow such requests.

Further Information

If the information in this document is not sufficient to help you solve connectivity problems, consult the Wolfram Research Technical Support troubleshooting guide at http://support.wolfram.com/technotes/networkconnectivityissues.html

Notebook Security

Mathematica provides users with access to their computer's file system (Files), interprocess communication (*MathLink Mathematica* Functions), evaluation of data as code (Converting between Expressions and Strings), and the ability to run arbitrary external programs (Calling External Programs). While these features enable *Mathematica* users to create powerful programs that can perform truly useful tasks, they bring with them the potential for misuse.

The *Mathematica* notebook front end provides three mechanisms for evaluating code: Shift+Return evaluations, initialization cells, and dynamic content.

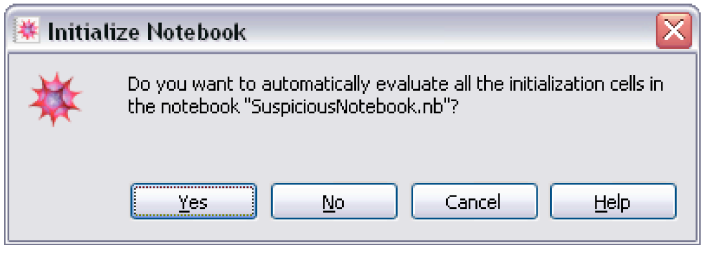
Note that this tutorial contains live controls, so if you change anything it will immediately change the settings on your system.

Shift +Return Evaluations

Because Shift +Return evaluations require user interaction to start them, *Mathematica* provides no safeguards against potentially malicious code that is evaluated using this mechanism. Users should ensure that they do not perform Shift +Return evaluations on code from untrusted sources. When writing their own code, users should take great care to ensure that the code does not have unintended consequences. For example, *Mathematica* will not provide a warning when the user evaluates a program to delete files from his or her computer.

Initialization Cells

Initialization cells provide users with a convenient way to evaluate startup code needed by a given notebook when the user first evaluates any input in that notebook. Since this code will be automatically evaluated, likely without the user ever seeing the initialization code, *Mathematica* will display an alert prompt asking the user to confirm his or her intent to run the initialization code. Users should not evaluate initialization code in a notebook that was obtained from an untrusted source unless the code has been determined to be safe.



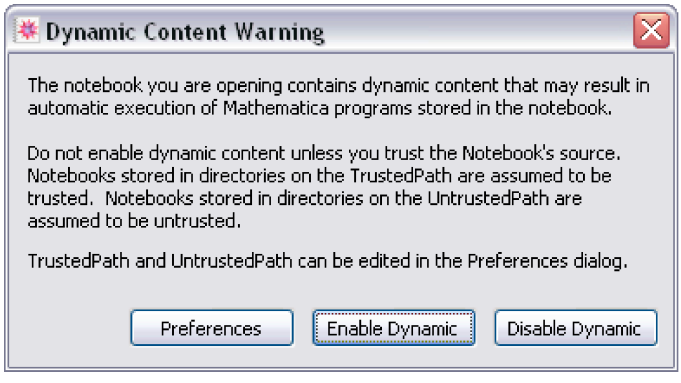
- Clicking the **Yes** button will first evaluate all of the initialization cells in the notebook, then evaluate the selected cells.
- Clicking the **No** button will not evaluate any of the initialization cells, but will still evaluate the selected cells. Note that this may cause errors in the evaluations since they may rely on startup code that has not yet been evaluated.
- Clicking the **Cancel** button will cause neither the initialization cells nor the selected cells to be evaluated.

Dynamic Content

Mathematica 7 has amazing dynamic interactivity features. Notebooks containing interactive `Dynamic` content can automatically evaluate code without any additional action by the user, aside from opening the notebook file. Many times this is exactly what the user will want, while other times the user should be alerted before this sort of automatic evaluation takes place.

When the user opens a notebook containing dynamic content, *Mathematica* will first determine whether the notebook's directory is trusted, untrusted, or neither.

- If the notebook's directory is trusted, the notebook will be allowed to automatically perform dynamic evaluations without alerting the user.
- If the notebook's directory is untrusted, the user will be alerted upon any attempt by the notebook to perform dynamic evaluations.



- If the notebook's directory is neither trusted nor untrusted, the behavior will depend on the value of the `TrustByDefault` option explained as follows.

Mathematica provides some options which can be used to configure which notebooks will alert the user about automatic evaluations and which notebooks will not.

TrustedPath

The value of the `TrustedPath` option is a list of directories that are always trusted by *Mathematica*. Any notebook file located in any directory in `TrustedPath` is trusted by *Mathematica*. *Mathematica* will never display an alert when a trusted notebook is opened, and the notebook can automatically perform dynamic evaluations.

By default, the TrustedPath option value contains $InstallationDirectory, $BaseDirectory, and $UserBaseDirectory so that *Mathematica* installation files and additional installed applications will be able to display dynamic content without alerting the user.

Here are the directories on your computer that are currently trusted by *Mathematica*:

```
Dynamic[Column[ToFileName /@
    CurrentValue[$FrontEnd, {"NotebookSecurityOptions", "TrustedPath"}]]]
/Applications/Mathematica.app/
/Library/Mathematica/
/home/usr2/larrya/Library/Mathematica/
```

Edit TrustedPath ...

UntrustedPath

The value of the UntrustedPath option is a list of directories that are always untrusted by *Mathematica*. Any notebook file located in any directory in UntrustedPath is untrusted by *Mathematica*. *Mathematica* will always display an alert when an untrusted notebook is opened and attempts to perform dynamic evaluations.

By default, the UntrustedPath option value contains the user's desktop folder (where web browser downloads are likely to be stored), the user's configuration folder (where email attachments are likely to be stored), and the computer's temporary directory. If the user has configured his or her web browser or email program to save downloaded files in nonstandard locations, then the user is encouraged to add these locations to the UntrustedPath option value.

Here are the directories on your computer that are currently untrusted by *Mathematica*:

```
Dynamic[Column[ToFileName /@
    CurrentValue[$FrontEnd, {"NotebookSecurityOptions", "UntrustedPath"}]]]
/home/usr2/larrya/Desktop/
/home/usr2/larrya/Downloads/
/home/usr2/larrya/Library/
/tmp/
/var/
/private/
```

Edit UntrustedPath...

Nesting

Directories in `TrustedPath` and `UntrustedPath` can be nested. A notebook is trusted if the most deeply nested directory containing the notebook is trusted. Consider the following example:

- `FrontEnd`FileName[{$HomeDirectory, "Desktop"}]` is untrusted.
- `FrontEnd`FileName[{$HomeDirectory, "Desktop", "SafeNotebooks"}]` is trusted.
- `FrontEnd`FileName[{$HomeDirectory, "Desktop"}, "SomeDownload.nb"]` would be untrusted because `"Desktop"` is untrusted.
- `FrontEnd`FileName[{$HomeDirectory, "Desktop", "SafeNotebooks"}, "MyNotebook.nb"]` would be trusted because `"SafeNotebooks"` is trusted.

TrustByDefault

The `TrustByDefault` option determines whether *Mathematica* should display an alert when the user opens notebooks with dynamic content whose containing directories are neither trusted nor untrusted. Below are the possible values for the `TrustByDefault` option.

`True`	a notebook which is not located in a directory in `UntrustedPath` is considered to be trusted and will not display an alert when opened
`False`	a notebook which is not located in a directory in `TrustedPath` is considered to be untrusted and will display an alert when opened
`Automatic`	a notebook which is not located in any directory in either `TrustedPath` or `UntrustedPath` will display an alert when opened only if the notebook contains unsafe dynamic content (see below)

Values for `TrustByDefault` option.

The current value of the `TrustByDefault` option is: Automatic

Unsafe Dynamic Content

Dynamic content is considered unsafe if it:

- uses File operations
- uses interprocess communication via *MathLink Mathematica* Functions
- uses *J/Link* or *.NET/Link*

- uses Low-Level Notebook Programming
- uses data as code by Converting between Expressions and Strings
- uses Namespace Management
- uses Options Management
- uses External Programs

Changing Option Values

`TrustedPath`, `UntrustedPath`, and `TrustByDefault` are options in the `NotebookSecurityOptions` category. They can be changed using the Preferences... dialog or the Option Inspector... .

Any attempt to change the value of the `TrustedPath`, `UntrustedPath`, or `TrustByDefault` options will cause *Mathematica* to prompt the user to confirm the change. *Mathematica* does this as a security precaution so that malicious code cannot change the value of these options without the user's knowledge.

MathLink and External Program Communication

Introduction to *MathLink*

In many cases, you will find it convenient to communicate with external programs at a high level, and to exchange structured data with them.

On almost all computer systems, *Mathematica* supports the *MathLink* communication standard, which allows higher-level communication between *Mathematica* and external programs. In order to use *MathLink*, an external program has to include some special source code and a *MathLink* library, which are usually distributed with *Mathematica*.

MathLink allows external programs both to call *Mathematica*, and to be called by *Mathematica*. "*MathLink* and External Program Communication" discusses some of the details of *MathLink*. By using *MathLink*, you can, for example, treat *Mathematica* essentially like a subroutine embedded inside an external program. Or you can create a front end that implements your own user interface, and communicates with the *Mathematica* kernel via *MathLink*.

You can also use *MathLink* to let *Mathematica* call individual functions inside an external program. As described in "*MathLink* and External Program Communication", you can set up a *MathLink* template file to specify how particular functions in *Mathematica* should call functions inside your external program. From the *MathLink* template file, you can generate source code to include in your program. Then when you start your program, the appropriate *Mathematica* definitions are automatically made, and when you call a particular *Mathematica* function, code in your external program is executed.

`Install["`*command*`"]`	start an external program and install *Mathematica* definitions to call functions it contains
`Uninstall[`*link*`]`	terminate an external program and uninstall definitions for functions in it

Calling functions in external programs.

This starts the external program `simul`, and installs *Mathematica* definitions to call various functions in it.

```
In[1]:= Install["simul"]
Out[1]= LinkObject[simul, 5, 4]
```

Here is a usage message for a function that was installed in *Mathematica* to call a function in the external program.

```
In[2]:= ?srun

   srun[{a, r, gamma}, x] performs a simulation with the
      specified parameters.
```

When you call this function, it executes code in the external program.

```
In[3]:= srun[{3, 0, 7}, 5]
Out[3]= 6.78124
```

This terminates the `simul` program.

```
In[4]:= Uninstall["simul"]
Out[4]= simul
```

You can use *MathLink* to communicate with many types of programs, including with *Mathematica* itself. There are versions of the *MathLink* library for a variety of common programming languages. The *J/Link* system provides a standard way to integrate *Mathematica* with Java, based on *MathLink*. With *J/Link* you can take any Java class, and immediately make its methods accessible as functions in *Mathematica*.

How *MathLink* Is Used

MathLink provides a mechanism through which programs can interact with *Mathematica*.

