1 Introduction

MetaPost is a batch-oriented graphics language based on Knuth's METAFONT[1], but with PostScript[2] output and numerous features for integrating text and graphics. The author has tried to make this paper as independent as possible of the user's manual [5], but fully appreciating all the material requires some knowledge of the MetaPost language.

We concentrate on the mechanics of producing particular kinds of graphs because the question of what type of graph is best in a given situation is covered elsewhere; e.g., Cleveland [2, 4, 3] and Tufte [11]. The goal is to provide at least the power of UNIX[3] *grap* [1], but within the MetaPost language. Hence the package is implemented using MetaPost's powerful macro facility.

The graph macros provide the following functionality:

1. Automatic scaling
2. Automatic generation and labeling of tick marks or grid lines
3. Multiple coordinate systems
4. Linear and logarithmic scales
5. Separate data files
6. Ability to handle numbers outside the usual range
7. Arbitrary plotting symbols
8. Drawing, filling, and labeling commands for graphs

In addition to these items, the user also has access to all the features described in the MetaPost user's manual [5]. These include access to almost all the features of PostScript®, ability to use and manipulate typeset text, ability to solve linear equations, and data types for points, curves, pictures, and coordinate transformations.

Section 2 describes the graph macros from a user's perspective and presents several examples. Sections 3 and 4 discuss auxiliary packages for manipulating and typesetting numbers and Section 5 gives some concluding remarks. Appendix A summarizes the graph-drawing macros, and Appendix B describes some recent additions to the MetaPost language that have not been presented elsewhere.

2 Using the Graph Macros

A MetaPost input file that uses the graph macros should begin with

```
input graph
```

This reads a macro file `graph.mp` and defines the graph-drawing commands explained below. The rest of the file should be one or more instances of

`beginfig(`⟨figure number⟩`);`
⟨graphics commands⟩ `endfig;`

[1] METAFONT is a trademark of Addison Wesley Publishing Company.
[2] PostScript is a registered trademark of Adobe Systems Inc.
[3] UNIX is a registered trademark of UNIX System Laboratories, Inc.

followed by `end`.

The following ⟨graphics commands⟩ suffice to generate the graph in Figure 1 from the data file `agepop91.d`:

```
draw begingraph(3in,2in);
  gdraw "agepop91.d";
  endgraph;
```

(Each line of `agepop91.d` gives an age followed the estimated number of Americans of that age in 1991 [10].)

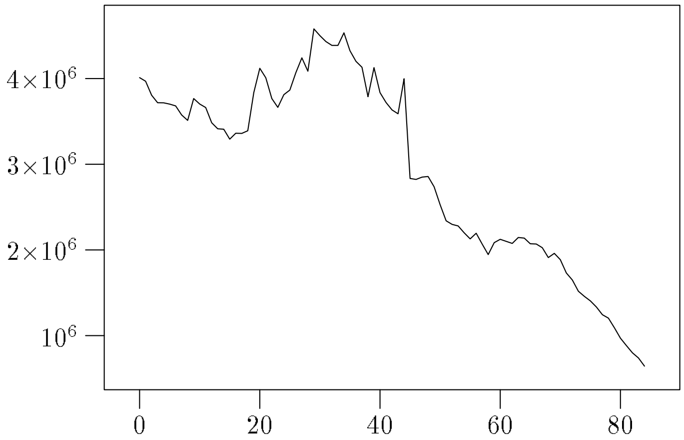


Figure 1: A graph of the 1991 age distribution in the United States

2.1 Basic Graph-Drawing Commands

All graphs should begin with

`begingraph(`⟨width⟩`,`⟨height⟩`);`

and end with `endgraph`. This is syntactically a ⟨picture expression⟩, so it should be preceded by `draw` and followed by a semicolon as in the example.[4] The ⟨width⟩ and ⟨height⟩ give the dimensions of the graph itself without the axis labels.

The command

`gdraw` ⟨expression⟩ ⟨option list⟩

draws a graph line. If the ⟨expression⟩ is of type string, it names a data file; otherwise it is a path that gives the function to draw. The ⟨option list⟩ is zero or more drawing options

`withpen`⟨pen expression⟩ | `withcolor`⟨color expression⟩ | `dashed`⟨picture expression⟩

that give the line width, color, or dash pattern as explained in the User's Manual [5].

In addition to the standard drawing options, the ⟨option list⟩ in a `gdraw` statement can contain

`plot` ⟨picture expression⟩

[4] See the User's Manual [5] for explanations of `draw` commands and syntactic elements like ⟨picture expression⟩.

The ⟨picture expression⟩ gives a plotting symbol to be drawn at each path knot. The `plot` option suppresses line drawing so that[5]

```
gdraw "agepop91.d" plot btex $\bullet$ etex
```

generates only bullets as shown in Figure 2. (Following the `plot` option with a `withpen` option would cause the line to reappear superimposed on the plotting symbols.)

