DAG— A Program that Draws Directed Graphs

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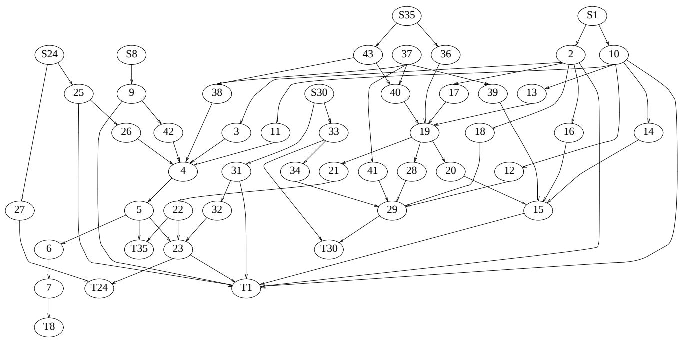
ABSTRACT

dag is a *pic* or POSTSCRIPT preprocessor that draws directed graphs. It works well on acyclic graphs and other graphs that can be drawn as hierarchies. Graph descriptions contain nodes, edges, and optional control statements. Here is a drawing of a graph from Forrester's book, *World Dynamics* (Wright-Allen, Cambridge, MA, 1971). It took 2.1 CPU seconds on a VAX-8650 to make this drawing.



I. Introduction

Directed graphs have many applications in computing, such as describing data structures, finite automata, data flow, procedure calls, and software configuration dependencies. A picture is a good way to represent a directed graph. It is seldom easy to understand much about a graph from a list of edges, but with a picture one can quickly find individual nodes, groups of related nodes, and trace paths in the graph. The main obstacle is that it can be difficult and tedious to draw graphs by hand.

dag is a program that draws directed graphs from edge lists. It does particularly well on acyclic graphs such as trees, DAGs, and other hierarchical graphs. It reads descriptions in a concise language and makes *pic* [K82] or POSTSCRIPT [A85] drawings. As a *pic* pre-processor, *dag* fits in the troff pipeline:

```
dag file | pic | troff
```

II. Basics

This section describes how to give a basic description of a graph as a list of edges. Figure 1 shows a *dag* description, and a reduced copy of the resulting picture.

```
.GS 4 4
"5th Edition"     "6th Edition" "PWB 1.0";
"6th Edition"     "Interdata" "Wollongong"
                  "Mini Unix" "1 BSD" "LSX";
"Interdata"       "7th Edition" "Unix/TS 3.0"
                  "PWB 2.0";
"7th Edition"     "8th Edition" "32V" "V7M"
                  "Ultrix–11" "Xenix" "UniPlus+";
"V7M"             "Ultrix–11";
"8th Edition"     "9th Edition";
"1 BSD"           "2 BSD";
"2 BSD"           "2.8 BSD";
"2.8 BSD""2.9 BSD" "Ultrix–11";
"32V"             "3 BSD";
"3 BSD"           "4 BSD";
"4 BSD"           "4.1 BSD";
"4.1 BSD""4.2 BSD" "2.8 BSD" "8th Edition";
"4.2 BSD""4.3 BSD" "Ultrix–32";
"PWB 1.0""PWB 1.2" "USG 1.0";
"PWB 1.2""PWB 2.0";
"USG 1.0""CB Unix 1" "USG 2.0";
"CB Unix 1"       "CB Unix 2";
"CB Unix 2"       "CB Unix 3";
"CB Unix 3"       "Unix/TS++" "PDP–11 Sys V";
"USG 2.0""USG 3.0";
"USG 3.0""Unix/TS 3.0";
"PWB 2.0""Unix/TS 3.0";
"Unix/TS 1.0"     "Unix/TS 3.0";
"Unix/TS 3.0"     "TS 4.0";
"Unix/TS++"       "TS 4.0";
"CB Unix 3"       "TS 4.0";
"TS 4.0"          "System V.0";
"System V.0"      "System V.2";
"System V.2"      "System V.3";
.GE
```

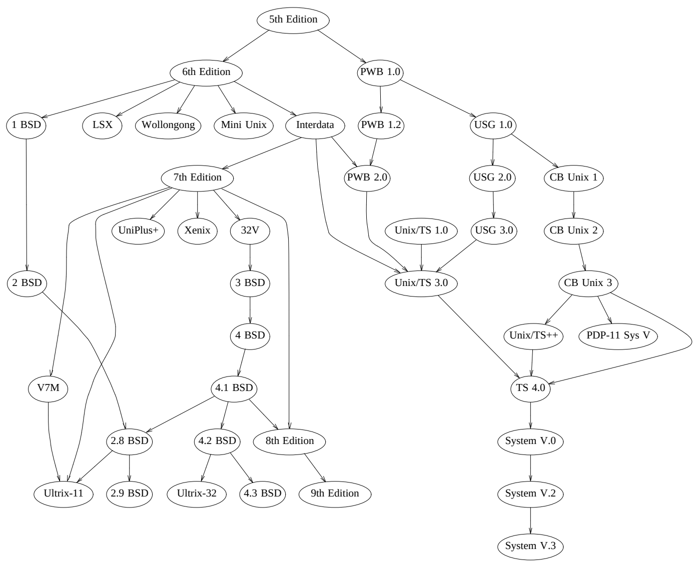


Figure 1

Graph descriptions begin with `.GS` and end with `.GE`. (In other versions of Unix, *dag* recognizes `GD` instead of `GS`.) If the maximum width and height of the drawing are given on the `GS` line, the drawing is scaled appropriately. The drawing in Figure 1 has a 4 inch by 4 inch bounding box.

A graph description is a list of semicolon-terminated statements. All the statements in Figure 1 are *edge* statements that name a tail node and a list of head nodes. Edges fan out from the tail node. The statement `"5th Edition" "6th Edition" "PWB 1.0";` makes an edge from `5th Edition` to `6th Edition`, and another from `5th Edition` to `PWB 1.0`. Because the syntax of edge statements is simple, graph descriptions can be generated from the output of other tools, such as **cflow**, profilers, or **make** utilities, without much effort. There is also a verbose form for edge statements:

```
edge from "5th Edition" to "6th Edition", to "PWB 1.0";
```

The keywords `edge`, `from`, `to`, and commas are optional. Node names may be quoted to protect white space, punctuation, or *dag* keywords.