- Calling functions in an external program from within *Mathematica*.
- Calling *Mathematica* from within an external program.
- Setting up alternative front ends to *Mathematica*.
- Exchanging data between *Mathematica* and external programs.
- Exchanging data between concurrent *Mathematica* processes.

Some typical uses of *MathLink*.

MathLink provides a general interface for external programs to communicate with *Mathematica*. Many standard software systems now have *MathLink* compatibility either built in or available in add-on modules.

In addition, the *MathLink* Developer Kit bundled with most versions of *Mathematica* provides the tools you need to create your own *MathLink*-compatible programs.

Once you have a *MathLink*-compatible program, you can transparently establish a link between it and *Mathematica*.

The link can either be on a single computer, or it can be over a network, potentially with a different type of computer at each end.

- Implementing inner loops in a low-level language.
- Handling large volumes of data external to *Mathematica*.
- Sending *Mathematica* graphics or other data for special processing.
- Connecting to a system with an existing user interface.

A few uses of *MathLink*-compatible programs.

MathLink-compatible programs range from very simple to very complex. A minimal *MathLink*-compatible program is just a few lines long. But it is also possible to build very large and sophisticated *MathLink*-compatible programs. Indeed, the *Mathematica* notebook front end is one example of a sophisticated *MathLink*-compatible program.

- *MathLink* is a mechanism for exchanging *Mathematica* expressions between programs.

The basic idea of *MathLink*.

Much of the power of *MathLink* comes from its use of *Mathematica* expressions. The basic idea is that *MathLink* provides a way to exchange *Mathematica* expressions between programs, and such expressions can represent absolutely any kind of data.

- An array of numbers.
- A collection of geometrical objects.
- A sequence of commands.
- A stream of text.
- Records in a database.
- The cells of a *Mathematica* notebook.

A few examples of data represented by *Mathematica* expressions in *MathLink*.

The *MathLink* library consists of a collection of routines that allow external programs to send and receive *Mathematica* expressions using the fundamental C data types.

The *MathLink* Developer Kit provides utilities for incorporating these routines into external programs. Utilities are included for a variety of languages, although here we discuss mainly the case of C.

An important feature of the *MathLink* library is that it is completely platform independent: it can transparently use any interprogram communication mechanism that exists on your computer system.

Installing Existing *MathLink*-Compatible Programs

One of the most common uses of *MathLink* is to allow you to call functions in an external program from within *Mathematica*. Once the external program has been set up, all you need do to be able to use it is to "install" it in your current *Mathematica* session.

`Install["`*prog*`"]`	install a *MathLink*-compatible external program
`Uninstall[`*link*`]`	uninstall the program

Setting up external programs with functions to be called from within *Mathematica*.

This installs a *MathLink*-compatible external program called `bitprog`.

```
In[1]:= Install["bitprog"]
Out[1]= LinkObject[./bitprog, 6, 5]
```

`BitShift` is one of the functions inside `bitprog`.

```
In[2]:= BitShift[111, 3]
Out[2]= 13
```

You can use it just as you would a function within *Mathematica*.

```
In[3]:= Table[BitShift[111, i], {i, 3, 8}]
Out[3]= {13, 6, 3, 1, 0, 0}
```

When you have a package written in the *Mathematica* language a single version will run unchanged on any computer system. But external programs typically need to be compiled separately for every different type of computer.

Mathematica has a convention of keeping versions of external programs in directories that are named after the types of computers on which they will run. And assuming that this convention has been followed, `Install["prog"]` should always install the version of *prog* appropriate for the particular kind of computer that you are currently using.

`Install["name`"]`	install a program found anywhere on `$Path`

Using context names to specify programs to install.

When you ask to read in a *Mathematica* language file using `<< name`` , *Mathematica* will automatically search all directories in the list `$Path` in order to find a file with the appropriate name. Similarly, if you use `Install["name`"]` *Mathematica* will automatically search all directories in `$Path` in order to find an external program with the name *name*`.exe`. `Install["name`"]` allows you to install programs that are stored in a central directory without explicitly having to specify their location.

Setting Up External Functions to Be Called from *Mathematica*

If you have a function defined in an external program, then what you need to do in order to make it possible to call the function from within *Mathematica* is to add appropriate *MathLink* code that passes arguments to the function, and takes back the results it produces.

In simple cases, you can generate the necessary code just by giving an appropriate *MathLink template* for each external function.

```
:Begin:
:Function:      f
:Pattern:       f[x_Integer, y_Integer]
:Arguments:     {x, y}
:ArgumentTypes: {Integer, Integer}
:ReturnType:    Integer
:End:
```

A file `f.tm` containing a *MathLink* template for an external function `f`.

:Begin:	begin the template for a particular function
:Function:	the name of the function in the external program
:Pattern:	the pattern to be defined to call the function
:Arguments:	the arguments to the function
:ArgumentTypes:	the types of the arguments to the function
:ReturnType:	the type of the value returned by the function
:End:	end the template for a particular function
:Evaluate:	*Mathematica* input to evaluate when the function is installed

The elements of a *MathLink* template.

Once you have constructed a *MathLink* template for a particular external function, you have to combine this template with the actual source code for the function. Assuming that the source code is written in the C programming language, you can do this just by adding a line to include the standard *MathLink* header file, and then inserting a small `main` program.

Include the standard *MathLink* header file.

```
#include "mathlink.h"
```

Here is the actual source code for the function `f`.

```
int f(int x, int y) {
   return x+y;
}
```

This sets up the external program to be ready to take requests from *Mathematica*.

```
int main(int argc, char *argv[]) {
   return MLMain(argc, argv);
}
```

A file `f.c` containing C source code.

Note that the form of `main` required on different systems may be slightly different. The release notes included in the *MathLink* Developer Kit on your particular computer system should give the appropriate form.

mcc	preprocess and compile *MathLink* source files
mprep	preprocess *MathLink* source files

Typical external programs for processing *MathLink* source files.

MathLink templates are conventionally put in files with names of the form *file*`.tm`. Such files can also contain C source code, interspersed between templates for different functions.

Once you have set up the appropriate files, you then need to process the *MathLink* template information, and compile all of your source code. Typically you do this by running various external programs, but the details will depend on your computer system.

Under Unix, for example, the *MathLink* Developer Kit includes a program named `mcc` which will preprocess *MathLink* templates in any file whose name ends with `.tm`, and then call `cc` on the resulting C source code. `mcc` will pass command-line options and other files directly to `cc`.

This preprocesses `f.tm`, then compiles the resulting C source file together with the file `f.c`.

```
mcc -o f.exe f.tm f.c
```

This installs the binary in the current *Mathematica* session.

```
In[1]:= Install["f.exe"]
Out[1]= LinkObject[f.exe, 4, 4]
```

Now `f[x, y]` calls the external function `f (int x, int y)` and adds two integers together.

```
In[2]:= f[6, 9]
Out[2]= 15
```

The external program handles only machine integers, so this gives a peculiar result.

```
In[3]:= f[2^31 - 1, 5]
Out[3]= -2 147 483 644
```

On Windows, the *MathLink* Developer Kit includes a program named `mprep`, which you have to call directly, giving as input all of the `.tm` files that you want to preprocess. `mprep` will generate C source code as output, which you can then feed to a C compiler.

`Install["`*prog*`"]`	install an external program
`Uninstall[`*link*`]`	uninstall an external program
`Links["`*prog*`"]`	show active links associated with "*prog*"
`Links[]`	show all active links
`LinkPatterns[`*link*`]`	show patterns that can be evaluated on a particular link

Handling links to external programs.

This finds the link to the `f.exe` program.

```
In[4]:= Links["f.exe"]
Out[4]= {LinkObject[./f.exe, 8, 6]}
```

This shows the *Mathematica* patterns that can be evaluated using the link.

```
In[5]:= LinkPatterns[%[[1]]]
Out[5]= {f[x_Integer, y_Integer]}
```

`Install` sets up the actual function `f` to execute an appropriate `ExternalCall` function.

```
In[6]:= ? f

   Global`f

   f[x_Integer, y_Integer] :=
    ExternalCall[LinkObject[./f.exe, 8, 6], CallPacket[0, {x, y}]]
```

When a *MathLink* template file is processed, two basic things are done. First, the `:Pattern:` and `:Arguments:` specifications are used to generate a *Mathematica* definition that calls an external function via *MathLink*. And second, the `:Function:`, `:ArgumentTypes:` and `:ReturnType:` specifications are used to generate C source code that calls your function within the external program.

```
:Begin:
```

This gives the name of the actual C function to call in the external program.

```
:Function:      prog_add
```

This gives the *Mathematica* pattern for which a definition should be set up.

```
:Pattern:       SkewAdd[x_Integer, y_Integer:1]
```

The values of the two list elements are the actual arguments to be passed to the external function.

```
:Arguments:     {x, If[x > 1, y, y + x - 2]}
```

This specifies that the arguments should be passed as integers to the C function.

```
:ArgumentTypes: {Integer, Integer}
```

This specifies that the return value from the C function will be an integer.

```
:ReturnType:    Integer
```

```
:End:
```

Both the `:Pattern:` and `:Arguments:` specifications in a *MathLink* template can be any *Mathematica* expressions. Whatever you give as the `:Arguments:` specification will be evaluated every time you call the external function. The result of the evaluation will be used as the list of arguments to pass to the function.

Sometimes you may want to set up *Mathematica* expressions that should be evaluated not when an external function is called, but instead only when the external function is first installed.

You can do this by inserting `:Evaluate:` specifications in your *MathLink* template. The expression you give after `:Evaluate:` can go on for several lines: it is assumed to end when there is first a blank line, or a line that does not begin with spaces or tabs.

This specifies that a usage message for `SkewAdd` should be set up when the external program is installed.

```
:Evaluate:    SkewAdd::usage = "SkewAdd[x, y] performs
      a skew addition in an external program."
```

When an external program is installed, the specifications in its *MathLink* template file are used in the order they were given. This means that any expressions given in `:Evaluate:` specifications that appear before `:Begin:` will have been evaluated before definitions for the external function are set up.

Here are *Mathematica* expressions to be evaluated before the definitions for external functions are set up.

```
:Evaluate:  BeginPackage["XPack`"]
:Evaluate:  XF1::usage = "XF1[x, y] is one external function."
:Evaluate:  XF2::usage = "XF2[x] is another external function."
:Evaluate:  Begin["`Private`"]
```

This specifies that the function XF1 in *Mathematica* should be set up to call the function f in the external C program.

```
:Begin:
:Function:       f
:Pattern:        XF1[x_Integer, y_Integer]
:Arguments:      {x, y}
:ArgumentTypes:  {Integer, Integer}
:ReturnType:     Integer
:End:
```

This specifies that XF2 in *Mathematica* should call g. Its argument and return value are taken to be approximate real numbers.

```
:Begin:
:Function:       g
:Pattern:        XF2[x_?NumberQ]
:Arguments:      {x}
:ArgumentTypes:  {Real}
:ReturnType:     Real
:End:
```

These *Mathematica* expressions are evaluated after the definitions for the external functions. They end the special context used for the definitions.

```
:Evaluate:  End[ ]
:Evaluate:  EndPackage[ ]
```

Here is the actual source code for the function f. There is no need for the arguments of this function to have the same names as their *Mathematica* counterparts.

```
int f(int i, int j) {
   return i + j;
}
```

Here is the actual source code for g. Numbers that you give in *Mathematica* will automatically be converted into C double types before being passed to g.

```
double g(double x) {
   return x*x;
}
```

By using `:Evaluate:` specifications, you can evaluate *Mathematica* expressions when an external program is first installed. You can also execute code inside the external program at this time simply by inserting the code in `main()` before the call to `MLMain()`. This is sometimes useful if you need to initialize the external program before any functions in it are used.