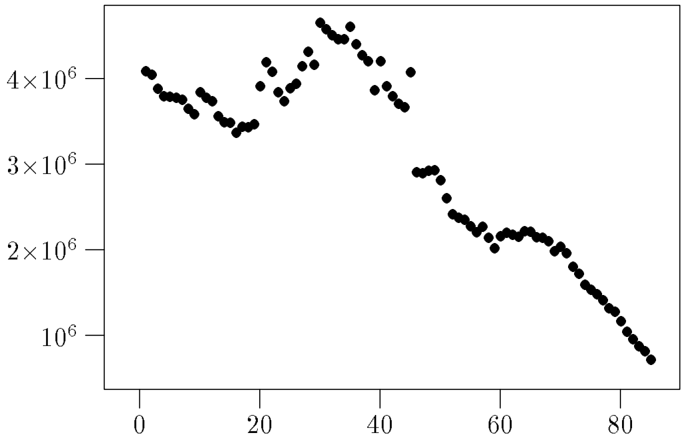


Figure 2: The 1991 age distribution plotted with bullets

The `glabel` and `gdotlabel` commands add labels to a graph. The syntax for `glabel` is

`glabel.` ⟨label suffix⟩`(`⟨string or picture expression⟩`,` ⟨location⟩`)` ⟨option list⟩

where ⟨location⟩ identifies the location being labeled and ⟨label suffix⟩ tells how the label is offset relative to that location. The `gdotlabel` command is identical, except it marks the location with a dot. A ⟨label suffix⟩ is as in plain MetaPost: ⟨empty⟩ centers the label on the location; `lft`, `rt`, `top`, `bot` offset the label horizontally or vertically; and `ulft`, `urt`, `llft`, `lrt` give diagonal offsets. The ⟨location⟩ can be a pair of graph coordinates, a knot number on the last `gdraw` path, or the special location `OUT`. Thus

```
gdotlabel.top(btex $(50,0)$ etex, 50,0)
```

would put a dot at graph coordinates `(50,0)` and place the typeset text "$(50,0)$" above it. Alternatively,

```
glabel.ulft("Knot3", 3)
```

typesets the string `"Knot3"` and places it above and to the left of Knot 3 of the last `gdraw` path. (The knot number 3 the path's "time" parameter [5, Section 8.2].)

The ⟨location⟩ `OUT` places a label relative to the whole graph. For example, replacing "`gdraw "agepop91.d"`" with

```
glabel.lft(btex \vbox{\hbox{Population} \hbox{in millions}} etex, OUT);
glabel.bot(btex Age in years etex, OUT);
gdraw "agepopm.d";
```

in the input for Figure 1 generates Figure 3. This improves the graph by adding axis labels and using a new data file `agepopm.d` where the populations have been divided by one million to avoid

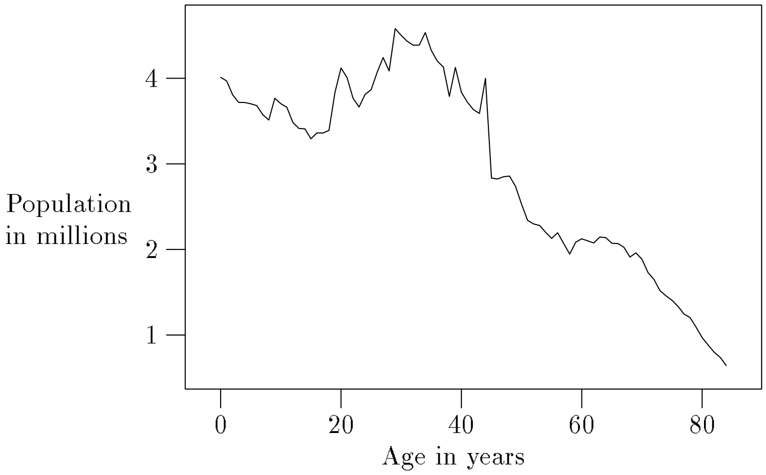


Figure 3: An improved version of the 1991 age distribution graph

large numbers. We shall see later that simple transformations such as this can be achieved without generating new data files.

All flavors of TEX can handle multi-line labels via the `\hbox` within `\vbox` arrangement used above, but LATEX users will find it more natural to use the `tabular` environment [9]. Troff user's can use nofill mode:

```
btex .nf
Population
in millions etex
```

2.2 Coordinate Systems

The graph macros automatically shift and rescale coordinates from data files, `gdraw` paths, and `glabel` locations to fit the graph. Whether the range of y coordinates is 0.64 to 4.6 or 640,000 to 4,600,000, they get scaled to fill about 88% of the height specified in the `begingraph` statement. Of course line widths, labels, and plotting symbols are not rescaled.

The `setrange` command controls the shifting and rescaling process by specifying the minimum and maximum graph coordinates:

$$\texttt{setrange(}\langle\text{coordinates}\rangle\texttt{,}\ \langle\text{coordinates}\rangle\texttt{)}$$

where

$$\begin{aligned}\langle\text{coordinates}\rangle &\rightarrow \langle\text{pair expression}\rangle\\ &\quad\mid \langle\text{numeric or string expression}\rangle\texttt{,}\langle\text{numeric or string expression}\rangle\end{aligned}$$

The first ⟨coordinates⟩ give $(x_{\min}, y_{\min})$ and the second give $(x_{\max}, y_{\max})$. The lines $x = x_{\min}$, $x = x_{\max}$, $y = y_{\min}$, and $y = y_{\max}$ define the rectangular frame around the graph in Figures 1–3. For example, an adding a statement

```
setrange(origin, whatever,whatever)
```

to the input for Figure 3 yields Figure 4. The first ⟨coordinates⟩ are given by the predefined pair constant `origin`, and the other coordinates are left unspecified. Any unknown value would work as well, but `whatever` is the standard MetaPost representation for an anonymous unknown value.

[5] Troff users should replace `btex $\bullet$ etex` with `btex \(bu etex`.

```
draw begingraph(3in,2in);
 glabel.lft(btex \vbox{\hbox{Population} \hbox{in millions}} etex, OUT);
 glabel.bot(btex Age in years etex, OUT);
 setrange(origin, whatever,whatever);
 gdraw "agepopm.d";
 endgraph;
```

Figure 4: The 1991 age distribution graph and the input that creates it.