As shown, *dag* places nodes in ranks so that edges point downward if possible. Nodes are ordered from left to right within ranks to reduce edge crossings and long edges. If there are cycles in the graph it is not possible for all edges to point downward, so some edges will be inverted. For instance, the following graph contains a cycle $a \rightarrow b \rightarrow c \rightarrow a$, so the edge $c \rightarrow a$ points upward.

```
.GS
edge from a to b;
edge from b to c;
edge from c to a;
.GE
```

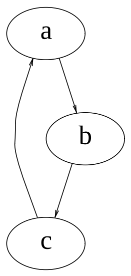


Figure 2

Edges that point backward can be made:

```
.GS
backedge from a to b;
edge from b to c;
edge from c to a;
.GE
```

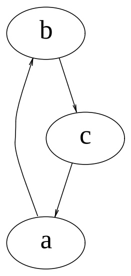


Figure 3

Path statements create chains of edges. Here is a way to rewrite part of the description of Figure 1:

```
path from "Unix/TS 1.0" to "Unix/TS 3.0" to "TS 4.0" to "System V.0";
```

Beginning a graph description with `.GR` instead of `.GS` makes edges point from left-to-right as shown in Figure 4.

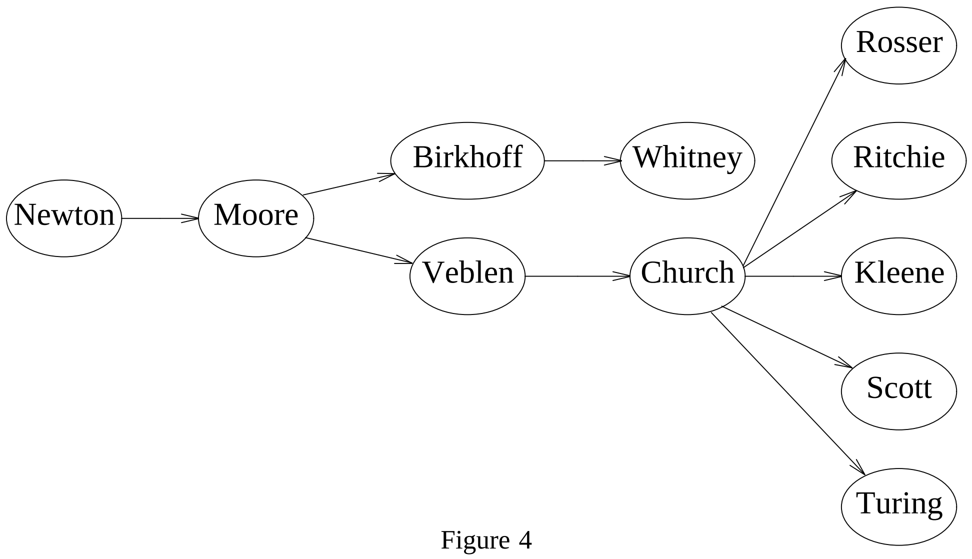


Figure 4

A backpath is a chain of back-edges.

```
backpath from Subaru to Honda to Ferrari;
```

III. Node Attributes

This section explains how to control the way nodes are drawn. The node attributes are shape, size, label, pointsize of the label, and color. By default nodes are drawn as ½´´ by ¾´´ ellipses labeled with the node name in 14-point type. The size may be increased to fit the label.

`draw nodes` sets default attributes for nodes created afterward in a graph description; nodes already created are not affected. `draw` *nodelist* sets attributes of individual nodes. Nodes in the *nodelist* are created if they do not already exist.

III.1 Node Shapes

The pre-defined shapes are `Box`, `Square`, `Circle`, `Doublecircle`, `Ellipse`, `Diamond`, and `Plaintext`. Shape names are capitalized to avoid conflict with *pic* keywords. Here is an example involving node shapes:

```
edge from a to b;
draw ETA, Apollo, NeXT as Box;
draw nodes as Plaintext;
edge from x to y;
```

`a` and `b` are drawn as ellipses; `ETA`, `Apollo`, and `NeXT` as boxes; and `x` and `y` as `Plaintext` because `Plaintext` became the default before `x` and `y` were created.

User-defined node shapes are created by writing *pic* macros or POSTSCRIPT procedures. Shapes have three arguments: the node label, width, and height. In a *pic* macro these are `$1, $2,` and `$3`. In a POSTSCRIPT procedure the arguments are passed on the stack. To draw a node, *dag* moves to its center point and calls the shape with the necessary arguments. It is usually convenient to define macros within the graph description in a block between `.PS` and `.PE`. The contents of this block are passed straight through *dag* and appear in the graphics code after the standard prologue but before any nodes or edges are drawn.

There are two limitations on user-defined shapes. First, *dag* assumes height and width and independent. So if a user-defined shape has a fixed aspect ratio, fine-tuning may be needed to make the drawing look right. Second, because *dag* doesn't know how to compute the boundary of user-defined shapes, and *pic* macros aren't general enough for the job, edges in *pic* drawings are clipped to a node's bounding rectangle. The second limitation does not apply to shapes written in POSTSCRIPT since the user also supplies a clipping procedure (see Appendix B). Figure 5 shows an example shape macro in *pic*.

III.2 Node Labels

The default label of a node is its name. Another label can be set, which is particularly useful to allow distinct nodes to share a common label.

```
draw "/usr/src/cmd" label "cmd";
draw "/usr/local/src/cmd" label "cmd";
```

III.3 Node Colors

Nodes may have color in POSTSCRIPT drawings. A color value is a string that is passed to the procedure `dagsetcolor` in the emitted POSTSCRIPT code. In the standard POSTSCRIPT prologue this procedure accepts a hue-saturation-brightness triple. Macros for common colors can be defined in a `.PS/.PE` block:

```
.GS
.PS
define Triplecircle % [
            circle rad .5  * $2;
            circle rad .475 * $2 at last circle.c;
            circle rad .45  * $2 at last circle.c;
            $1 at last circle.c;
      ] %
.PE
edge from 1 to 2;
draw 1 as Triplecircle height 1 width 1;
draw 2 as Circle height 1 width 1;
.GE
```

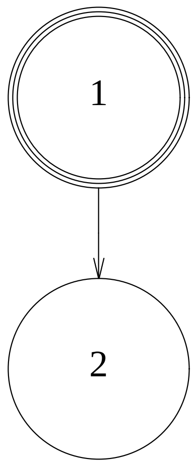


Figure 5

```
.PS
/red [.1 1 1] def
.PE
draw important_node color red;
```

Other interpretations of color values may be implemented by redefining `dagsetcolor` and defining compatible node shapes. Appendix B explains how to make gray-scale shaded nodes this way.