`MLEvaluateString(stdlink,"`*string*`")`
evaluate a string as *Mathematica* input

Executing a command in *Mathematica* from within an external program.

```
int diff(int i, int j) {
```

This evaluates a *Mathematica* `Print` function if `i < j`.

```
  if (i < j) MLEvaluateString(stdlink, "Print[\"negative\"]");
  return i - j;
}
```

This installs an external program containing the `diff` function defined above.

```
In[7]:= Install["diffprog"]
Out[7]= LinkObject[./diffprog, 9, 7]
```

Calling `diff` causes `Print` to be executed.

```
In[8]:= diff[4, 7]

   negative

Out[8]= -3
```

Note that any results generated in the evaluation requested by `MLEvaluateString()` are ignored. To make use of such results requires full two-way communication between *Mathematica* and external programs, as discussed in "Two-Way Communication with External Programs".

Handling Lists, Arrays and Other Expressions

MathLink allows you to exchange data of any type with external programs. For more common types of data, you simply need to give appropriate `:ArgumentTypes:` or `:ReturnType:` specifications in your *MathLink* template file.

Mathematica specification		*C specification*
`Integer`	integer	`int`
`Real`	floating-point number	`double`
`IntegerList`	list of integers	`int*,long`
`RealList`	list of floating-point numbers	`double*,long`
`String`	character string	`char*`
`Symbol`	symbol name	`char*`
`Manual`	call *MathLink* routines directly	`void`

Basic type specifications.

Here is the *MathLink* template for a function that takes a list of integers as its argument.

```
:Begin:
:Function:       h
:Pattern:        h[a_List]
:Arguments:      {a}
:ArgumentTypes:  {IntegerList}
:ReturnType:     Integer
:End:
```

Here is the C source code for the function. Note the extra argument `alen` which is used to pass the length of the list.

```
int h(int *a, long alen) {

   int i, tot=0;

   for(i=0; i<alen; i++)
      tot += a[i];

   return tot;
}
```

This installs an external program containing the specifications for the function `h`.

```
In[1]:= Install["hprog"]
Out[1]= LinkObject[./hprog, 11, 8]
```

This calls the external code.

```
In[2]:= h[{3, 5, 6}]
Out[2]= 14
```

This does not match the pattern `h[a_List]` so does not call the external code.

```
In[3]:= h[67]
Out[3]= h[67]
```

The pattern is matched, but the elements in the list are of the wrong type for the external code, so `$Failed` is returned.

```
In[4]:= h[{a, b, c}]
Out[4]= $Failed
```

You can mix basic types of arguments in any way you want. Whenever you use `IntegerList` or `RealList`, however, you have to include an extra argument in your C program to represent the length of the list.

Here is an `:ArgumentTypes:` specification.

```
:ArgumentTypes:  {IntegerList, RealList, Integer}
```

Here is a possible corresponding C function declaration.

```
void f(int *a, long alen, double *b, long blen, int c)
```

Note that when a list is passed to a C program by *MathLink* its first element is assumed to be at position 0, as is standard in C, rather than at position 1, as is standard in *Mathematica*.

In addition, following C standards, character strings specified by `String` are passed as `char*` objects, terminated by `\0` null bytes. "Portability of *MathLink* Programs" discusses how to handle special characters.

`MLPutInteger32 (stdlink,int` *i*`)`	put a single integer
`MLPutReal64 (stdlink,double` *x*`)`	put a single floating-point number
`MLPutInteger32List (stdlink,int*`*a*`,int` *n*`)`	put a list of *n* integers starting from location *a*
`MLPutReal64List (stdlink,double*`*a*`,int` *n*`)`	put a list of *n* floating-point numbers starting from location *a*
`MLPutInteger32Array (stdlink,int*`*a*`,int*`*dims*`,NULL,int` *d*`)`	put an array of integers to form a depth *d* list with dimensions *dims*
`MLPutReal64Array (stdlink,double*`*a*`,int*`*dims*`,NULL,int` *d*`)`	put an array of floating-point numbers
`MLPutString (stdlink,char*`*s*`)`	put a character string
`MLPutSymbol (stdlink,char*`*s*`)`	put a character string as a symbol name
`MLPutFunction (stdlink,char*`*s*`,int` *n*`)`	begin putting a function with head *s* and *n* arguments

MathLink functions for sending data to *Mathematica*.

When you use a *MathLink* template file, what `mprep` and `mcc` actually do is to create a C program that includes explicit calls to *MathLink* library functions. If you want to see an example of how to use the *MathLink* library functions directly, you can look at the source code of this program. Note when you use `mcc`, you typically need to give a `-g` option, otherwise the source code that is generated is automatically deleted.

If your external function just returns a single integer or floating-point number, then you can specify this just by giving `Integer` or `Real` as the `:ReturnType:` in your *MathLink* template file. But because of the way memory allocation and deallocation work in C, you cannot directly give `:ReturnType:` specifications such as `IntegerList` or `RealList`. And instead, to return such structures, you must explicitly call *MathLink* library functions within your C program, and give `Manual` as the `:ReturnType:` specification.

Here is the *MathLink* template for a function that takes an integer as an argument, and returns a list of the digits in its binary representation using explicit *MathLink* functions.

```
:Begin:
:Function:       bits
:Pattern:        bits[i_Integer]
:Arguments:      {i}
:ArgumentTypes:  {Integer}
:ReturnType:     Manual
:End:
```

The return type of the function is declared as `void`.

```
void bits(int i) {

   int a[32], k;
```

This puts values into the C array `a`.

```
   for(k=0; k<32; k++) {
       a[k] = i%2;
       i >>= 1;
       if (i==0) break;
   }

   if (k<32) k++;
```

This sends `k` elements of the array `a` back to *Mathematica*.

```
    MLPutInteger32List(stdlink, a, k);
    return ;
}
```

This installs the program containing the external function `bits`.

```
In[5]:= Install["bitsprog"]
Out[5]= LinkObject[bitsprog, 5, 5]
```

The external function now returns a list of bits.

```
In[6]:= bits[14]
Out[6]= {0, 1, 1, 1}
```

If you declare an array in C as `int a[n1][n2][n3]`, then you can use `MLPutInteger32Array()` to send it to *Mathematica* as a depth 3 list.

Here is a declaration for a 3-dimensional C array.

```
int a[8][16][100];
```

This sets up the array `dims` and initializes it to the dimensions of `a`.

```
int dims[] = {8, 16, 100};
```

This sends the 3-dimensional array `a` to *Mathematica*, creating a depth 3 list.

```
MLPutInteger32Array(stdlink, a, dims, NULL, 3);
```

You can use *MathLink* functions to create absolutely any *Mathematica* expression. The basic idea is to call a sequence of *MathLink* functions that correspond directly to the `FullForm` representation of the *Mathematica* expression.

This sets up the *Mathematica* function `Plus` with 2 arguments.

```
MLPutFunction(stdlink, "Plus", 2);
```

This specifies that the first argument is the integer `77`.

```
MLPutInteger32(stdlink, 77);
```

And this specifies that the second argument is the symbol `x`.

```
MLPutSymbol(stdlink, "x");
```

In general, you first call `MLPutFunction()`, giving the head of the *Mathematica* function you want to create, and the number of arguments it has. Then you call other *MathLink* functions to fill in each of these arguments in turn. "Expressions" discusses the general structure of *Mathematica* expressions and the notion of heads.

This creates a *Mathematica* list with 2 elements.

```
MLPutFunction(stdlink, "List", 2);
```

The first element of the list is a list of 10 integers from the C array `r`.

```
MLPutInteger32List(stdlink, r, 10);
```

```
    The second element of the main list is itself a list with 2 elements.
MLPutFunction(stdlink, "List", 2);

    The first element of this sublist is a floating-point number.
MLPutReal64(stdlink, 4.5);

    The second element is an integer.
MLPutInteger32(stdlink, 11);
```

`MLPutInteger32Array()` and `MLPutReal64Array()` allow you to send arrays which are laid out in memory in the one-dimensional way that C pre-allocates them. But if you create arrays during the execution of a C program, it is more common to set them up as nested collections of pointers. You can send such arrays to *Mathematica* by using a sequence of `MLPutFunction()` calls, ending with an `MLPutInteger32List()` call.

```
    This declares a to be a nested list of lists of lists of integers.
int ***a;

    This creates a Mathematica list with n1 elements.
MLPutFunction(stdlink, "List", n1);
for (i=0; i<n1; i++) {

    This creates a sublist with n2 elements.
  MLPutFunction(stdlink, "List", n2);
  for (j=0; j<n2; j++) {

    This writes out lists of integers.
      MLPutInteger32List(stdlink, a[i][j], n3);
  }
}
```

It is important to realize that any expression you create using *MathLink* functions will be evaluated as soon as it is sent to *Mathematica*. This means, for example, that if you wanted to transpose an array that you were sending back to *Mathematica*, all you would need to do is to wrap

a Transpose around the expression representing the array. You can then do this simply by calling MLPutFunction(stdlink, "Transpose", 1); just before you start creating the expression that represents the array.

The idea of postprocessing data that you send back to *Mathematica* has many uses. One example is as a way of sending lists whose length you do not know in advance.

This creates a list in *Mathematica* by explicitly appending successive elements.

```
In[7]:= t = {}; Do[t = Append[t, i^2], {i, 5}]; t
Out[7]= {1, 4, 9, 16, 25}
```

This creates a list in which each successive element is in a nested sublist.

```
In[8]:= t = {}; Do[t = {t, i^2}, {i, 5}]; t
Out[8]= {{{{{{}, 1}, 4}, 9}, 16}, 25}
```

Flatten flattens out the list.

```
In[9]:= Flatten[t]
Out[9]= {1, 4, 9, 16, 25}
```

Sequence automatically flattens itself.

```
In[10]:= {Sequence[1, Sequence[4, Sequence[]]]}
Out[10]= {1, 4}
```

In order to call MLPutInteger32List(), you need to know the length of the list you want to send. But by creating a sequence of nested Sequence objects, you can avoid having to know the length of your whole list in advance.

This sets up the List around your result.

```
MLPutFunction(stdlink, "List", 1);

while( condition ) {
     /* generate an element */
```

Create the next level Sequence object.

```
  MLPutFunction(stdlink, "Sequence", 2);
```

Put the element.

```
  MLPutInteger32(stdlink,  i );
}
```

This closes off your last `Sequence` object.

```
MLPutFunction(stdlink, "Sequence", 0);
```

`MLGetInteger32 (stdlink,int*`i`)`	get an integer, storing it at address i
`MLGetReal64 (stdlink,double*`x`)`	get a floating-point number, storing it at address x

Basic functions for explicitly getting data from *Mathematica*.