Notice that the syntax for `setrange` allows coordinate values to be given as strings. Many commands in the graph package allow this option. It is provided because the MetaPost language uses fixed point numbers that must be less than 32768. This limitation is not as serious as it sounds because good graph design dictates that coordinate values should be "of reasonable magnitude" [2, 11]. If you really want x and y to range from 0 to 1,000,000,

```
setrange(origin, "1e6","1e6")
```

does the job. Any fixed or floating point representation is acceptable as long as the exponent is introduced by the letter "`e`".

Coordinate systems need not be linear. The `setcoords` command allows either or both axes to have logarithmic spacing:

$\langle$coordinate setting$\rangle \rightarrow$ `setcoords(`$\langle$coordinate type$\rangle$`,` $\langle$coordinate type$\rangle$`)`
$\langle$coordinate type$\rangle \rightarrow$ `log` | `linear` | `-log` | `-linear`

A negative $\langle$coordinate type$\rangle$ makes x (or y) run backwards so it is largest on the left side (or bottom) of the graph.

Figure 5 graphs execution times for two matrix multiplication algorithms using

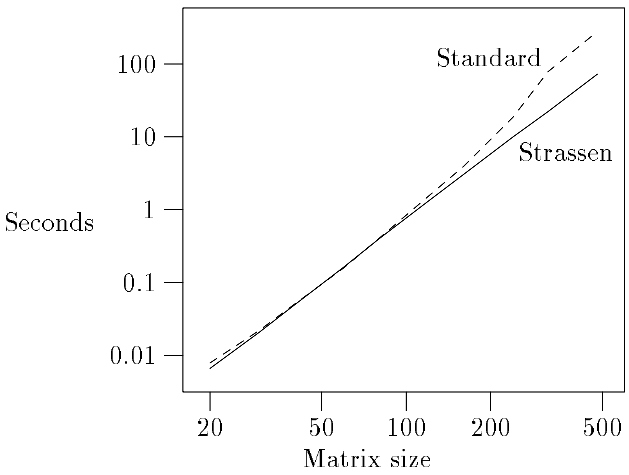
```
setcoords(log,log)
```

to specify logarithmic spacing on both axes. The data file `matmul.d` gives timings for both algorithms:

```
20 .007861  standard MM: size, seconds
30 .022051
40 .050391
60 .15922
80 .4031
120 1.53
160 3.915
240 18.55
320 78.28
480 279.24

20 .006611  Strassen: size, seconds
30 .020820
40 .049219
60 .163281
80 .3975
120 1.3125
160 3.04
240 9.95
320 22.17
480 72.60
```

A blank line in a data file ends a data set. Subsequent `gdraw` commands access additional data sets by just naming the same data file again. Since each line gives one x coordinate and one y coordinate, commentary material after the second data field on a line is ignored.




```
draw begingraph(2.3in,2in);
 setcoords(log,log);
 glabel.lft(btex Seconds etex,OUT);
 glabel.bot(btex Matrix size etex,
   OUT);
 gdraw "matmul.d" dashed evenly;
 glabel.ulft(btex Standard etex,8);
 gdraw "matmul.d";
 glabel.lrt(btex Strassen etex,7);
 endgraph;
```

Figure 5: Timings for two matrix multiplication algorithms with the corresponding MetaPost input.

Placing a `setcoords` command between two `gdraw` commands graphs two functions in different coordinate systems as shown in Figure 6. Whenever you give a `setcoords` command, the interpreter examines what has been drawn, selects appropriate x and y ranges, and scales everything to fit. Everything drawn afterward is in a new coordinate system that need not have anything in common with the old coordinates unless `setrange` commands enforce similar coordinate ranges. For instance, the two `setrange` commands force both coordinate systems to have x ranging from 80 to 90 and y starting at 0.

When you use multiple coordinate systems, you have to specify where the axis labels go. The default is to put tick marks on the bottom and the left side of the frame using the coordinate system in effect when the `endgraph` command is interpreted. Figure 6 uses the

```
autogrid(,otick.lft)
```

to label the left side of the graph with the y coordinates in effect before the `setcoords` command.

```
draw begingraph(6.5cm,4.5cm);
 setrange(80,0, 90,whatever);
 glabel.bot(btex Year etex, OUT);
 glabel.lft(btex \vbox{\hbox{Emissions in} \hbox{thousands of}
   \hbox{metric tons} \hbox{(heavy line)}}etex, OUT);
 gdraw "lead.d" withpen pencircle scaled 1.5pt;
 autogrid(,otick.lft);
 setcoords(linear,linear);
 setrange(80,0, 90,whatever);
 glabel.rt(btex \vbox{\hbox{Micrograms} \hbox{per cubic}
   \hbox{meter of air} \hbox{(thin line)}}etex, OUT);
 gdraw "lead.d";
 autogrid(otick.bot,otick.rt);
 endgraph;
```

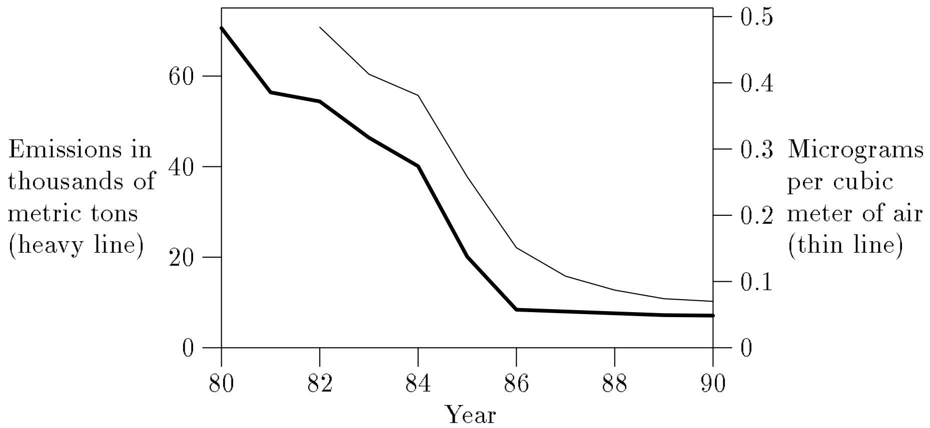


Figure 6: Annual lead emissions and average level at atmospheric monitoring stations in the United States. The MetaPost input is shown above the graph.