IV. Edge Attributes

This section explains how to control the way edges are drawn. The edge attributes are label, pointsize of the label, ink style, color, and weight. Attributes may be set when edges are created. `draw edges` sets default attributes for edges created afterward in the graph description. Previously created edges cannot be changed because unlike nodes, edges do not have identifiers.

IV.1 Edge Labels

A label is a text string or fragment of executable graphics code drawn at the midpoint of an edge. Text labels are preferred. Graphics code is available for extreme cases, but it is discouraged because it is dependent on the target graphics language. Graphics code is enclosed in curly braces as shown below.

```
edge from a to b label "x" ;
edge from b to c label {circle rad .1};
```

Figure 6 is the description of a finite automaton with labeled edges and its picture.

IV.2 Edge Weights

Edge weights or costs are integers. Increasing the weight of an edge makes *dag* try to shorten it. The default weight is 1; *dag* internally increases the weight of long edges to improve the drawing. In the Unix History graph of Figure 1, we might want to favor the edge `"2 BSD" "2.8 BSD"` over `"4.1 BSD" "2.8 BSD"`. This suggests:

```
edge from "2 BSD" to "2.8 BSD" weight 1000;
```

It's best to use large values to swamp the internal adjustment, otherwise a little experimenting with weights will probably be needed.

```
.GR 6
draw nodes as Circle width .5 height .5;
draw LR_0 LR_3 LR_4 LR_8 as Doublecircle width .5 height .5;
draw edges pointsize 8;
LR_0 LR_2 label "SS(B)";
LR_0 LR_1 label "SS(S)";
LR_1 LR_3 label "S($end)";
LR_2 LR_6 label "SS(b)";
LR_2 LR_5 label "SS(a)";
LR_2 LR_4 label "S(A)";
LR_5 LR_7 label "S(b)";
LR_5 LR_5 label "S(a)";
LR_6 LR_6 label "S(b)";
LR_6 LR_5 label "S(a)";
LR_7 LR_8 label "S(b)";
LR_7 LR_5 label "S(a)";
LR_8 LR_6 label "S(b)";
LR_8 LR_5 label "S(a)";
.GE
```

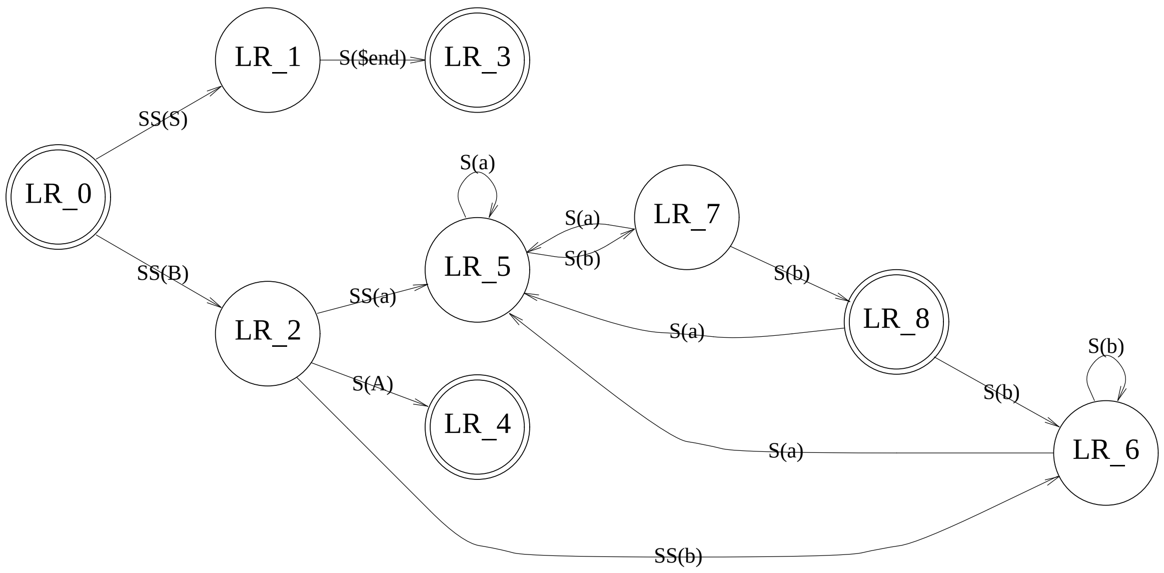


Figure 6

IV.3 Edge Styles

The graph description may name the ‘‘ink’’ or line style for edges: `solid`, `dotted`, `dashed`, or `invis`.

```
edge from "2 BSD" to "2.8 BSD" dashed;
```

Unfortunately *troff* does not have dotted or dashed splines so they appear as solid splines in *pic* output.

IV.4 Edge Colors

Edge colors are much like node colors.

```
edge from "2 BSD" to "2.8 BSD" color "[.2 1 1 ]";
draw edges "[.3 .5 .5]";
```

V. Spacing Control

Separate statements set the minimum spacing in inches between adjacent nodes or ranks.

```
separate nodes .75;
separate ranks 2;
separate ranks 2 exactly;
separate ranks 2 equally;
```

Because some drawings have edges that are almost horizontal and thus hard to read, *dag* may increase the separation between certain ranks to improve the drawing. When this happens, a side-effect is that ranks are not equally spaced. The adverb ‘‘`equally`’’ tells *dag* to maintain even spacing between ranks, which may be more aesthetically pleasing and readable. ‘‘`exactly`’’ inhibits the rank spacing adjustment.