MathLink provides functions like `MLPutInteger32()` to send data from an external program into *Mathematica*. *MathLink* also provides functions like `MLGetInteger32()` that allow you to get data from *Mathematica* into an external program.

The list that you give for `:ArgumentTypes:` in a *MathLink* template can end with `Manual`, indicating that after other arguments have been received, you will call *MathLink* functions to get additional expressions.

```
:Begin:
:Function:       f
```

The function `f` in *Mathematica* takes 3 arguments.

```
:Pattern:        f[i_Integer, x_Real, y_Real]
```

All these arguments are passed directly to the external program.

```
:Arguments:      {i, x, y}
```

Only the first argument is sent directly to the external function.

```
:ArgumentTypes:  {Integer, Manual}
:ReturnType:     Real
:End:
```

The external function only takes one explicit argument.

```
double f(int i) {
```

This declares the variables x and y.

```
 double x, y;
```

MLGetReal64() explicitly gets data from the link.

```
 MLGetReal64(stdlink, &x);
 MLGetReal64(stdlink, &y);

 return i+x+y;
}
```

MathLink functions such as MLGetInteger32 (*link*, *pi*) work much like standard C library functions such as fscanf (*fp*, "%d", *pi*). The first argument specifies the link from which to get data. The last argument gives the address at which the data that is obtained should be stored.

MLCheckFunction (stdlink,"*name*",int*n)	check the head of a function and store how many arguments it has

Getting a function via *MathLink*.

```
:Begin:
:Function:       f
```

The function f in *Mathematica* takes a list of integers as an argument.

```
:Pattern:        f[a:{___Integer}]
```

The list is passed directly to the external program.

```
:Arguments:      {a}
```

The argument is to be retrieved manually by the external program.

```
:ArgumentTypes:  {Manual}

:ReturnType:     Integer
:End:
```

The external function takes no explicit arguments.

```
int f(void) {
```

This declares local variables.

```
int n, i;
int a[MAX];
```

This checks that the function being sent is a list, and stores how many elements it has in `n`.

```
MLCheckFunction(stdlink, "List", &n);
```

This gets each element in the list, storing it in `a[i]`.

```
for (i=0; i<n; i++)
   MLGetInteger32(stdlink, a+i);
```

In simple cases, it is usually possible to ensure on the *Mathematica* side that the data you send to an external program has the structure that is expected. But in general the return value from `MLCheckFunction()` will be MLSUCCESS only if the data consists of a function with the name you specify.

Note that if you want to get a nested collection of lists or other objects, you can do this by making an appropriate sequence of calls to `MLCheckFunction()`.

`MLGetInteger32List (stdlink,int**a,int*n)`	get a list of integers, allocating the memory needed to store it
`MLGetReal64List (stdlink,double**a,int*n)`	get a list of floating-point numbers
`MLReleaseInteger32List (stdlink,int*a,int n)`	release the memory associated with a list of integers
`MLReleaseReal64List (stdlink,double*a,int n)`	release the memory associated with a list of floating-point numbers

Getting lists of numbers.

When an external program gets data from *Mathematica*, it must set up a place to store the data. If the data consists of a single integer, as in `MLGetInteger32 (stdlink, &n)`, then it suffices just to have declared this integer using `int n`.

But when the data consists of a list of integers of potentially any length, memory must be allocated to store this list at the time when the external program is actually called.

MLGetInteger32List(stdlink, &a, &n) will automatically do this allocation, setting a to be a pointer to the result. Note that memory allocated by functions like MLGetInteger32List() is always in a special reserved area, so you cannot modify or free it directly.

Here is an external program that will be sent a list of integers.

```
int f(void) {
```

This declares local variables. a is an array of integers.

```
  int n;
  int *a;
```

This gets a list of integers, making a be a pointer to the result.

```
  MLGetInteger32List(stdlink, &a, &n);
```

This releases the memory used to store the list of integers.

```
  MLReleaseInteger32List(stdlink, a, n);
...
}
```

If you use IntegerList as an :ArgumentTypes: specification, then *MathLink* will automatically release the memory used for the list after your external function exits. But if you get a list of integers explicitly using MLGetInteger32List(), then you must not forget to release the memory used to store the list after you have finished with it.

MLGetInteger32Array(stdlink,int**a,int**dims,char***heads,int*d)	get an array of integers of any depth
MLGetReal64Array(stdlink,double**a,int**dims,char***heads,int*d)	get an array of floating-point numbers of any depth
MLReleaseInteger32Array(stdlink,int*a,int*dims,char**heads,int d)	release memory associated with an integer array
MLReleaseRealArray(stdlink,double*a,int*dims,char**heads,int d)	release memory associated with a floating-point array

Getting arrays of numbers.

`MLGetInteger32List()` extracts a one-dimensional array of integers from a single *Mathematica* list. `MLGetInteger32Array()` extracts an array of integers from a collection of lists or other *Mathematica* functions nested to any depth.

The name of the *Mathematica* function at level i in the structure is stored as a string in $heads[i]$. The size of the structure at level i is stored in $dims[i]$, while the total depth is stored in d.

If you pass a list of complex numbers to your external program, then `MLGetReal64Array()` will create a two-dimensional array containing a sequence of pairs of real and imaginary parts. In this case, $heads[0]$ will be `"List"` while $heads[1]$ will be `"Complex"`.

Note that you can conveniently exchange arbitrary-precision numbers with external programs by converting them to lists of digits in *Mathematica* using `IntegerDigits` and `RealDigits`.

`MLGetString (stdlink,char**s)`	get a character string
`MLGetSymbol (stdlink,char**s)`	get a symbol name
`MLReleaseString (stdlink,char*s)`	release memory associated with a character string
`MLReleaseSymbol (stdlink,char*s)`	release memory associated with a symbol name

Getting character strings and symbol names.

If you use `String` as an `:ArgumentTypes:` specification, then *MathLink* will automatically release the memory that is used to store the string after your function exits. This means that if you want to continue to refer to the string, you must allocate memory for it, and explicitly copy each character in it.

If you get a string using `MLGetString()`, however, then *MathLink* will not automatically release the memory used for the string when your function exits. As a result, you can continue referring to the string. Be careful not to modify the contents of the string by writing to the memory that is returned by `MLGetString()`. When you no longer need the string, you must nevertheless explicitly call `MLReleaseString()` in order to release the memory associated with it.

`MLGetFunction (stdlink,char**s,int*n)`	begin getting a function, storing the name of the head in s and the number of arguments in n
`MLReleaseSymbol (stdlink,char*s)`	release memory associated with a function name

Getting an arbitrary function.

If you know what function to expect in your external program, then it is usually simpler to call `MLCheckFunction()`. But if you do not know what function to expect, you have no choice but to call `MLGetFunction()`. If you do this, you need to be sure to call `MLReleaseSymbol()` to release the memory associated with the name of the function that is found by `MLGetFunction()`.

Portability of *MathLink* Programs

The *Mathematica* side of a *MathLink* connection is set up to work exactly the same on all computer systems. But inevitably there are differences between external programs on different computer systems.

For a start, different computer systems almost always require different executable binaries. When you call `Install["prog"]`, therefore, you must be sure that *prog* corresponds to a program that can be executed on your particular computer system.

`Install["file"]`	try to execute *file* directly
`Install["file",LinkProtocol->"type"]`	use the specified protocol for low-level data transport
`$SystemID`	identify the type of computer system being used
`Install["dir"]`	try to execute a file with a name of the form *dir* / `$SystemID` / *dir*

Installing programs on different computer systems.

Mathematica follows the convention that if *prog* is an ordinary file, then `Install["prog"]` will just try to execute it. But if *prog* is a directory, then *Mathematica* will look for a subdirectory of that directory whose name agrees with the current value of `$SystemID`, and will then try to execute a file named *prog* within that subdirectory.

`mcc -o` *prog* ...	put compiled code in the file *prog* in the current directory
`mcc -xo` *prog* ...	put compiled code in *prog* / `$SystemID` / *prog*

Typical Unix commands for compiling external programs.

Even though the executable binary of an external program is inevitably different on different computer systems, it can still be the case that the source code in a language such as C from which this binary is obtained can be essentially the same.

But to achieve portability in your C source code there are several points that you need to watch.

For a start, you should never make use of extra features of the C language or C runtime libraries that happen to be provided on a particular system, but are not part of standard C. In addition, you should try to avoid dealing with segmented or otherwise special memory models.

The include file `mathlink.h` contains standard C prototypes for all the functions in the *MathLink* library.

`MLPutInteger32 ()`	`MLGetInteger32 ()`	integer corresponding to C type `int`, that is, 32 bits
`MLPutInteger16 ()`	`MLGetInteger16 ()`	integer of type `short`, that is, 16 bits
`MLPutInteger64 ()`	`MLGetInteger64 ()`	64-bit integer
`MLPutReal64 ()`	`MLGetReal64 ()`	IEEE double-precision real number, corresponding to the C-language type `double`
`MLPutReal32 ()`	`MLGetReal32 ()`	IEEE single-precision real number, corresponding to the C-language type `float`
`MLPutReal128 ()`	`MLGetReal128 ()`	IEEE quad-precision real number

MathLink functions that use specific C types.

If you are going to call *MathLink* library functions in a portable way, it is essential that you use the same types as they do.

If your programs correctly match the argument types for the *MathLink* library functions, you do not have to worry about C type differences between computer systems. *MathLink* automatically converts the C types to the appropriate sizes for each platform. *MathLink* also swaps bytes as needed to correctly transfer numbers across platforms, and it converts between floating-point number formats with the smallest possible loss of precision.

`MLPutString (stdlink,char*s)`	put a null-terminated C character string
`MLPutUnicodeString (stdlink,unsigned short*s,int n)`	put a string encoded in terms of 16-bit UCS-2 Unicode characters
`MLPutByteString (stdlink,unsigned char*s,int n)`	put a string containing only 8-bit character codes
`MLPutUTF8String (stdlink, const unsigned char*s,int n)`	put a string of UTF-8 encoded Unicode characters
`MLPutUTF16String (stdlink, const unsigned short*s,int n)`	put a string of UTF-16 encoded Unicode characters
`MLPutUTF32String (stdlink, const unsigned int*s,int n)`	put a string of UTF-32 encoded Unicode characters
`MLGetString (stdlink,char**s)`	get a null-terminated C character string
`MLGetUnicodeString (stdlink,unsigned short**s,long*n)`	get a string encoded in terms of 16-bit UCS-2 Unicode characters
`MLGetByteString (stdlink,unsigned char**s,long*n,long spec)`	get a string containing only 8-bit character codes, using *spec* as the code for all 16-bit characters
`MLGetUTF8String (stdlink, const unsigned char**s, int*m,int*n)`	get a string of UTF-8 encoded Unicode characters
`MLGetUTF16String (stdlink, const unsigned short**s,int*m,int*n)`	get a string of UTF-16 encoded Unicode characters
`MLGetUTF32String (stdlink, const unsigned int**s,int*n)`	get a string of UTF-32 encoded Unicode characters

Manipulating general strings.