This suppresses the default axis labels, so another `autogrid` command is needed to label the bottom and right sides of the graph using the new coordinate system. The general syntax is

`autogrid(`⟨axis label command⟩`,` ⟨axis label command⟩`)` ⟨option list⟩

where

⟨axis label command⟩ → ⟨empty⟩ | ⟨grid or tick⟩ ⟨label suffix⟩
⟨grid or tick⟩ → `grid` | `itick` | `otick`

The ⟨label suffix⟩ should be `lft`, `rt`, `top`, or `bot`.

The first argument to `autogrid` tells how to label the x axis and the second argument does the same for y. An ⟨empty⟩ argument suppresses labeling for that axis. Otherwise, the ⟨label suffix⟩ tells which side of the graph gets the numeric label. Be careful to use `bot` or `top` for the x axis and `lft` or `rt` for the y axis. Use `otick` for outward tick marks, `itick` for inward tick marks, and `grid` for grid lines. The ⟨option list⟩ tells how to draw the tick marks or grid lines. Grid lines tend to be a little overpowering, so it is a good idea to give a `withcolor` option to make them light gray so they do not make the graph too busy.

2.3 Explicit Grids and Framing

In case `autogrid` is not flexible enough, axis label commands generate grid lines or tick marks one at a time. The syntax is

⟨grid or tick⟩`.`⟨label suffix⟩`(`⟨label format⟩`,` ⟨numeric or string expression⟩`)` ⟨option list⟩

where ⟨grid or tick⟩ and ⟨label suffix⟩ are as in `autogrid`, and ⟨label format⟩ is either a format string like `"%g"` or a picture containing the typeset numeric label.

The axis label commands use a macro

`format(`⟨format string⟩`,` ⟨numeric or string expression⟩`)`

to typeset numeric labels. Full details appear in Section 4, but when the ⟨format string⟩ is `"%g"`, it uses decimal notation unless the number is large enough or small enough to require scientific notation.

The example in Figure 7 invokes

`format("%g",y)`

explicitly so that grid lines can be placed at transformed coordinates. It defines the transformation `newy`$(y) = y/75 + \ln y$ and shows that this function increases almost linearly.[6] This is a little like using logarithmic y-coordinates, except that y is mapped to $y/75 + \ln y$ instead of just $\ln y$.

Figure 7 uses the command

`frame.`⟨label suffix⟩ ⟨option list⟩

to draw a special frame around the graph. In this case the ⟨label suffix⟩ is `llft` to draw just the bottom and left sides of the frame. Suffixes `lrt`, `ulft`, and `urt` draw other combinations of two sides; suffixes `lft`, `rt`, `top`, `bot` draw one side, and ⟨empty⟩ draws the whole frame. For example

```
frame dashed evenly
```

[6] The manual [5] explains how `vardef` defines functions and `mlog` computes logarithms.

```
vardef newy(expr y) = (256/75)*y + mlog y enddef;
draw begingraph(3in,2in);
 glabel.lft(btex \vbox{\hbox{Population} \hbox{in millions}} etex, OUT);
 gdraw "ttimepop.d";
 for y=5,10,20,50,100,150,200,250:
   grid.lft(format("%g",y), newy(y)) withcolor .85white;
 endfor
 autogrid(grid.bot,) withcolor .85white;
 frame.llft;
 endgraph;
```

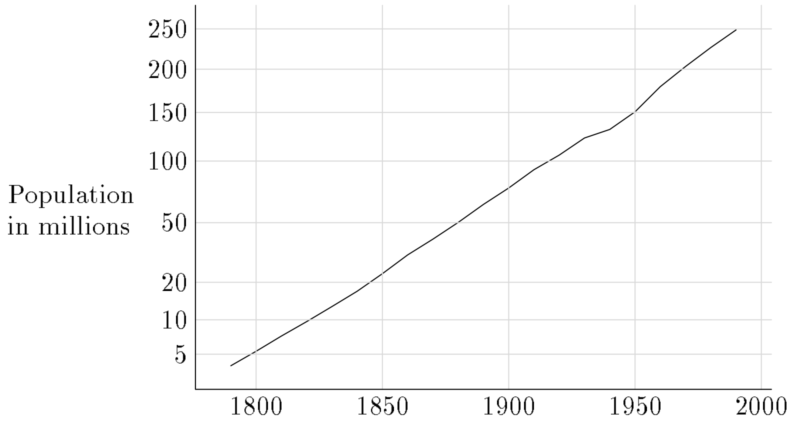


Figure 7: Population of the United States in millions versus time with the population re-expressed as $p/75 + \ln p$. The MetaPost input shown above the graph assumes a data file `ttimepop.d` that gives (year, $p/75 + \ln p$) pairs.

draws all four sides with dashed lines. The default four-sided frame is drawn only when there is no explicit `frame` command.

To label an axis as `autogrid` does but with the labels transformed somehow, use

`auto.x` or `auto.y`

for positioning tick marks or grid lines. These macros produce comma-separated lists for use in `for` loops. Any x or y values in these lists that cannot be represented accurately within MetaPost's fixed-point number system are given as strings. A standard macro package that is loaded via

```
input sarith
```

defines arithmetic operators that work on numbers or strings. Binary operators `Sadd`, `Ssub`, `Smul`, and `Sdiv` do addition, subtraction multiplication, and division.