Another kind of spacing control is requested by putting the keyword `fill` on the `GS` line. This forces the drawing to fill the bounding box by increasing the node and rank separations. `fill` overrides ‘‘`separate ranks exactly`’’. For example:

```
.GS 6 8 fill
```

VI. Rank Assignment Control

The graph description may state that certain nodes should be placed on the minimum or maximum rank, or be kept as a group on the same rank.

```
minimum rank root1 root2 root3;
maximum rank leaf38 leaf39;
same rank add sub mul div shift;
```

Figure 7 is another drawing of Forrester’s *World Dynamics* graph. In this drawing, (1) source nodes *S1*, *S8*, *S24*, *S30* and *S35* are constrained to appear at the minimum rank, (2) target nodes *T1*, *T8*, *T24*, *T30* and *T35* are to appear at the maximum rank, and (3) all other nodes stay at the same ranks as in the drawing of the abstract.

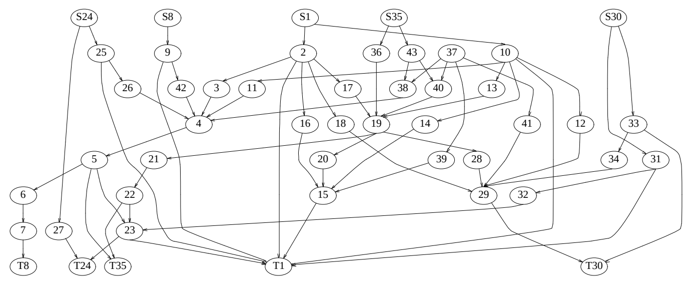


Figure 7

Figure 8 illustrates how a time-line can be created with `same rank` statements.

Forcing a group of nodes to be on the same rank can cause *flat*-edges, i.e., edges that point sideways instead of upward or downward. If possible, *dag* draws flat-edges from left to right. (This means that, as a side-effect, left-to-right order in a rank can be controlled by creating invisible flat-edges.) Figure 9 shows a graph description in which the relative placements of nodes are completely specified. The edge crossing is unavoidable.

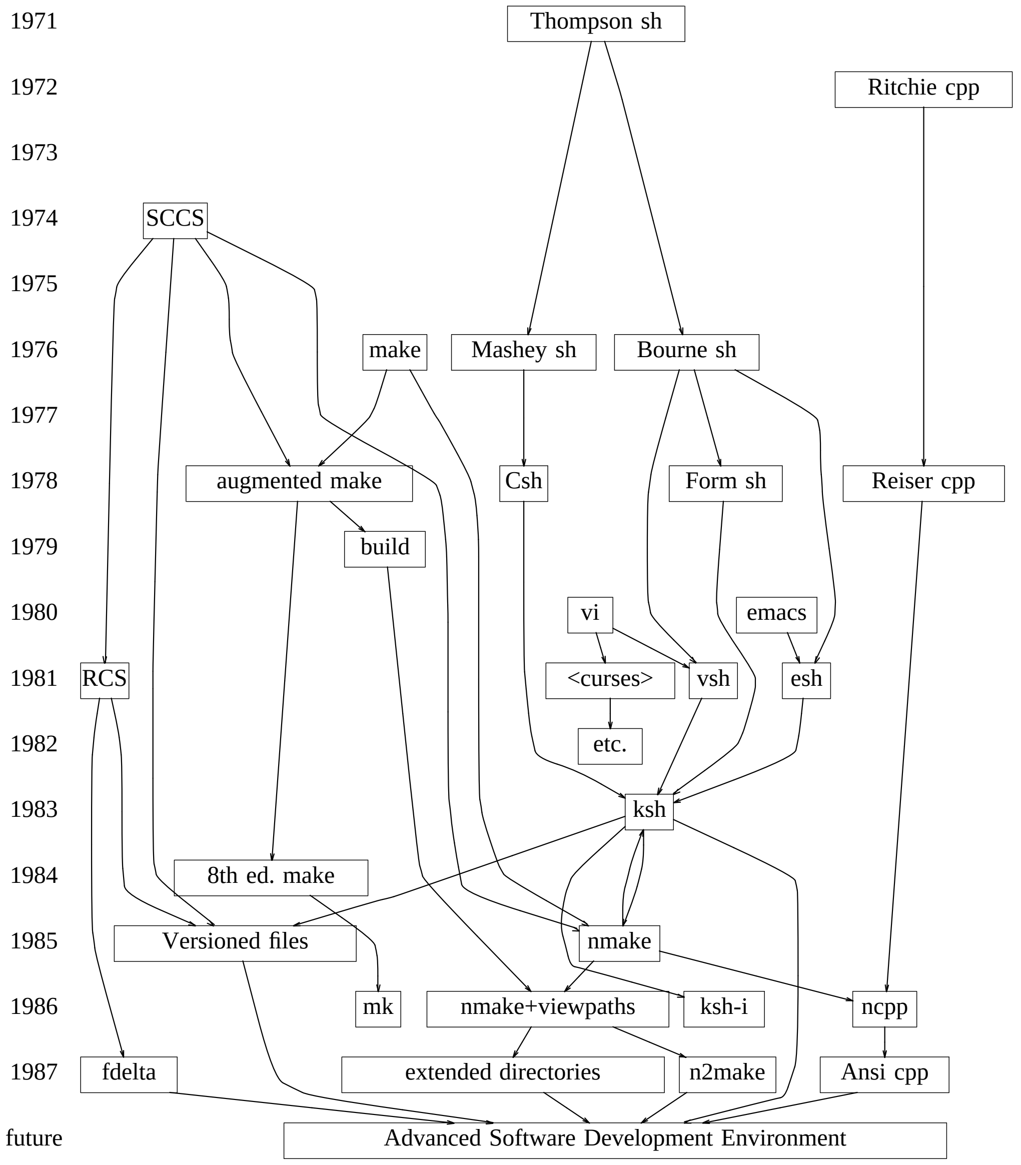


Figure 8

If edges are `ordered`, *dag* automatically places head nodes on the same rank and creates invisible flat-edges. Figure 10 is a small part of a parse tree. Ordered edges are needed to correctly represent the grammar.

```
.GS
same rank 1 2;
same rank 3 4;
1 4;
2 3;
1 2 invis;
3 4 invis;
.GE
```