In simple C programs, it is typical to use strings that contain only ordinary ASCII characters. But in *Mathematica* it is possible to have strings containing all sorts of special characters. These characters are specified within *Mathematica* using Unicode character codes, as discussed in "Raw Character Encodings".

C language `char *` strings typically use only 8 bits to store the code for each character. UCS-2 encoded strings, however, require 16 bits. As a result, the functions `MLPutUnicodeString()` and `MLGetUnicodeString()` work with arrays of `unsigned short` integers. The same is true of UTF-16 encoded strings and the corresponding functions `MLPutUTF16String()` and `MLGetUTF16String()`.

UTF-32 encoded strings require 32 bits for each character, and the corresponding functions `MLPutUTF32String()` and `MLGetUTF32String()` work with arrays of `unsigned int` integers.

If you know that your program will not have to handle special characters, then you may find it convenient to use `MLPutByteString()` and `MLGetByteString()`. These functions represent all characters directly using 8-bit character codes. If a special character is sent from *Mathematica*, then it will be converted by `MLGetByteString()` to a fixed code that you specify.

- `main()` may need to be different on different computer systems

A point to watch in creating portable *MathLink* programs.

Computer systems and compilers that have C runtime libraries based on the Unix model allow *MathLink* programs to have a main program of the form `main(argc, argv)` which simply calls `MLMain(argc, argv)`.

Some computer systems or compilers may however require main programs of a different form. You should realize that you can do whatever initialization you want inside `main()` before calling `MLMain()`. Once you have called `MLMain()`, however, your program will effectively go into an infinite loop, responding to requests from *Mathematica* until the link to it is closed.

Using *MathLink* to Communicate between *Mathematica* Sessions

`LinkCreate["`*name*`"]`	create a link for another program to connect to
`LinkConnect["`*name*`"]`	connect to a link created by another program
`LinkClose[`*link*`]`	close a *MathLink* connection
`LinkWrite[`*link*`,`*expr*`]`	write an expression to a *MathLink* connection
`LinkRead[`*link*`]`	read an expression from a *MathLink* connection
`LinkRead[`*link*`,Hold]`	read an expression and immediately wrap it with `Hold`
`LinkReadyQ[`*link*`]`	find out whether there is data ready to be read from a link
`LinkReadyQ[`*link*`,`*t*`]`	wait for up to *t* seconds to see if an expression becomes ready to read
`LinkReadyQ[{`$link_1$`,`$link_2$`,…}]`	find out whether there is data ready to be read from one of the links
`LinkReadyQ[{`$link_1$`,`$link_2$`,…},`*t*`]`	wait for up to *t* seconds to see if an expression becomes ready to read

MathLink connections between *Mathematica* sessions.

Session A

This starts up a link on port number 8000.

```
In[1]:= link = LinkCreate["8000", LinkProtocol → "TCPIP"]
Out[1]= LinkObject[8000@frog.wolfram.com,4470@frog.wolfram.com, 17, 5]
```

Session B

This connects to the link on port 8000.

```
In[2]:= Link = LinkConnect["8000", LinkProtocol → "TCPIP"]
Out[2]= LinkObject[8000@ frog.wolfram.com , 11, 4]
```

Session A

This evaluates `15!` and writes it to the link.

```
In[3]:= LinkWrite[link, 15!]
```

Session B

This reads from the link, getting the `15!` that was sent.

```
In[4]:= LinkRead[Link]
Out[4]= 1307674368000
```

This writes data back on the link.

```
In[5]:= LinkWrite[link, N[%^6]]
```

Session A

And this reads the data written in session B.

```
In[6]:= LinkRead[link]
Out[6]= 5.00032×10^72
```

One use of *MathLink* connections between *Mathematica* sessions is simply as a way to transfer data without using intermediate files.

Another use is as a way to dispatch different parts of a computation to different sessions.

Session A

This writes the expression `2 + 2` without evaluating it.

```
In[7]:= LinkWrite[link, Unevaluated[2 + 2]]
```

Session B

This reads the expression from the link, immediately wrapping it in `Hold`.

```
In[8]:= LinkRead[Link, Hold]
Out[8]= Hold[2 + 2]
```

This evaluates the expression.

```
In[9]:= ReleaseHold[%]
Out[9]= 4
```

When you call LinkWrite, it writes an expression to the *MathLink* connection and immediately returns. But when you call LinkRead, it will not return until it has read a complete expression from the *MathLink* connection.

You can tell whether anything is ready to be read by calling LinkReadyQ[*link*]. If LinkReadyQ returns True, then you can safely call LinkRead and expect immediately to start reading an expression. But if LinkReadyQ returns False, then LinkRead would block until an expression for it to read had been written by a LinkWrite in your other *Mathematica* session.

Session A

There is nothing waiting to be read on the link, so if LinkRead were to be called, it would block.

```
In[10]:= LinkReadyQ[link]
Out[10]= False
```

Session B

This writes an expression to the link.

```
In[11]:= LinkWrite[Link, x + y]
```

Session A

Now there is an expression waiting to be read on the link.

```
In[12]:= LinkReadyQ[link]
Out[12]= True
```

LinkRead can thus be called without fear of blocking.

```
In[13]:= LinkRead[link]
Out[13]= x + y
```

LinkReadyQ can take a list of link objects, evaluating each link in parallel to determine if there is data to read. As in the case of a single link, a second argument specifies a time out period, causing LinkReadyQ to wait until one of the links is ready to use.

`LinkCreate[ LinkProtocol->"TCPIP"]`	pick any unused port on your computer
`LinkCreate["number",LinkProtocol->"TCPIP"]`	use a specific port
`LinkConnect["number",LinkProtocol->"TCPIP"]`	connect to a port on the same computer
`LinkConnect["number@host",LinkProtocol->"TCPIP"]`	connect to a port on another computer

Ways to set up *MathLink* links over TCP/IP.

MathLink can use whatever mechanism for interprogram communication your computer system supports. In setting up connections between concurrent *Mathematica* sessions, a common mechanism is internet TCP ports.

Most computer systems have a few thousand possible numbered ports, some of which are typically allocated to standard system services.

You can use any of the unallocated ports for *MathLink* connections.

Session on `frog.wolfram.com`

This finds an unallocated port on `frog.wolfram.com`.

```
In[14]:= link = LinkCreate[LinkProtocol → "TCPIP"]
Out[14]= LinkObject["2981@frog.wolfram.com,2982@frog.wolfram.com", 5, 5]
```

Session on `toad.wolfram.com`

This connects to the port on `frog.wolfram.com`.

```
In[15]:= link = LinkConnect[
           "2981@frog.wolfram.com,2982@frog.wolfram.com", LinkProtocol → "TCPIP"]
Out[15]= LinkObject["2981@frog.wolfram.com,2982@frog.wolfram.com", 5, 5]
```

This sends the current machine name over the link.

```
In[16]:= LinkWrite[link, $MachineName]
```

Session on frog.wolfram.com

This reads the expression written on toad.

```
In[17]:= LinkRead[link]
Out[17]= toad
```

By using internet ports for *MathLink* connections, you can easily transfer data between *Mathematica* sessions on different machines. All that is needed is that an internet connection exists between the machines.

Note that because *MathLink* is completely system independent, the computers at each end of a *MathLink* connection do not have to be of the same type. *MathLink* nevertheless notices when they are, and optimizes data transmission in this case.

Calling Subsidiary *Mathematica* Processes

LinkLaunch["*prog*"]	start an external program and open a connection to it

Connecting to a subsidiary program via *MathLink*.

This starts a subsidiary *Mathematica* process on the computer system used here.

```
In[1]:= link = LinkLaunch["math -mathlink"]
Out[1]= LinkObject[math -mathlink, 4, 4]
```

Here is a packet representing the first input prompt from the subsidiary *Mathematica* process.

```
In[2]:= LinkRead[link]
Out[2]= InputNamePacket[In[1]:= ]
```

This writes a packet representing text to enter in the subsidiary *Mathematica* process.

```
In[3]:= LinkWrite[link, EnterTextPacket["10!"]]
```

Here is a packet representing the output prompt from the subsidiary *Mathematica* process.

```
In[4]:= LinkRead[link]
Out[4]= OutputNamePacket[Out[1]= ]
```

And here is the actual result from the computation.

```
In[5]:= LinkRead[link]
Out[5]= ReturnTextPacket[3628800]
```

The basic way that the various different objects involved in a *Mathematica* session are kept organized is by using *MathLink packets*. A *MathLink* packet is simply an expression with a definite head that indicates its role or meaning.

`EnterTextPacket["`*input*`"]`	text to enter corresponding to an input line
`ReturnTextPacket["`*output*`"]`	text returned corresponding to an output line
`InputNamePacket["`*name*`"]`	text returned for the name of an input line
`OutputNamePacket["`*name*`"]`	text returned for the name of an output line

Basic packets used in *Mathematica* sessions.

The fact that `LinkRead` returns an `InputNamePacket` indicates that the subsidiary *Mathematica* is now ready for new input.

```
In[6]:= LinkRead[link]
Out[6]= InputNamePacket[In[2]:= ]
```

This enters two `Print` commands as input.

```
In[7]:= LinkWrite[link, EnterTextPacket["Print[a]; Print[b];"]]
```

Here is the text from the first `Print`.

```
In[8]:= LinkRead[link]
Out[8]= TextPacket[a
]
```

And here is the text from the second `Print`.

```
In[9]:= LinkRead[link]
Out[9]= TextPacket[b
]
```

No output line is generated, so the new packet is an `InputNamePacket`.

```
In[10]:= LinkRead[link]
Out[10]= InputNamePacket[In[3]:= ]
```

TextPacket["*string*"]	text from Print etc.
MessagePacket[*symb*,"*tag*"]	a message name
DisplayPacket["*string*"]	parts of PostScript graphics
DisplayEndPacket["*string*"]	the end of PostScript graphics

Some additional packets generated in *Mathematica* sessions.

If you enter input to *Mathematica* using EnterTextPacket["*input*"], then *Mathematica* will automatically generate a string version of your output, and will respond with ReturnTextPacket["*output*"]. But if you instead enter input using EnterExpressionPacket[*expr*] then *Mathematica* will respond with ReturnExpressionPacket[*expr*] and will not turn your output into a string.

EnterExpressionPacket[*expr*]	an expression to enter corresponding to an input line
ReturnExpressionPacket[*expr*]	an expression returned corresponding to an output line

Packets for representing input and output lines using expressions.

This enters an expression into the subsidiary *Mathematica* session without evaluating it.

```
In[11]:= LinkWrite[link, Unevaluated[EnterExpressionPacket[Factor[x^6 - 1]]]]
```

Here are the next 3 packets that come back from the subsidiary *Mathematica* session.

```
In[12]:= Table[LinkRead[link], {3}]
Out[12]= {OutputNamePacket[Out[3]=],
 ReturnExpressionPacket[(-1 + x) (1 + x) (1 - x - x^2) (1 + x + x^2)], InputNamePacket[In[4]:=]}
```

InputNamePacket and OutputNamePacket packets are often convenient for making it possible to tell the current state of a subsidiary *Mathematica* session. But you can suppress the generation of these packets by calling the subsidiary *Mathematica* session with a string such as "math -mathlink -batchoutput".