One possible application is rescaling data. Figure 4 used a special data file `agepopm.d` that had y values divided by one million. This could be avoided by replacing "`gdraw "agepopm.d"`" by

```
gdraw "agepop91.d";
for u=auto.y: otick.lft(format("%g",u Sdiv "1e6"), u); endfor
autogrid(otick.bot,)
```

2.4 Processing Data Files

The most general tool for processing data files is the `gdata` command:

`gdata(`⟨string expression⟩`,` ⟨variable⟩`,` ⟨commands⟩`)`

It takes a file name, a variable v, and a list of commands to be executed for each line of the data file. The commands are executed with `i` set to the input line number and strings v`1`, v`2`, v`3`, ... set to the input fields on the current line. A null string marks the end of the v array.

Using a `glabel` command inside of `gdata` generates a scatter plot as shown in Figure 8. The data file `countries.d` begins

```
20.910 75.7 US
 1.831 66.7 Alg
```

where the last field in each line gives the label to be plotted. Setting `defaultfont` in the first line of input selects a small font for these labels. Without these labels, no `gdata` command would be needed. Replacing the `gdata` command with

```
gdraw "countries.d" plot btex$\circ$etex
```

would change the abbreviated country names to open circles.

Both `gdraw` and `gdata` ignore an optional initial '%' on each input line, parse data fields separated by white space, and stop if they encounter an input line with no data fields. Leading percent signs make graph data look like MetaPost comments so that numeric data can be placed at the beginning of a MetaPost input file.

It is often useful to construct one or more paths when reading a data file with `gdata`. The `augment` command is designed for this:

`augment.`⟨path variable⟩`(`⟨coordinates⟩`)`

If the path variable does not have a known value, it becomes a path of length zero at the given coordinates; otherwise a line segment to the given coordinates is appended to the path. The ⟨coordinates⟩ may be a pair expression or any combination of strings and numerics as explained at the beginning of Section 2.2.

```
defaultfont:="cmr7";
draw begingraph(3in,2in);
  glabel.lft(btex \vbox{\hbox{Life}\hbox{expectancy}} etex, OUT);
  glabel.bot(btex Per capita G.N.P. (thousands of dollars) etex, OUT);
  setcoords(log,linear);
  gdata("countries.d", s,
    glabel(s3, s1, s2);
  )
  endgraph;
```

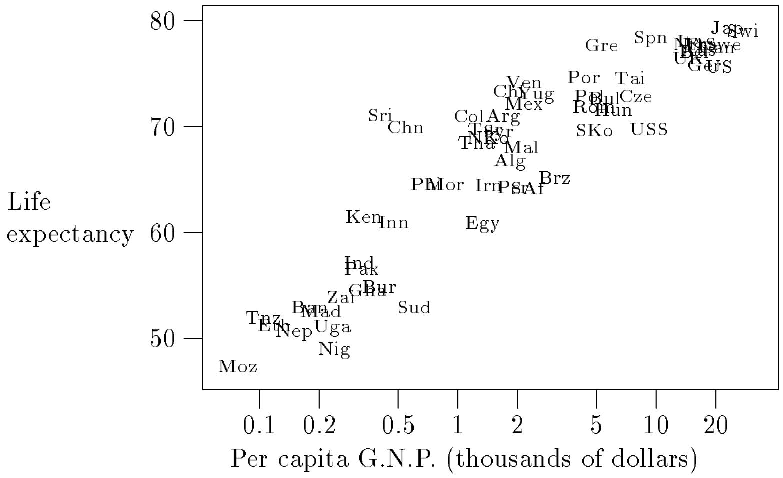


Figure 8: A scatter plot and the commands that generated it

If a file `timepop.d` gives t, p pairs, `augment` can be used like this to graph `newy(`p`)` versus t:

```
path p;
gdata("timepop.d", s, augment.p(s1, newy(scantokens s2)); );
gdraw p;
```

(MetaPost's `scantokens` primitive interprets a string as if it were the contents of an input file. This finds the numeric value of data field `s2`.)

Figure 9 shows how to use `augment` to read multiple column data and make multiple paths. Paths `p2`, `p3`, `p4`, `p5` give cumulative totals for columns 2 through 5 and pictures `lab2` through `lab5` give corresponding labels. The expression

```
image(unfill bbox lab[j]; draw lab[j])
```

executes the given drawing commands and returns the resulting picture: "`unfill bbox lab[j]`" puts down a white background and "`draw lab[j]`" puts the label on the background. The `gfill` command is just like `gdraw`, except it takes a cyclic path and fills the interior with a solid color. The color is black unless a `withcolor` clause specifies another color. See the manual [5] for explanations of `for` loops, arrays, colors, and path construction operators like `--`, `cycle`, and `reverse`.