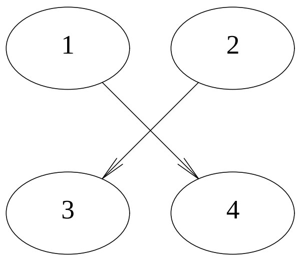


Figure 9

```
.GS
ordered edge from "for–stmt" to "for" "var" "=" "expr1" "to" "expr2";
ordered edge from "expr1" to "left_op" "*" "right_op";
.GE
```

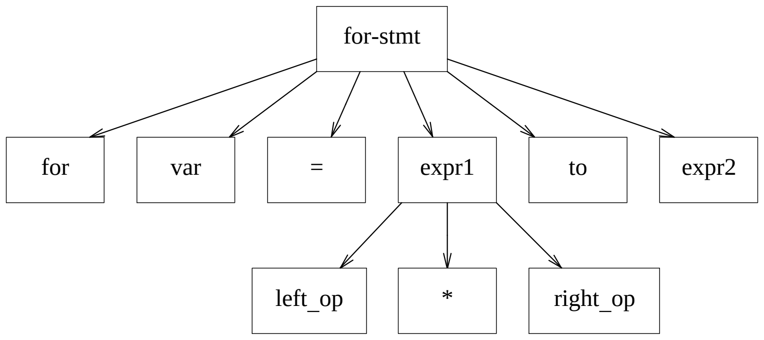


Figure 10

There are many other properties of a graph drawing that one might want to control, but it is difficult to build a good tool that achieves many, possibly conflicting, aesthetic goals. Users can exercise some control over node placement by setting edge weights and creating invisible edges. For finer control over drawings we suggest changing the drawing with a graphical editor or by modifying the generated code.

There are no absolute restrictions on the graphs that *dag* can draw. Self-edges and multi-edges are allowed. For picture clarity, it's best to avoid nodes with many incident edges. For instance, in procedure call graphs, it is a good idea to eliminate common library calls (*e.g.*, `stdio`) before making the drawing. Removing these less interesting nodes both yields a more informative drawing and reduces run time.

VII. Drawing Algorithms

dag has three main components: the parser, *draw_dag*, and the code generator. The parser is written in YACC. It constructs a graph of attributed nodes and edges in memory. The graph is passed to the drawing procedure *draw_dag*, which sets *X* and *Y* coordinates of nodes and spline control points of edges. The code generator traverses the attributed graph to emit target code in an obvious fashion. *draw_dag* is thus the heart of *dag*.

To design algorithms for drawing graphs, we need to define what makes a good drawing. We have chosen three desirable properties for drawings of directed graphs:

P1. The drawing should reveal the partial order implied by edges of the graph. Nodes are placed in ranks so that edges points downward. If the graph is not acyclic, cycles are broken by reversing edges.

P2. The drawing should not be cluttered with irrelevance. For example, edge crossings are undesirable because they suggest a connection that is not really present in the underlying abstract graph. Edges also should not intersect nodes that are not their endpoints.

P3. The drawing should reveal the relationships implied by edges by placing adjacent nodes in the graph close together.

Unfortunately, these goals conflict. For instance, the placement of nodes in ranks may make it impossible to avoid edge crossings. Also, the minimization of edge-crossings in a layout is computationally intractable. So we are satisfied to find heuristics that run quickly and make good layouts in common cases. We sketch these techniques briefly as an aid to understanding the behavior of *dag*.

draw_dag has four passes. The first pass finds an optimal rank assignment for the nodes, satisfying P1 and P3. The optimal rank assignment problem is to assign integer ranks to nodes such that the sum of the weighted edge lengths is minimized. The length of an edge here is taken as the difference in the ranks of its head and tail nodes. The optimal rank assignment problem can be formulated as an integer program. Because of its special characteristics the simplex method for linear programming can be used to solve these integer programs. However we have developed a combinatorial algorithm that finds the solution in a factor of $O(|E|)$ less time than the standard simplex algorithm and uses only $O(|E|)$ space. Following rank assignment, *draw_dag* creates dummy nodes where long edges cross ranks. The placement of dummy nodes determines edge crossings and is also an aid to drawing splines for long edges. Consequently, optimal rank assignment is important not only for drawing quality, but also to minimize the number of dummy nodes. This reduces edge crossing and improves the running time of subsequent passes that have a factor of $O(|V|)$ in their running time.

The second pass orders nodes from left to right within ranks. This pass tries to reduce edge crossings (P2) subject to the constraints on node order implied by flat edges (P1). It is based on an iterative technique like that of [S81][R86]. The key improvements are a new weight function and local optimizations. We call the weight function the ‘‘generalized median’’; it produces less crossings by reducing the effects of widely spread nodes, and is inexpensive to compute. Informally, the generalized median of a node with respect to an adjacent rank is defined as follows. When the number of neighbors of a node in the concerned adjacent rank is odd, the generalized median is simply the median position of its neighbors. When the number of neighbors is even, the generalized median is in between the left and the right median positions. The exact value is tilted toward the side where neighbor nodes are more tightly packed.

The generalized median heuristic (and other similar heuristics) tends to work better if the initial order of nodes is good. To enhance this condition, we apply transpositions of adjacent nodes to precondition the inputs to the generalized median method and to further optimize its solutions. The transposition heuristic can be viewed as a descent method to find local optima.

The third pass assigns absolute coordinates to nodes, respecting the ordering determined by the previous pass (P3). The optimal assignment can be formulated as a set of linear constraints and an objective function involving absolute values. This can be transformed into a linear program by a standard technique that involves introducing extra variables. `dag -O` works this way. Since this pass is the bottleneck in *draw_dag*, we have developed a fast heuristic based on computation of the generalized median positions of adjacent nodes with additional local optimizations.