Even if you suppress the explicit generation of InputNamePacket and OutputNamePacket packets, *Mathematica* will still process any input that you give with EnterTextPacket or EnterExpressionPacket as if you were entering an input line. This means for example that *Mathematica* will call $Pre and $Post, and will assign values to In[$Line] and Out[$Line].

EvaluatePacket[*expr*]	an expression to be sent purely for evaluation
ReturnPacket[*expr*]	an expression returned from an evaluation

Evaluating expressions without explicit input and output lines.

This sends an EvaluatePacket. The Unevaluated prevents evaluation before the packet is sent.

```
In[13]:= LinkWrite[link, Unevaluated[EvaluatePacket[10!]]]
```

The result is a pure ReturnPacket.

```
In[14]:= LinkRead[link]
Out[14]= ReturnPacket[3 628 800]
```

This sends an EvaluatePacket requesting evaluation of Print[x].

```
In[15]:= LinkWrite[link, Unevaluated[EvaluatePacket[Print[x]]]]
```

The first packet to come back is a TextPacket representing text generated by the Print.

```
In[16]:= LinkRead[link]
Out[16]= TextPacket[x
]
```

After that, the actual result of the Print is returned.

```
In[17]:= LinkRead[link]
Out[17]= ReturnPacket[Null]
```

In most cases, it is reasonable to assume that sending an EvaluatePacket to *Mathematica* will simply cause *Mathematica* to do a computation and to return various other packets, ending with a ReturnPacket. However, if the computation involves a function like Input, then *Mathematica* will have to request additional input before it can proceed with the computation.

This sends a packet whose evaluation involves an Input function.

```
In[18]:= LinkWrite[link, Unevaluated[EvaluatePacket[2 + Input["data ="]]]]
```

What comes back is an InputPacket which indicates that further input is required.

```
In[19]:= LinkRead[link]
Out[19]= InputPacket[data =]
```

There is nothing more to be read on the link at this point.

```
In[20]:= LinkReadyQ[link]
Out[20]= False
```

This enters more input.

```
In[21]:= LinkWrite[link, EnterTextPacket["x + y"]]
```

Now the `Input` function can be evaluated, and a `ReturnPacket` is generated.

```
In[22]:= LinkRead[link]
Out[22]= ReturnPacket[2 + x + y]
```

LinkInterrupt[*link*] — send an interrupt to a *MathLink*-compatible program

Interrupting a *MathLink*-compatible program.

This sends a very time-consuming calculation to the subsidiary process.

```
In[23]:= LinkWrite[link, EnterTextPacket["FactorInteger[2^777-1]"]]
```

The calculation is still going on.

```
In[24]:= LinkReadyQ[link]
Out[24]= False
```

This sends an interrupt.

```
In[25]:= LinkInterrupt[link]
```

Now the subsidiary process has stopped, and is sending back an interrupt menu.

```
In[26]:= LinkRead[link]
Out[26]= MenuPacket[1, Interrupt> ]
```

This closes the link.

```
In[27]:= LinkClose[link]
```

Two-Way Communication with External Programs

When you install a *MathLink*-compatible external program using `Install`, the program is set up to behave somewhat like a simplified *Mathematica* kernel. Every time you call a function in the external program, a `CallPacket` is sent to the program, and the program responds by sending back a result wrapped in a `ReturnPacket`.

This installs an external program, returning the `LinkObject` used for the connection to that program.

```
In[1]:= link = Install["bitsprog"]
Out[1]= LinkObject[bitsprog, 4, 4]
```

The function `ExternalCall` sends a `CallPacket` to the external program.

```
In[2]:= ?bits

        Global`bits

        bits[i_Integer] :=
         ExternalCall[LinkObject[bitsprog, 4, 4], CallPacket[0, {i}]]
```

You can send the `CallPacket` explicitly using `LinkWrite`. The first argument of the `CallPacket` specifies which function in the external program to call.

```
In[3]:= LinkWrite[link, CallPacket[0, {67}]]
```

Here is the response to the `CallPacket` from the external program.

```
In[4]:= LinkRead[link]
Out[4]= {1, 1, 0, 0, 0, 0, 1}
```

If you use `Install` several times on a single external program, *Mathematica* will open several *MathLink* connections to the program. Each connection will however always correspond to a unique `LinkObject`.

`$CurrentLink`	the *MathLink* connection to the external program currently being run

Identifying different instances of a single external program.

```
:Begin:
:Function:      addto
```

This gives $CurrentLink as an argument to addto.

```
:Pattern:       addto[$CurrentLink, n_Integer]

:Arguments:     {n}
:ArgumentTypes: {Integer}
:ReturnType:    Integer
:End:
```

This zeros the global variable counter every time the program is started.

```
int counter = 0;


int addto(int n) {
    counter += n;
    return counter;
}
```

This installs one instance of the external program containing addto.

```
In[5]:= ct1 = Install["addtoprog"]
Out[5]= LinkObject[addtoprog, 5, 5]
```

This installs another instance.

```
In[6]:= ct2 = Install["addtoprog"]
Out[6]= LinkObject[addtoprog, 6, 6]
```

This adds 10 to the counter in the first instance of the external program.

```
In[7]:= addto[ct1, 10]
Out[7]= 10
```

This adds 15 to the counter in the second instance of the external program.

```
In[8]:= addto[ct2, 15]
Out[8]= 15
```

This operates on the first instance of the program again.

```
In[9]:= addto[ct1, 20]
Out[9]= 30
```

If an external program maintains information about its state then you can use different instances of the program to represent different states. `$CurrentLink` then provides a way to refer to each instance of the program.

The value of `$CurrentLink` is temporarily set every time a particular instance of the program is called, as well as when each instance of the program is first installed.

`MLEvaluateString (stdlink,"`*string*`")`	send input to *Mathematica* but return no results

Sending a string for evaluation by *Mathematica*.

The two-way nature of *MathLink* connections allows you not only to have *Mathematica* call an external program, but also to have that external program call back to *Mathematica*.

In the simplest case, you can use the *MathLink* function `MLEvaluateString ()` to send a string to *Mathematica*. *Mathematica* will evaluate this string, producing whatever effects the string specifies, but it will not return any results from the evaluation back to the external program.

To get results back you need explicitly to send an `EvaluatePacket` to *Mathematica*, and then read the contents of the `ReturnPacket` that comes back.

This starts an `EvaluatePacket`.

```
MLPutFunction(stdlink, "EvaluatePacket", 1);
```

This constructs the expression `Factorial[7]` or `7!`.

```
MLPutFunction(stdlink, "Factorial", 1);
  MLPutInteger32(stdlink, 7);
```

This specifies that the packet you are constructing is finished.

```
MLEndPacket(stdlink);
```

This checks the `ReturnPacket` that comes back.

```
MLCheckFunction(stdlink, "ReturnPacket", &n);
```

This extracts the integer result for `7!` from the packet.

```
MLGetInteger32(stdlink, &ans);
```

`MLEndPacket (stdlink)`	specify that a packet is finished and ready to be sent to *Mathematica*

Sending a packet to *Mathematica*.

When you can send *Mathematica* an `EvaluatePacket[`*input*`]`, it may in general produce many packets in response, but the final packet should be `ReturnPacket[`*output*`]`. "Manipulating Expressions in External Programs" will discuss how to handle sequences of packets and expressions whose structure you do not know in advance.

Running Programs on Remote Computers

MathLink allows you to call an external program from within *Mathematica* even when that program is running on a remote computer. Typically, you need to start the program directly from the operating system on the remote computer. But then you can connect to it using commands within your *Mathematica* session.

Operating system on `toad.wolfram.com`

This starts the program `fprog` and tells it to create a new link.

```
fprog -linkcreate -linkprotocol TCPIP
```

The program responds with the specification of the link it has created.

```
Link created on: 2976@toad.wolfram.com,2977@toad.wolfram.com
```

Mathematica session on `frog.wolfram.com`

This connects to the link that has been created.

```
In[1]:= Install[LinkConnect[
          "2976@toad.wolfram.com,2977@toad.wolfram.com", LinkProtocol → "TCPIP"]]
Out[1]= LinkObject[2976@toad.wolfram.com,2977@toad.wolfram.com, 1, 1]
```

This now executes code in the external program on `toad.wolfram.com`.

```
In[2]:= f[16]
Out[2]= 561243
```

External programs that are created using `mcc` or `mprep` always contain the code that is needed to set up *MathLink* connections. If you start such programs directly from your operating system, they will prompt you to specify what kind of connection you want. Alternatively, if your operating system supports it, you can also give this information as a command-line argument to the external program.

prog`-linkcreate -linkprotocol TCPIP`	operating system command to run a program and have it create a link
`Install[LinkConnect["`*port1@host*`,`*port2@host*`",LinkProtocol->"TCPIP"]]`	*Mathematica* command to connect to the external program

Running an external program on a remote computer.

Running External Programs under a Debugger

MathLink allows you to run external programs under whatever debugger is provided in your software environment.

MathLink-compatible programs are typically set up to take arguments, usually on the command line, which specify what *MathLink* connections they should use.

In debugger:	`run -linkcreate -linkprotocol TCPIP`
In *Mathematica*:	`Install[LinkConnect["`*port*`",LinkProtocol->"TCPIP"]]`

Running an external program under a debugger.

Note that in order to get a version of an external program that can be run under a debugger, you need to compile the program so that the output is suitable for use with your debugger. Unix compilers commonly use `-g` as a command-line argument for producing a debuggable program. See your compiler documentation for specific information on the steps you should take.

Unix debugger

Set a breakpoint in the C function `f`.

```
break f
Breakpoint set: f: line 1
```

Start the external program.

```
run -linkcreate -linkprotocol TCPIP
```

The program responds with what port it is listening on.

```
Link created on: 2981@frog.wolfram.com,2982@frog.wolfram.com
```

Mathematica session

This connects to the program running under the debugger.

```
In[1]:= Install[LinkConnect[
          "2981@frog.wolfram.com,2982@frog.wolfram.com", LinkProtocol → "TCPIP"]]
Out[1]= LinkObject[2981@frog.wolfram.com,2982@frog.wolfram.com, 1, 1]
```

This calls a function which executes code in the external program.

```
In[2]:= f[16]
```

Unix debugger

The external program stops at the breakpoint.

```
Breakpoint: f(16)
```

This tells the debugger to continue.

```
continue
```

Mathematica session

Now `f` returns.

```
Out[3]= 561243
```

Manipulating Expressions in External Programs

Mathematica expressions provide a very general way to handle all kinds of data, and you may sometimes want to use such expressions inside your external programs. A language like C, however, offers no direct way to store general *Mathematica* expressions. But it is nevertheless

possible to do this by using the *loopback links* provided by the *MathLink* library. A loopback link is a local *MathLink* connection inside your external program, to which you can write expressions that can later be read back.