3 Manipulating Big Numbers

MetaPost inherits a fixed-point number system from Knuth's METAFONT [8]. Numbers are expressed in multiples of 2^{-16} and they must have absolute value less than 32768. Knuth chose this system

```
draw begingraph(3in,2in);
  glabel.lft(btex \vbox{\hbox{Quadrillions}\hbox{of BTU}} etex, OUT);
  path p[];
  numeric t;
  gdata("energy.d", $,
    t:=0; augment.p1($1,0);
    for j=2 upto 5:
       t:=t+scantokens $[j]; augment.p[j]($1,t);
    endfor)
  picture lab[];
  lab2=btex coal etex; lab3=btex crude oil etex;
  lab4=btex natural gas etex; lab5=btex hydroelectric etex;
  for j=5 downto 2:
    gfill p[j]--reverse p[j-1]--cycle withcolor .16j*white;
    glabel.lft(image(unfill bbox lab[j]; draw lab[j]), .7+length p[j]);
  endfor
  endgraph;
```

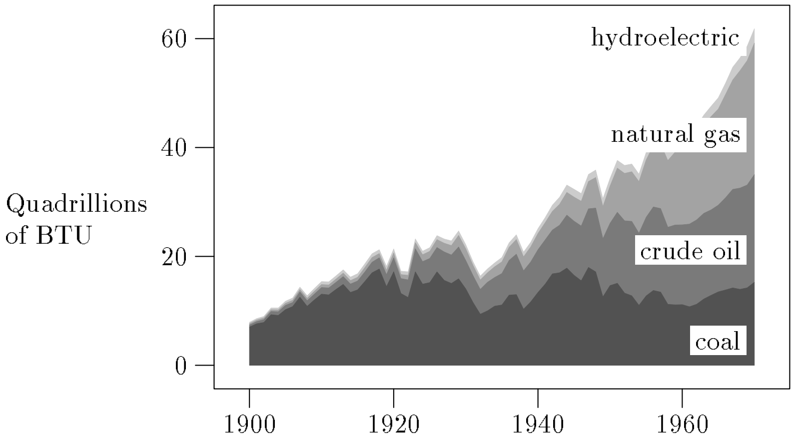


Figure 9: A graph of U.S. annual energy production and the commands that generated it

because it is perfectly adequate for font design, and it guaranteed to give identical results on all types of computers. Fixed-point numbers are seldom a problem in MetaPost because all computations are based on coordinates that are limited by the size the paper on which the output is to be printed. This does not hold for the input data in a graph-drawing application. Although graphs look best when coordinate axes are labeled with numbers of reasonable magnitude, the strict limits of fixed-point arithmetic would be inconvenient.

A simple way to handle large numbers is to include the line

```
input sarith
```

and then use binary operators `Sadd`, `Ssub`, `Smul`, and `Sdiv` in place of `+`, `-`, `*`, and `/`. These operators are inefficient but very flexible. They accept numbers or strings and return strings in exponential notation with the exponent marked by "`e`"; e.g., `"6.7e-11"` means 6.7×10^{-11}.

The unary operator[7]

`Sabs` ⟨string⟩

finds a string the represents the absolute value. Binary operators `Sleq` and `Sneq` perform numeric comparisons on strings and return boolean results.

The operation

`Scvnum` ⟨string⟩

finds the numeric value for a string if this can be done without overflowing MetaPost's fixed-point number system. If the string does not contain "`e`", it is much more efficient to use the primitive operation

`scantokens` ⟨string⟩

The above operators are based on a low-level package that manipulates numbers in "`Mlog` form." A number x in `Mlog` form represents

$$\mu^{2^{16}x}, \quad \text{where } \mu = -e^{2^{-24}}.$$

Any value between 1.61×10^{-28} and 3.88×10^{55} can be represented this way. (There is a constant `Mten` such that $k*$`Mten` represents 10^k for any integer k in the interval $[-29, 55]$.)

The main reason for mentioning `Mlog` form is that it allows graph data to be manipulated as a MetaPost path. The function

`Mreadpath(`⟨file name⟩`)`

reads a data file and returns a path where all the coordinates are in `Mlog` form. An internal variable `Gpaths` determines whether `gdraw` and `gfill` expect paths to be given in `Mlog` form. For example, this graphs the data in `agepop91.d` with y coordinates divided by one million:

```
interim Gpaths:=log;
gdraw Mreadpath("agepop91.d") shifted (0,-6*Mten);
```

4 Typesetting Numbers

The graph package needs to compute axis labels and then typeset them. The macro

`format(`⟨string expression⟩`,` ⟨numeric or string expression⟩`)`

[7] The argument to a unary operator need not be parenthesized unless it is an expression involving binary operators.

does this. You must first `input graph` or `input format` to load the macro file. The macro takes a format string and a number to typeset and returns a picture containing the typeset result. Thus

`format("%g",2+2)` yields 4

and

`format("%3g","6.022e23")` yields 6.02×10^{23}

A format string consists of

- an optional initial string not containing a percent sign,
- a percent sign,
- an optional numeric precision p,
- one of the conversion letters `e`, `f`, `g`, `G`,
- an optional final string β.

The initial and final strings are typeset in the default font (usually `cmr10`), and the typeset number is placed between them. For the `e` and `g` formats, the precision p is the number of significant digits allowed after rounding; for `f` and `G`, the number is rounded to the nearest multiple of 10^{-p}. If the precision is not specified, the default is $p = 3$. The `e` format always uses scientific notation and the `f` format uses ordinary decimal notation but reverts to scientific notation if the number is at least 10000. The `g` and `G` formats also revert to scientific notation for non-zero numbers of magnitude less than 0.001.

The `format` macro needs a set of templates to determine what font to use, how to position the exponent, etc. The templates are normally initialized automatically, but it is possible to set them explicitly by passing five picture expressions to `init_numbers`. For instance, the default definition for TeX users is

```
init_numbers(btex$-$etex, btex$1$etex, btex${\times}10$etex,
    btex${}^-$etex, btex${}^2$etex)
```

The first argument tells how to typeset a leading minus sign; the second argument is an example of a 1-digit mantissa; third comes whatever to put after the mantissa in scientific notation; next come a leading minus sign for the exponent and a sample 1-digit exponent.