The final pass finds the spline control points for edges. There are several cases to consider, including self-edges, edges between nodes on the same rank, adjacent ranks, or nonadjacent ranks, possibly in the presence of multi-edges. Short edges are easy to draw; we use a single B-spline [M85] that is shaped according to the number of parallel multi-edges being drawn. Long edges, or edges that have endpoints on nonadjacent ranks, are more difficult since they may pass near other nodes and change direction. The B-spline control points are chosen for

- smoothness,
- avoiding node intersections, and
- avoiding edge crossings.

The dummy nodes are created with a height a little larger than the highest non-dummy node in the same rank, and width usually twice the default node separation. This is big enough to make a spline inside the boundaries of the dummy node, if necessary. On the other hand, if there is space next to the dummy node, it is often preferable to encroach on it to draw a smoother spline.

The edge drawing procedure in *draw_dag* visits each dummy node to choose its spline control points. If a straight line between the neighbors of the dummy node does not intersect any other node, nor change the order of edge crossings, then the dummy node is deleted (Figure 11a). This removes small bumps in the edges. Next, *draw_dag* aims the incident edges as close to the center of the dummy node box as possible, without intersecting adjacent nodes. *draw_dag* uses the points where the edges intersect the dummy node as spline control points. It also finds a third point to determine how the spline bends as it passes through the dummy node. If the intersection of the edges lies inside the dummy node (Figure 11b), *draw_dag* chooses it as the third control point. Otherwise, *draw_dag* tries to move the edges toward each other so they do intersect (Figure 11c) and again takes the intersection as the third control point. If the edges can't be made to intersect, but the angle between them is acute, *draw_dag* can still make a smooth spline by choosing the midpoint of the opposite side. When the angle is obtuse, that is, the edges are close to being parallel, then it chooses the midpoint of the dummy node box. In the latter case the spline has two points of inflection as it passes through the dummy node, which is not as smooth as the other cases which have only one, but the extra turn is necessary when an edge makes a jog as it passes through a rank near other nodes (Figure 11d).

Moving an edge may create an edge intersection near an incident real (non-dummy) node, as in Figure 11e. Such intersections are eliminated by sorting the incident edges according to the *X* coordinates of the other endpoints, and moving their nearby endpoints slightly (Figure 11f).

Tables 1-3 show the performance of *draw_dag* using various node placement methods. The tables list the time spent in the three node placement passes: time spent on level (or rank) assignment t_{level}, time spent ordering nodes within ranks to reduce edge crossings t_{cross}, and time spent finding final coordinates t_{coord}. The total time t_{total} is the sum of these plus time spent in initialization and creating splines. The times were measured on a VAX-8650 under the 4.3BSD UNIX System and averaged over 5 runs to reduce statistical fluctuation. Times were measured on three graphs, the *World Dynamics* graph from the abstract of this paper and two procedure call graphs from **C** programs. *World Dynamics* has 48 nodes and 69 edges. The initial placement has 126 crossings. *CallGraph-1* in Figure 12 has 38 nodes, 58 edges, and the initial placement has 128 crossings. *CallGraph-2* in Figure 13 is *dag*'s call graph of 170 nodes and 258 edges. Its initial placement has 1170 crossings.

We tried three algorithms for ordering of nodes within ranks: (1) *gmedian* is *dag*'s generalized median algorithm, (2) *bcenter* is the barycenter method described in [S81], and (3) *rmedian* is the ''right median'' [E86], which orders nodes using the position of the median neighbor when the number of neighbors is odd, and the right median neighbor otherwise. We also tried all three methods in combination with transposition of adjacent nodes. To simplify the comparison of relative performance, the iterative loop for minimizing edge crossing is set to terminate after exactly 20 iterations. In practice, the loop termination is determined by an adaptive parameter that depends on the convergent rate of a solution. Thus, for example, the total time for the *World Dynamics* graph using *gmedian+* is slightly higher than it would be in an actual run. The experiments show that generalized median behaves well in a variety of test cases, and in about the same run-time as the other methods. All three methods improved by adding transposition, which seems well worth the extra computational expense. In Table 1, transposition reduced edge crossing by 30%.