`MLINK MLLoopbackOpen (stdenv,int*`*errno*`)`	open a loopback link
`void MLClose (MLINK` *link*`)`	close a link
`int MLTransferExpression (MLINK` *dest*`,MLINK` *src*`)`	get an expression from *src* and put it onto *dest*

Functions for manipulating loopback links.

This opens a loopback link.

```
...
ml = MLLoopbackOpen(stdenv, &errno);
```

This puts the expression `Power[x, 3]` onto the loopback link.

```
MLPutFunction(ml, "Power", 2);
  MLPutSymbol(ml, "x");
  MLPutInteger32(ml, 3);
...
```

This gets the expression back from the loopback link.

```
MLGetFunction(ml, &head, &n);
  MLGetSymbol(ml, &sname);
  MLGetInteger32(ml, &k);
...
```

This closes the loopback link again.

```
MLClose(ml);
```

You can use `MLTransferExpression()` to take an expression that you get via `stdlink` from *Mathematica*, and save it in a local loopback link for later processing.

You can also use `MLTransferExpression()` to take an expression that you have built up on a local loopback link, and transfer it back to *Mathematica* via `stdlink`.

This puts `21!` onto a local loopback link.

```
...
MLPutFunction(ml, "Factorial", 1);
  MLPutInteger32(ml, 21);
```

This sends the head `FactorInteger` to *Mathematica*.

```
MLPutFunction(stdlink, "FactorInteger", 1);
```

This transfers the `21!` from the loopback link to `stdlink`.

```
MLTransferExpression(stdlink, ml);
```

You can put any sequence of expressions onto a loopback link. Usually you get the expressions off the link in the same order as you put them on.

And once you have got an expression off the link it is usually no longer saved. But by using `MLCreateMark()` you can mark a particular position in a sequence of expressions on a link, forcing *MathLink* to save every expression after the mark so that you can go back to it later.

`MLMARK MLCreateMark (MLINK` *link*`)`	create a mark at the current position in a sequence of expressions on a link
`MLSeekMark (MLINK` *link*`,MLMARK` *mark*`,int` *n*`)`	go back to a position *n* expressions after the specified mark on a link
`MLDestroyMark (MLINK` *link*`,MLMARK` *mark*`)`	destroy a mark in a link

Setting up marks in *MathLink* links.

This puts the integer `45` onto a loopback link.

```
...
MLPutInteger32(ml, 45);
```

This puts `33` onto the link.

```
MLPutInteger32(ml, 33);
```

And this puts `76`.

```
MLPutInteger32(ml, 76);
```

This will read `45` from the link. The `45` will no longer be saved.

```
MLGetInteger32(ml, &i);
```

This creates a mark at the current position on the link.

```
mark = MLCreateMark(ml);
```

This will now read 33.

```
MLGetInteger32(ml, &i);
```

And this will read 76.

```
MLGetInteger32(ml, &i);
```

This goes back to the position of the mark.

```
MLSeekMark(ml, mark, 0);
```

Now this will read 33 again.

```
MLGetInteger32(ml, &i);
```

It is important to destroy marks when you have finished with them, so no unnecessary expressions will be saved.

```
MLDestroyMark(ml, mark);
```

The way the *MathLink* library is implemented, it is very efficient to open and close loopback links, and to create and destroy marks in them. The only point to remember is that as soon as you create a mark on a particular link, *MathLink* will save subsequent expressions that are put on that link, and will go on doing this until the mark is destroyed.

`int MLGetNext (MLINK link)`	find the type of the next object on a link
`int MLGetArgCount (MLINK link,int*n)`	store in n the number of arguments for a function on a link
`int MLGetSymbol (MLINK link,char**name)`	get the name of a symbol
`int MLGetInteger32 (MLINK link,int*i)`	get a machine integer
`int MLGetReal64 (MLINK link,double*x)`	get a machine floating-point number
`int MLGetString (MLINK link,char**string)`	get a character string

Functions for getting pieces of expressions from a link.

MLTKFUNC	composite function—head and arguments
MLTKSYM	*Mathematica* symbol
MLTKINT	integer
MLTKREAL	floating-point number
MLTKSTR	character string

Constants returned by MLGetNext().

```
switch(MLGetNext(ml)) {

  This reads a composite function.

    case MLTKFUNC:
    MLGetArgCount(ml, &n);
     recurse for head
    for (i = 0; i < n; i++) {
         recurse for each argument
    }
    …

  This reads a single symbol.

    case MLTKSYM:
    MLGetSymbol(ml, &name);
    …

  This reads a machine integer.

    case MLTKINT:
    MLGetInteger32(ml, &i);
    …
}
```

By using MLGetNext() it is straightforward to write programs that can read any expression. The way *MathLink* works, the head and arguments of a function appear as successive expressions on the link, which you read one after another.

Note that if you know that the head of a function will be a symbol, then you can use MLGetFunction() instead of MLGetNext(). In this case, however, you still need to call MLReleaseSymbol() to disown the memory used to store the symbol name.

int MLPutNext (MLINK *link*, int *type*)	prepare to put an object of the specified type on a link
int MLPutArgCount (MLINK *link*, int *n*)	give the number of arguments for a composite function
int MLPutSymbol (MLINK *link*, char***name*)	put a symbol on the link
int MLPutInteger32 (MLINK *link*, int *i*)	put a machine integer
int MLPutReal64 (MLINK *link*, double *x*)	put a machine floating-point number
int MLPutString (MLINK *link*, char***string*)	put a character string

Functions for putting pieces of expressions onto a link.

`MLPutNext()` specifies types of expressions using constants such as `MLTKFUNC` from the `mathlink.h` header file—just like `MLGetNext()`.

Error and Interrupt Handling

When you are putting and getting data via *MathLink* various kinds of errors can occur. Whenever any error occurs, *MathLink* goes into a completely inactive state, and all *MathLink* functions you call will return 0 immediately.

int MLError (MLINK *link*)	return a number identifying the current error, or 0 if none has occurred
char***MLErrorMessage (MLINK *link*)	return a character string describing the current error
int MLClearError (MLINK *link*)	clear the current error, returning *MathLink* if possible to an active state

Handling errors in *MathLink* programs.

When you do complicated operations, it is often convenient to check for errors only at the end. If you find that an error occurred, you must then call `MLClearError()` to activate *MathLink* again.

`int MLNewPacket (MLINK link)`	skip to the end of the current packet

Clearing out the remains of a packet.

After an error, it is common to want to discard the remainder of the packet or expression that you are currently processing. You can do this using `MLNewPacket()`.

In some cases, you may want to set it up so that if an error occurs while you are processing particular data, you can then later go back and reprocess the data in a different way. You can do this by calling `MLCreateMark()` to create a mark before you first process the data, and then calling `MLSeekMark()` to seek back to the mark if you need to reprocess the data. You should not forgot to call `MLDestroyMark()` when you have finally finished with the data—otherwise *MathLink* will continue to store it.

`int MLAbort`	a global variable set when a program set up by `Install` is sent an abort interrupt

Aborting an external program.

If you interrupt *Mathematica* while it is in the middle of executing an external function, it will typically give you the opportunity to try to abort the external function. If you choose to do this, what will happen is that the global variable `MLAbort` will be set to `1` inside your external program.

MathLink cannot automatically back out of an external function call that has been made. So if you have a function that can take a long time, you should explicitly check `MLAbort` every so often, returning from the function if you find that the variable has been set.

Running *Mathematica* from Within an External Program

To run *Mathematica* from within an external program requires making use of many general features of *MathLink*. The first issue is how to establish a *MathLink* connection to *Mathematica*.

When you use *MathLink* templates to create external programs that can be called from *Mathematica*, source code to establish a *MathLink* connection is automatically generated, and all you have to do in your external program is to call `MLMain (argc, argv)`. But in general you need to call several functions to establish a *MathLink* connection.

MLENV MLInitialize (0)	initialize *MathLink* library functions
MLINK MLOpenArgcArgv (MLENV *env*,int *argc*,char**argv*,int**errno*)	
	open a *MathLink* connection taking parameters from an argv array
MLINK MLOpenString (MLENV *env*,char**string*,int**errno*)	
	open a *MathLink* connection taking parameters from a single character string
int MLActivate (MLINK *link*)	activate a *MathLink* connection, waiting for the program at the other end to respond
void MLClose (MLINK *link*)	close a *MathLink* connection
void MLDeinitialize (MLENV *env*)	deinitialize *MathLink* library functions

Opening and closing *MathLink* connections.

Include the standard *MathLink* header file.

```
#include "mathlink.h"


int main(int argc, char *argv[]) {

   MLENV env;
   MLINK link;
   int errno;
```

This initializes *MathLink* library functions.

```
   env = MLInitialize(0);
```

This opens a *MathLink* connection, using the same arguments as were passed to the main program.

```
   link = MLOpenArgcArgv(env, argc, argv, &errno);
```

This activates the connection, waiting for the other program to respond.

```
   MLActivate(link);

   ...
}
```

Often the argv that you pass to MLOpenArgcArgv() will come directly from the argv that is passed to main () when your whole program is started.

The elements in the argv array are character strings which mirror the arguments and options used in the *Mathematica* functions LinkLaunch, LinkCreate and LinkConnect.

"-linklaunch"	operate like LinkLaunch["*name*"]
"-linkcreate"	operate like LinkCreate["*name*"]
"-linkconnect"	operate like LinkConnect["*name*"]
"-linkname","*name*"	give the name to use
"-linkprotocol","*protocol*"	give the link protocol to use (TCPIP, Pipes, etc.)

Possible elements of the argv array passed to MLOpenArgcArgv().

As an alternative to MLOpenArgcArgv() you can use MLOpenString(), which takes parameters concatenated into a single character string with spaces in between.

Once you have successfully opened a *MathLink* connection to the *Mathematica* kernel, you can then use standard *MathLink* functions to exchange data with it.

int MLEndPacket (MLINK *link*)	indicate the end of a packet
int MLNextPacket (MLINK *link*)	find the head of the next packet
int MLNewPacket (MLINK *link*)	skip to the end of the current packet

Functions often used in communicating with the *Mathematica* kernel.

Once you have sent all the pieces of a packet using MLPutFunction() etc., *MathLink* requires you to call MLEndPacket() to ensure synchronization and consistency.

One of the main issues in writing an external program which communicates directly with the *Mathematica* kernel is handling all the various kinds of packets that the kernel can generate.

The function MLNextPacket() finds the head of the next packet that comes from the kernel, and returns a constant that indicates the type of the packet.

