Using Graph-Grammar Parsing for Automatic Graph Drawing

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1.0 Introduction

Directed graphs, or digraphs, are an excellent means of conveying the structure and operation of many types of systems. They are capable of representing not only the overall structure of such a system, but also the smallest details in a simple and effective way. However, drawing digraphs by hand can be tedious and time consuming, especially if the number of vertices and arcs is large. In addition, much time can be spent just trying to plan how the graph should be organized on the page. These facts reveal the need for an automated system capable of converting a textual description of a digraph into a well organized and readable drawing of the digraph.

Many researchers have studied this problem and many graph drawing systems have been developed [see 3 for complete list]. The aesthetic criteria of the systems vary. The objectives may include requirements of uniform edge length, minimum number of edge crossings, straight edges, grid drawings (edges are either horizontal or vertical), minimal bends in the edges, minimum area covered, and display of symmetries. Some limit the input graphs to a particular class such as planar graphs, trees, graphs with maximum degree of four, or some application-specific graphs such as petri nets, network representation, digital system schematic diagrams, PERT diagrams, flowcharts, etc. CG (Clan-based Graph Drawing Tool) is a tool we use for our work with program dependency graphs. Like *dot* [10] and its predecessor DAG [9], CG takes a textual description of an arbitrary directed graph and produces a visual representation of it. CG uses a unique graph parsing method to determine intrinsic substructures in the graph and to produce a parse tree. The tree is given attributes that specify the node layout. One example attribute set is presented in this paper, but the layout can be tailored to suit different aesthetic criteria. CG then uses tree properties and adapts the work of Suigyama [12], Warfield[13], Eens [7] and Farin [8] in routing the edges. The objectives of the system are to provide an aesthetically pleasing visual layout for arbitrary directed graphs. CG incorporates techniques to reduce edge crossings, guarantee few bends in long arcs, and to shorten long arcs whenever possible.

CG is the first graph drawing tool to use a graph grammar as the fundamental structure that describes the node layout. Brandenburg [1] defines a layout graph grammar as a graph grammar together with a layout specification. The layout specification associates a finite set of layout constraints with each production. Our approach is to classify the productions of the graph parse and associate layout attributes with each production type in the parse tree of the graph.

2.0 Node Layout

The node layout is determined by the combination of (1) parsing of the graph into logically cohesive subgraphs and (2) defining layout attributes to apply to the resulting parse tree. The parse is based on a simple graph grammar, and the attributes that are now programmed into CG produce a layout whose nodes are balanced both vertically and horizontally.

2.1 Graph Decomposition

Clan-based graph decomposition (CGD) is a parse of a directed acyclic graph (DAG) into a hierarchy of subgraphs. The subgraphs defined by our graph grammar and parse are called *clans*. Let G be a DAG. A subset $X \subseteq G$ is a *clan* iff for all $x, y \in X$ and all $z \in G - X$, (a) z is an ancestor of x iff z is an ancestor of y, and (b) z is a descendant of x iff z is a descendant of y. An alternate description of a clan depicts it as a subset of vertices where every element not in the subset is related in the same way (i.e. ancestor, descendant or neither) to each member in the subset. Trivial clans include singleton sets and the entire graph. In Figure 1, sets {2,3}, {2,3,4,5,6}, {1,2,3,4,5,6}, and {2,3,4,5,6,7} are the nontrivial clans. C={2,3} is a clan since vertex 1 is an ancestor of each element of C and 5 and 7 are descendants of each element of C. The set {2,3,4} is not a clan since 6 is a descendant of only vertex 4.

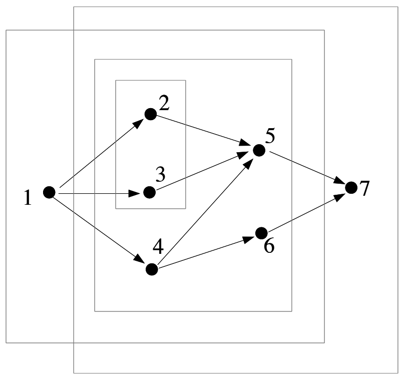


Figure 1. Clans

A simple clan *C,* with more than three vertices, is classified as one of three types. It is (i) *primitive* if the only clans in *C* are the trivial clans; (ii) *independent* if every subgraph of *C* is a clan; or (iii) *linear* if for every pair of vertices *x* and *y* in *C*, *x* is an ancestor or descendant of *y*. Independent clans are sets of isolated vertices. Linear clans are sequences of one or more vertices $v_i, v_{i+1}, \ldots, v_{j-1}, v_j$ where for $i < k$, v_i is an ancestor of v_k. Any graph can be constructed from these simple clans.

Graph-grammars

String grammars are a special case of graph-grammars. A string is isomorphic to a linear graph, and in a production of the string grammar, the replacement string is connected to the host string in a natural way.