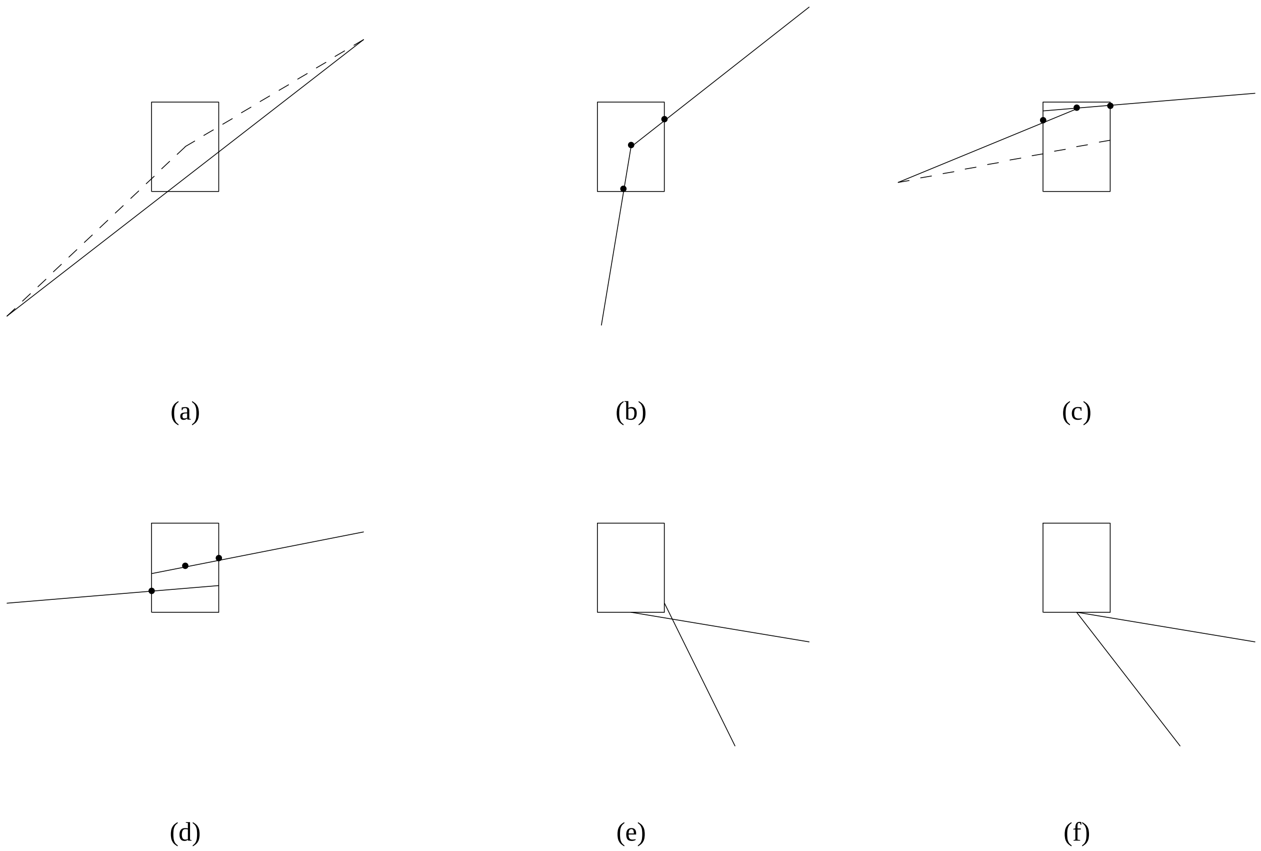


Figure 11

World Dynamics					
Method	n_{cross}	t_{level}	$t_{crossing}$	t_{coord}	t_{total}
gmedian	59	.06	.47	.56	1.18
bcenter	59	.06	.44	.47	1.08
rmedian	62	.05	.45	.51	1.11
gmedian+	41	.06	1.30	.49	1.96
bcenter+	43	.06	1.23	.50	1.88
rmedian+	47	.05	1.25	.49	1.88

Table 1

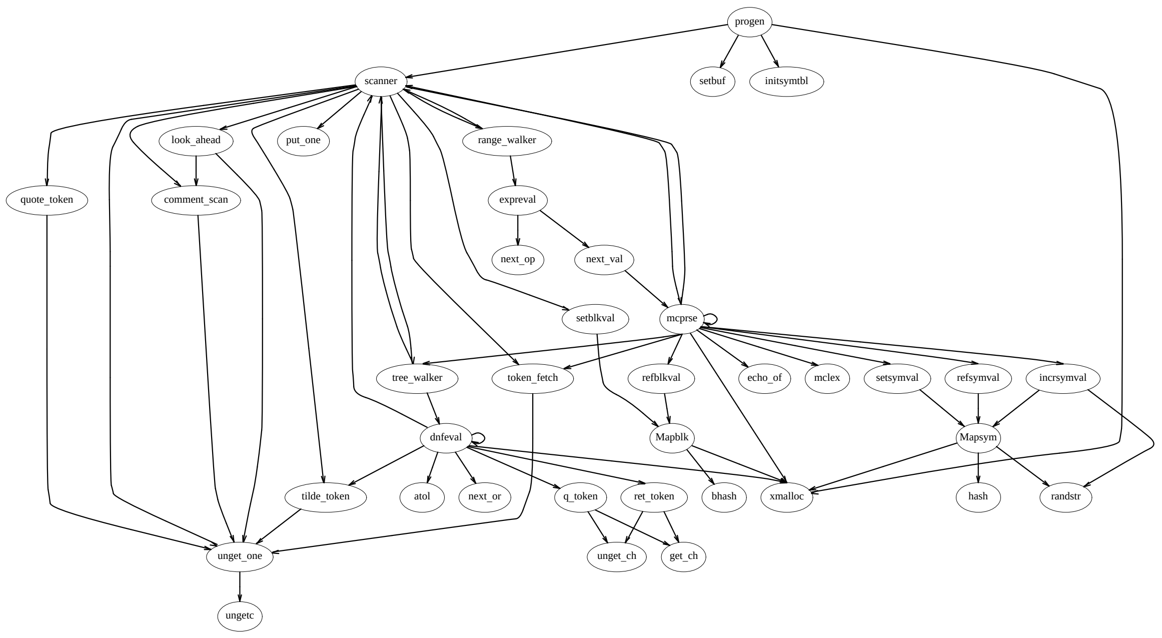


Figure 12. CallGraph-1.

CallGraph-1					
Method	n_{cross}	t_{level}	$t_{crossing}$	t_{coord}	t_{total}
gmedian	12	.04	.38	.57	1.08
bcenter	10	.04	.44	.90	1.48
rmedian	14	.04	.43	.70	1.26
gmedian+	11	.03	.73	.85	1.73
bcenter+	11	.04	.77	.64	1.56
rmedian+	11	.05	.89	.64	1.67

Table 2

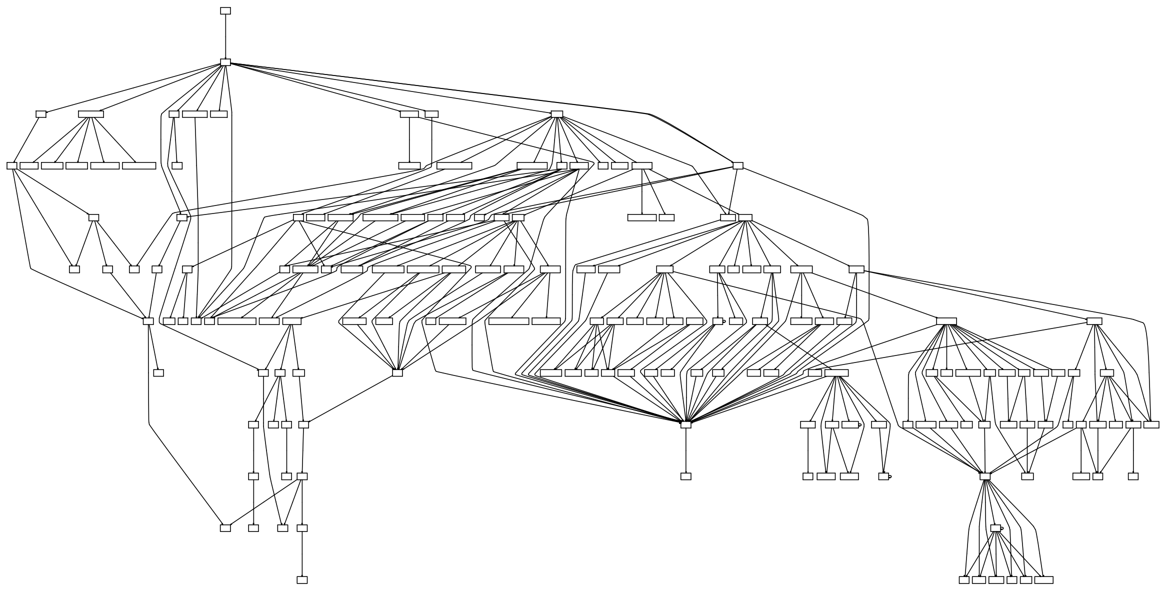


Figure 13. CallGraph-2.