Mathematica packet	*constant*	
`ReturnPacket[`*expr*`]`	`RETURNPKT`	result from a computation
`ReturnTextPacket["`*string*`"]`	`RETURNTEXTPKT`	textual form of a result
`InputNamePacket["`*name*`"]`	`INPUTNAMEPKT`	name of an input line
`OutputNamePacket["`*name*`"]`	`OUTPUTNAMEPKT`	name of an output line
`TextPacket["`*string*`"]`	`TEXTPKT`	textual output from functions like `Print`
`MessagePacket[`*symb*`,"`*tag*`"]`	`MESSAGEPKT`	name of a message generated by *Mathematica*
`InputPacket["`*prompt*`"]`	`INPUTPKT`	request for a response to an `Input` function
`CallPacket[`*i*`,`*list*`]`	`CALLPKT`	request for a call to an external function

Some packets recognized by `MLNextPacket()`.

This keeps on reading data from a link, discarding it until an error or a `ReturnPacket` is found.

```
while ((p = MLNextPacket(link)) && p != RETURNPKT)
    MLNewPacket(link);
```

If you want to write a complete front end to *Mathematica*, you will need to handle all of the possible types of packets that the kernel can generate. Typically you can do this by setting up an appropriate `switch` on the value returned by `MLNextPacket()`.

The *MathLink* Developer Kit contains sample source code for several simple but complete front ends.

`int MLReady (MLINK` *link*`)`	test whether there is data waiting to be read on a link
`int MLReadyParallel (MLENV` *e*`, MLINK *`*links*`, int` *n*`, mltimeval` *t*`)`	test in parallel whether there is data to be read from a list of links
`int MLFlush (MLINK` *link*`)`	flush out buffers containing data waiting to be sent on a link

Flow of data on links.

One feature of more sophisticated external programs such as front ends is that they may need to perform operations while they are waiting for data to be sent to them by *Mathematica*. When you call a standard *MathLink* library function such as `MLNextPacket()` your program will normally block until all the data needed by this function is available.

You can avoid blocking by repeatedly calling `MLReady()`, and only calling functions like `MLNextPacket()` when `MLReady()` no longer returns `0`. `MLReady()` is the analog of the *Mathematica* function `LinkReadyQ`.

Note that *MathLink* sometimes buffers the data that you tell it to send. To make sure that all necessary data has been sent you should call `MLFlush()`. Only after doing this does it make sense to call `MLReady()` and wait for data to be sent back.

MathLink Interface 3

The library now fully supports the Unicode character encoding forms UTF-8, UTF-16, and UTF-32. Use the following new API functions to put or get Unicode characters to or from a link.

`MLPutUTF8String()`	`MLGetUTF8String()`
`MLPutUTF16String()`	`MLGetUTF16String()`
`MLPutUTF32String()`	`MLGetUTF32String()`
`MLPutUTF8Symbol()`	`MLGetUTF8Symbol()`
`MLPutUTF16Symbol()`	`MLGetUTF16Symbol()`
`MLPutUTF32Symbol()`	`MLGetUTF32Symbol()`
`MLReleaseUTF8String()`	`MLReleaseUTF8Symbol()`
`MLReleaseUTF16String()`	`MLReleaseUTF16Symbol()`
`MLReleaseUTF32String()`	`MLReleaseUTF32Symbol()`

The *MathLink* library header file `mathlink.h` no longer contains obsolete platform support sections such as those defined by `MACINTOSH_MATHLINK` or `OS2_MATHLINK`. `MACINTOSH_MATHLINK` definitions referred to Mac-OS 9 and earlier. `DARWIN_MATHLINK` contains all platform-specific definitions for Mac OS X.

All uses of special alternative names for common C types have been removed from the API. The *MathLink* header file `mathlink.h` still contains versions of the API functions with these types for use with Interface 2 and older programs.

Previous *MathLink* type	C type
`uchar_ct`	`unsigned char`
`ucharp_ct`	`unsigned char *`
`ucharpp_ct`	`unsigned char **`
`ucharppp_ct`	`unsigned char ***`
`ushort_ct`	`unsigned short`
`ushortp_ct`	`unsigned short *`
`ushortpp_ct`	`unsigned short **`
`ushortppp_ct`	`unsigned short ***`
`uint_ct`	`unsigned int`
`uintp_ct`	`unsigned int *`
`uintpp_ct`	`unsigned int **`

int_ct	int
voidp_ct	void *
voidpp_ct	void **
charp_ct	char *
charpp_ct	char **
charppp_ct	char ***
long_ct	long
longp_ct	long *
longpp_ct	long **
long_st	long
longp_st	long *
longpp_st	long **
ulong_ct	unsigned long
ulongp_ct	unsigned long *
kushortp_ct	const unsigned short *
kushortpp_ct	const unsigned short **
kuintp_ct	const unsigned int *
kuintpp_ct	const unsigned int **
kucharp_ct	const unsigned char *
kucharpp_ct	const unsigned char **
kcharp_ct	const char *
kcharpp_ct	const char **
kvoidp_ct	const void *

The memory allocator/deallocator functions passed to the library using `MLSetAllocParameter()` now must be thread-safe.

API functions that previously took a `MLParametersPointer` type as an argument or returned a `MLParametersPointer` type now instead take or return a `char *` type.

API functions that take as an argument or return a `mlapi_result` type now take or return type `int`.

API functions that take as an argument or return a `mlapi_error` type now take or return type `int`.

API functions that take as an argument or return a `mlapi_token` type now take or return type `int`.

API functions that take as an argument or return a `mlapi_packet` type now take or return type `int`.

API functions that take as an argument or return a `MLPointer` type now take or return `void *`.

The MLOpen* functions previously took type long * for the error variable but now take type int *.

The header file mathlink.h now contains several new error definitions related to the Unicode character encoding forms.

Error code	Interpretation
MLEPDATABAD	*MathLink* encountered invalid character data in given character encoding
MLEPSCONVERT	Unable to convert from given character encoding to *MathLink* encoding
MLEGSCONVERT	Unable to convert from *MathLink* encoding to requested character encoding

MLPutMessage() and MLGetMessage() now use types int and int * respectively instead of the dev_message and dev_message * types.

MLSeekMark() and MLSeekToMark() now use type int rather than type long for the expression index.

The functions in the following table took long types for some arguments; they now take int.

MLGetRawData()	MLGetData()
MLGetArgCount()	MLGetRawArgCount()
MLBytesToGet()	MLRawBytesToGet()
MLExpressionsToGet()	MLTakeLast()
MLPutRawSize()	MLPutRawData()
MLPutArgCount()	MLPutComposite()
MLBytesToPut()	

MLGetReal() is now an actual API function rather than a #define alias to MLGetDouble(). MLGetReal() still has the same functionality as MLGetDouble().

MLActivate() is now an actual API function rather than a #define alias to MLConnect(). MLActivate() still has the same functionality as MLConnect().

The functions in column one listed below are now obsolete. New programs should use the functions listed in column two for replacement functionality.

MLCheckFunction()	MLTestHead()
MLCheckFunctionWithArg()	MLTestHead()
MLGetShortInteger()	MLGetInteger16()
MLGetInteger()	MLGetInteger32()

`MLGetLongInteger()`	`MLGetInteger64()` for 64-bit integers or `MLGetInteger32()` for 32-bit integers
`MLGetFloat()`	`MLGetReal32()`
`MLGetDouble()`	`MLGetReal64()`
`MLGetLongDouble()`	`MLGetReal128()`
`MLGetShortIntegerArrayData()`	`MLGetInteger16ArrayData()`
`MLGetIntegerArrayData()`	`MLGetInteger32ArrayData()`
`MLGetLongIntegerArrayData()`	`MLGetInteger64ArrayData()` for 64-bit integers or `MLGetInteger32ArrayData()` for 32-bit integers
`MLGetFloatArrayData()`	`MLGetReal32ArrayData()`
`MLGetDoubleArrayData()`	`MLGetReal64ArrayData()`
`MLGetLongDoubleArrayData()`	`MLGetReal128ArrayData()`
`MLGetShortIntegerArray()`	`MLGetInteger16Array()`
`MLGetIntegerArray()`	`MLGetInteger32Array()`
`MLGetLongIntegerArray()`	`MLGetInteger64Array()` for 64-bit integers or `MLGetInteger32Array()` for 32-bit integers
`MLGetFloatArray()`	`MLGetReal32Array()`
`MLGetDoubleArray()`	`MLGetReal64Array()`
`MLGetLongDoubleArray()`	`MLGetReal128Array()`
`MLDisownShortIntegerArray()`	`MLReleaseInteger16Array()`
`MLDisownIntegerArray()`	`MLReleaseInteger32Array()`
`MLDisownLongIntegerArray()`	`MLReleaseInteger64Array()` for 64-bit integers or `MLReleaseInteger32Array()` for 32-bit integers
`MLDisownFloatArray()`	`MLReleaseReal32Array()`
`MLDisownDoubleArray()`	`MLReleaseReal64Array()`
`MLDisownLongDoubleArray()`	`MLReleaseReal128Array()`
`MLGetIntegerList()`	`MLGetInteger32List(()`
`MLGetRealList()`	`MLGetReal64List()`
`MLDisownIntegerList()`	`MLReleaseInteger32List()`
`MLDisownRealList()`	`MLReleaseReal64List()`

`MLPutShortInteger()`	`MLPutInteger16()`
`MLPutInteger()`	`MLPutInteger32()`
`MLPutLongInteger()`	`MLPutInteger64()` for 64-bit integers or `MLPutInteger32()` for 32-bit integers
`MLPutFloat()`	`MLPutReal32()`
`MLPutDouble()`	`MLPutReal64()`
`MLPutLongDouble()`	`MLPutReal128()`
`MLPutShortIntegerArrayData()`	`MLPutInteger16ArrayData()`
`MLPutIntegerArrayData()`	`MLPutInteger32ArrayData()`
`MLPutLongIntegerArrayData()`	`MLPutInteger64ArrayData()` for 64-bit integers or `MLPutInteger32ArrayData()` for 32-bit integers
`MLPutFloatArrayData()`	`MLPutReal32ArrayData()`
`MLPutDoubleArrayData()`	`MLPutReal64ArrayData()`

MLPutLongDoubleArrayData()	MLPutReal128ArrayData()
MLPutShortIntegerArray()	MLPutInteger16Array()
MLPutIntegerArray()	MLPutInteger32Array()
MLPutLongIntegerArray()	MLPutInteger64Array() for 64-bit integers or MLPutInteger32Array() for 32-bit integers
MLPutFloatArray()	MLPutReal32Array()
MLPutDoubleArray()	MLPutReal64Array()
MLPutLongDoubleArray()	MLPutReal128Array()
MLPutIntegerList()	MLPutInteger32List()
MLPutRealList()	MLPutReal64List()
MLGetUnicodeString()	MLGetUCS2String()
MLGetUnicodeSymbol()	MLGetUCS2Symbol()
MLPutUnicodeString()	MLPutUCS2String()
MLPutUnicodeSymbol()	MLPutUCS2Symbol()
MLPut16BitCharacters()	MLPutUCS2Characters()
MLDisownUnicodeString()	MLReleaseUCS2String()
MLDisownUnicodeSymbol()	MLReleaseUCS2Symbol()

Interface 3 changes the default linkprotocol for linkmode Listen and linkmode Connect links. By default the *MathLink* library will create "SharedMemory" links for linkmode Listen and linkmode Connect links on all platforms.