Picture variable `Fe_plus` gives a leading plus sign for positive numbers, and `Fe_base` gives whatever should precede the exponent when typesetting a power of ten. Calling `init_numbers` initializes `Fe_plus` to an empty picture and constructs `Fe_base` from its second and third arguments.

5 Conclusion

The graph package makes it convenient to generate graphs from within the MetaPost language. The primary benefits are the power of the MetaPost language and its ability to interact with TeX or troff for typesetting labels. Typeset labels can be stored in picture variables and manipulated in various ways such measuring the bounding box and providing a white background.

We have seen how to generate shaded regions and control line width, color, and styles of dashed lines. Numerous other variations are possible. The full MetaPost language [5] provides many other potentially useful features. It also has enough computing power to be useful for generating and processing data.

A Summary of the Graph Package

In the following descriptions, italic letters such as w and h denote expression parameters and words in angle brackets denote other syntactic elements. Unless specified otherwise, expression parameters can be either numerics or strings. An ⟨option list⟩ is a list of drawing options such as `withcolor .5white` or `dashed evenly`; a ⟨label suffix⟩ is one of `lft`, `rt`, `top`, `bot`, `ulft`, `urt`, `llft`, `lrt`.

A.1 Graph Administration

`begingraph(`w`,`h`)` Begin a new graph with the frame width and height given by numeric parameters w and h.

`endgraph` End a graph and return the resulting picture.

`setcoords(`t_x`,` t_y`)` Set up a new coordinate system as specified by numeric flags t_x, t_y. Flag values are ±`linear` and ±`log`.

`setrange(`⟨coordinates⟩`,` ⟨coordinates⟩`)` Set the lower and upper limits for the current coordinate system. Each ⟨coordinates⟩ can be a single pair expression or two numeric or string expressions.

A.2 Drawing and Labeling

All of the drawing and labeling commands can be followed by an ⟨option list⟩. In addition to the usual MetaPost drawing options, the list can contain a `plot` ⟨picture⟩ clause to plot a specified picture at each data point.

The drawing and labeling commands are closely related to a set of similarly named commands in plain MetaPost. The `gdrawarrow` and `gdrawdblarrow` commands are included to maintain this relationship.

`gdotlabel.`⟨label suffix⟩`(`p`,` ⟨location⟩`)` This is like `glabel` except it also puts a dot at the location being labeled.

`gdraw` p Draw path p, or if p is a string, read coordinate pairs from file p and draw a polygonal line through them.

`gdrawarrow` p This is like `dgraw` p except it adds an arrowhead at the end of the path.

`gdrawdblarrow` p This is like `dgraw` p except it adds an arrowheads at each end of the path.

`gfill` p Fill cyclic path p or read coordinates from the file named by string p and fill the resulting polygonal outline.

`glabel.`⟨label suffix⟩`(`p`,` ⟨location⟩`)` If p is not a picture, it should be a string. Typeset it using `defaultfont`, then place it near the given location and offset as specified by the ⟨label suffix⟩. The ⟨location⟩ can be x and y coordinates, a pair giving x and y, a numerc value giving a time on the last path drawn, or `OUT` to label the outside of the graph.

A.3 Grids, Tick Marks, and Framing

`auto.`⟨`x` or `y`⟩ Generate default x or y coordinates for tick marks.

`autogrid(`⟨axis label command⟩`,` ⟨axis label command⟩`)` Draw default axis labels using the specified commands for the x and y axes. An ⟨axis label command⟩ may be ⟨empty⟩ or it may be `itick`, `otick`, or `grid` followed by a ⟨label suffix⟩.

`frame.`⟨label suffix⟩ ⟨option list⟩ Draw a frame around the graph, or draw the part of the frame specified by the ⟨label suffix⟩.

`grid.`⟨label suffix⟩`(`f`,`z`)` Draw a grid line across the graph from the side specified by the ⟨label suffix⟩, and label it there using format string f and coordinate value z. If f is a picture, it gives the label.

`itick.`⟨label suffix⟩`(`f`,`z`)` This is like `grid` except it draws an inward tick mark.

`otick.`⟨label suffix⟩`(`f`,`z`)` This is like `grid` except it draws an outward tick mark.

A.4 Miscellaneous Commands

`augment.`⟨variable⟩`(`⟨coordinates⟩`)` Append ⟨coordinates⟩ to the path stored in ⟨variable⟩.

`format(`f`,` x`)` Typeset x according to format string f and return the resulting picture.

`gdata(`f`,` ⟨variable⟩`,` ⟨commands⟩`)` Read the file named by string f and execute ⟨commands⟩ for each input line using the ⟨variable⟩ as an array to store data fields.

`init_numbers(`s`,` m`,` x`,` t`,` e`)` Provide five pictures as templates for future `format` operations: s is a leading minus; m is a sample mantissa; x follows the mantissa; t is a leading minus for the exponent e.

`Mreadpath(`f`)` Read a path for the data file named by string f and return it in "`Mlog` form".

A.5 Arithmetic on Numeric Strings

It is necessary to `input sarith` before using the following macros:

`Sabs` x Compute $|x|$ and return a numeric string.

x `Sadd` y Compute $x + y$ and return a numeric string.

`Scvnum` x Return the numeric value for string x.

x `Sdiv` y Compute x/y and return a numeric string.

x `Sleq` y Return the boolean result of the comparison $x \leq y$.

x `Smul` y Compute $x * y$ and return a numeric string.

x `Sneq` y Return the boolean result of the comparison $x \neq y$.

x `Ssub` y Compute $x - y$ and return a numeric string.

A.6 Internal Variables and Constants

`Autoform` Format string used by `autogrid`. Default: `"%g"`.

`Fe_base` What precedes the exponent when typesetting a power of ten.

`Fe_plus` Picture of the leading plus sign for positive exponents.