CallGraph-2					
Method	n_{cross}	t_{level}	$t_{crossing}$	t_{coord}	t_{total}
gmedian	193	.50	2.87	2.91	6.52
bcenter	249	.53	2.73	2.82	6.36
rmedian	227	.53	2.96	3.07	6.84
gmedian+	154	.51	8.11	3.32	12.23
bcenter+	145	.52	8.21	3.05	12.04
rmedian+	200	.50	8.35	3.75	12.86

Table 3

VIII. Conclusions

dag is a practical tool for drawing directed graphs. We have favored ease of use over low-level drawing control, by providing a simple graph description language and a few well-tuned heuristics that produce good drawings quickly in common cases.

IX. References

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[M85] Mortenson, Michael E. *Geometric Modeling*, Wiley and Sons (1985).

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[S81] Sugiyama, K.,S. Tagawa, and M. Toda. ‘‘Methods for Visual Understanding of Hierarchical System Structures’’, *IEEE Transactions on Systems, Man, and Cybernetics* **SMC-11**:2, pp. 109-125 (February 1981).

Appendix A. DAG Syntax

```
program          :     statement-list
                 ;

statement-list   :     statement-list statement
                 |     /* empty */
                 ;

statement        :     draw-statement
                 |     edge-statement
                 |     control-statement
                 ;

draw-statement   :     draw node-list node-desc ;
                 |     draw nodes node-desc ;
                 |     draw edges edge-desc ;
                 ;

node-list        :     node-list [,] node-name
                 |     node-name
                 ;

node-desc        :     node-desc-item
                 |     node-desc node-desc-item
                 ;

node-desc-item   :     width float
                 |     height float
                 |     pointsize integer
                 |     label string
                 |     label { drawing-code }
                 |     as { drawing-code }
                 |     as string
                 |     color string
                 ;

edge-statement   :     [ordered] [[back]edge from] node-name [to] head-list ;
                 |     [back]path [from] node-name [to] head-list ;
                 ;

head-list        |     head-list head
                 |     head-list [,] [to] head
                 |     /* empty */
                 ;

head             :     node-name edge-desc
                 |     node-name
                 ;

edge-desc        :     edge-desc-item
                 |     edge-desc edge-desc-item
                 ;
```

```
edge-desc-item   :   weight integer
                 |   label string
                 |   label { drawing-code }
                 |   pointsize integer
                 |   color string
                 |   inkvalue
                 ;

inkvalue         :   solid
                 |   dashed
                 |   dotted
                 |   invis
                 ;

control-statement:   separate sep-list ;
                 |   minimum rank node-list ;
                 |   maximum rank node-list ;
                 |   same rank node-list ;
                 ;

sep-list         :   sep-list sep-item
                 |   /* empty */
                 ;

sep-item         :   nodes float
                 |   ranks float
                 |   ranks float exactly
                 |   ranks float equally
                 ;

node-name        :   string
                 ;
```

A *string* is any sequence of non-whitespace, non-punctuation characters, or any quoted string that does not contain a newline.

drawing-code is any sequence of characters containing balanced left and right curly braces.

Appendix B. PostScript Interface

`dag –Tps` generates PostScript code. The drawing is in the default PostScript coordinate system [A85]. Two procedures are needed to define a new node shape. The first draws the shape over the current point. It takes three arguments off the stack: the node width, height, and name. The second procedure computes where edges intersect the shape. Its arguments are the *x* and *y* dimensions of the shape, and a ray. The first point is the origin and the second point that defines the ray is always on the bounding box of the node when it is placed at (0,0). This procedure returns the point where the ray intersects the shape (or if it misses the shape, then the nearest point or at least the point on the bounding box that was passed as an argument). The argument points are always in the same quadrant.

For some examples of shape-drawing procedures, examine the output of `dag –Tps` for definitions of procedures such as `Ellipse` and `Ellipse_clip`.

Shaded nodes may be useful when color output is not available. Here is an example.

```
.GR
.PS
/setdagcolor {/daggrayscale exch def} def

/ShadedBox {
  /height exch def
  /width exch def
  /nodename exch def
  currentpoint 2 copy
  newpath
    moveto
    width –2 div
    height –2 div
    rmoveto
    width 0 rlineto
    0 height rlineto
    width neg 0 rlineto
  closepath
  gsave
    daggrayscale setgray
    fill
  grestore
  stroke
  moveto
  nodename width .9 mul height .9 mul daglabel
} def

/ShadedBox_clip { Box_clip } def
.PE
draw nodes as ShadedBox;
draw nodes color "1";
draw a color ".7";
draw b color ".9";
a b c;
.GE
```

`setdagcolor` is called before drawing a node or edge. The color value is emitted as POSTSCRIPT code which usually pushes something on the stack that `setdagcolor` consumes. For drawing shaded boxes, colors will be real values between 0 and 1, where 0 is black and 1 is white. Thus `setdagcolor` is redefined to store its argument it in the global variable `daggrayscale` where `ShadedBox` can find it later.

In the definition of `ShadedBox`, the path of rectangle is created and then the sequence `daggrayscale setgray fill` shades its interior. The shading is done within `gsave/grestore` because we don't want to shade the outline of the box itself, or its label.

Since `ShadedBox` has the same boundary as `Box`, `ShadedBox_clip` is implemented by calling `Box_clip`.