`Gmarks` Minimum number of tick marks per axis for `auto` and `autogrid`. Default: 4.

`Gminlog` Minimum largest/smallest ratio for logarithmic spacing with `auto` and `autogrid`. Default: 3.0.

`Gpaths` Code for coordinates used in `gdraw` and `gfill` paths: `linear` for standard form, log for "`Mlog` form".

`Mten` The "`Mlog` form" for 10.0

B New Language Features

The `graph.mp` macros and the arithmetic routines in `marith.mp` and `sarith.mp` use various language features that were introduced in Version 0.60 of the MetaPost language. We summarize these features here because they are not covered in existing documentation [5, 6]. Also new is the built-in macro

`image(`⟨drawing commands⟩`)`

that was used in Section 2.4 to find the picture produced by a sequence of drawing commands.

B.1 Reading and Writing Files

A new operator

`readfrom` ⟨file name⟩

returns a string giving the next line of input from the named file. The ⟨file name⟩ can be any primary expression of type string. If the file has ended or cannot be read, the result is a string consisting of a single null character. The preloaded `plain` macro package introduces the name `EOF` for this string. After `readfrom` has returned `EOF`, additional reads from the same file cause the file to be reread from the start.

The opposite of `readfrom` is the command

`write` ⟨string expression⟩ `to`⟨file name⟩

This writes a line of text to the specified output file, opening the file first if necessary. All such files are closed automatically when the program terminates. They can also be closed explicitly by using `EOF` as the ⟨string expression⟩. The only way to tell if a `write` command has succeeded is to close the file and use `readfrom` to look at it.

B.2 Extracting Information from Pictures

MetaPost pictures are composed of stroked lines, filled outlines, pieces of typeset text, clipping paths, and `setbounds` paths. (A `setbounds` path gives an artificial bounding box as is needed for TeX output.) A picture can have many components of each type. They can be accessed via an iteration of the form

`for` ⟨symbolic token⟩ `within` ⟨picture expression⟩`:` ⟨loop text⟩ `endfor`

The ⟨loop text⟩ can be anything that is balanced with respect to `for` and `endfor`. The ⟨symbolic token⟩ is a loop variable that scans the components of the picture in the order in which they were drawn. The component for a clipping or `setbounds` path includes everything the path applies to. Thus if a single clipping or `setbounds` path applies to everything in the ⟨picture expression⟩, the whole picture could be thought of as one big component. In order to make the contents of such a picture accessible, the `for`...`within` iteration ignores the enclosing clipping or `setbounds` path in this case.

Once the `for`...`within` iteration has found a picture component, there are numerous operators for identifying it and extracting relevant information. The operator

`stroked` ⟨primary expression⟩

tests whether the expression is a known picture whose first component is a stroked line. Similarly, the `filled` and `textual` operators return `true` if the first component is a filled outline or a piece of typeset text. The `clipped` and `bounded` operators test whether the argument is a known picture that starts with a clipping path or a `setbounds` path. This is true if the first component is clipped or bounded or if the entire picture is enclosed in a clipping or `setbounds` path.

There are also numerous part extraction operators that test the first component of a picture. If `p` is a picture and `stroked p` is true, `pathpart p` is the path describing the line that got stroked, `penpart p` is the pen that was used, `dashpart p` is the dash pattern, and the color is

`(redpart p, greenpart p, bluepart p)`

If the line is not dashed, `dashpart p` returns an empty picture.

The same part extraction operators work when `filled p` is true, except that `dashpart p` is not meaningful in that case. For text components, `textual p` is true, `textpart p` gives the text that got typeset, `fontpart p` gives the font that was used, and `xpart p`, `ypart p`, `xxpart p`, `xypart p`, `yxpart p`, `yypart p` tell how the text has been shifted, rotated, and scaled. The `redpart`, `greenpart`, and `bluepart` operators also work for text components.

When `clipped p` or `bounded p` is true, `pathpart p` gives the clipping or `setbounds` path and the other part extraction operators are not meaningful. Such non-meaningful part extractions do not generate errors—they return null values instead: the trivial path `(0,0)` for `pathpart`, `nullpen` for `penpart`, an empty picture for `dashpart`, zero for `redpart`, `greenpart`, `bluepart`, and the null string for `textpart` or `fontpart`.

One final operator for extracting information from a picture is

`length` ⟨picture primary⟩

This returns the number of components that a `for`...`within` iteration would find.

B.3 Other New Features

The `marith.mp` and `sarith.mp` packages use numbers of magnitude 4096 more. Since such numbers can cause overflow problems in MetaPost's linear equation solving and path fitting algorithms, they are normally allowed only as intermediate results. This limitation is removed when the internal variable `warningcheck` is zero. In earlier versions of MetaPost, the limitation could be removed for variables but explicit constants were always restricted to be less than 4096.

For completeness, we also mention one other new feature of MetaPost Version 0.60. When TEX material is included in a picture via the `btex`...`etex` feature, the thickness of horizontal and vertical rules gets rounded to exactly the right number of pixels; i.e., interpreting MetaPost output according to the PostScript® scan conversion rules [7] makes the pixel width equal to the ceiling of the unrounded width. In fact, a similar relationship holds for all line widths. The generated PostScript sets line widths by first transforming to device coordinates and rounding appropriately.

Atts.
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Drawing Graphs with MetaPost

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ABSTRACT

This paper describes a graph-drawing package that has been implemented as an extension to the MetaPost graphics language. MetaPost has a powerful macro facility for implementing such extensions. There are also some new language features that support the graph macros. Existing features for generating and manipulating pictures allow the user to do things that would be difficult to achieve in a stand-alone graph package.