In a sequential graph rewriting system or graph-grammar, graphs are generated from some initial graph by productions where the mother graph, a subgraph of the host graph, is replaced by another graph, the daughter graph. The main problem of graph-grammars is specifying the edges that connect the daughter graph to the host graph. The specification of the edges connecting the daughter graph to the host graph is called the *embedding rule*. More formally, a *graph-grammar* is a system $GG = (N, T, z, P, H)$ where N and T are the nonterminal and terminal vertex labels, resp., z is a vertex called the axiom or start graph, P is a set of productions and H is an embedding rule. The particular graph-grammar of the work in this paper is called the *clan generation system, CGS*. All host and daughter graphs in CGS are Hasse graphs, i.e. directed graphs with no transitive edges. The axiom is a single vertex. P is a set of pairs (v,D) where v is any graph vertex and D is a primitive, independent or linear clan.

For CGS, the reconnection rule or embedding rule is *heredity*. All host and daughter graphs in CGS are Hasse graphs, i.e. directed graphs with no transitive edges. An embedding is called *hereditary* when in-edges to the mother graph, a single vertex, are replaced with in-edges to the sources of the daughter graph and out-edges from the mother node are replaced with out-edges from the sinks of the daughter graph. More formally, let the mother graph be vertex u. For each vertex v in the set of source vertices in the daughter graph, (w,v) is an edge in the resultant graph whenever (w,u) is an edge in the host graph. For sink vertices, t, of the daughter graph,(t,w) is an edge in the resultant graph whenever (u,w) is an edge in the host graph.

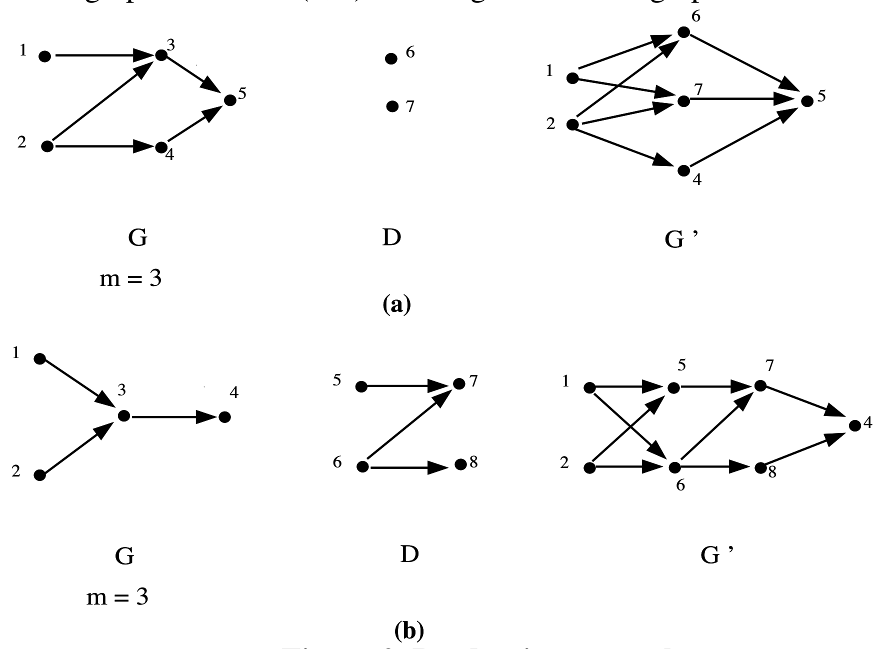


Figure 2. Production examples

Let us call a production of this system a *CGS-production*. In applications of CGS-productions, the daughter graph becomes a clan in the resultant graph. Figure 2 shows example productions with the mother vertex identified as vertex *3*.

Quotient graph

The concept of a *quotient graph* is important because it permits the classification of complex clans into the categories of linear, primitive or independent. Let C be a clan and with $\{C_1,,...C_k\}$ a partition of C where each C_i is a maximal proper subclan of C. The *quotient graph* of C denoted $C/C_1...C_k$, is the graph with vertices $C_1,...,C_k$. Pair(C_i,C_j) is an edge of $C/C_1..C_k$ iff $x \in C_i$, $y \in C_j$, and (x,y) is an edge of C. In Figure 1, the clans that partition the entire graph are: $C_1 = \{1\}$, $C_2 = \{2,3,4,5,6\}$, $C_3 = \{7\}$, and the quotient graph is linear. The clans that partition C_2 are {2,3}, {4}, {5}, and {6} and the quotient graph is primitive. Every clan can be identified as linear, primitive or independent according to the classification of its quotient graph. Figure 3(a) shows the parse tree of the graph of Figure 1.

Theorem 1: When the original graph is a Hasse graph, the graph generated by CGS is also a Hasse graph [11].

Theorem 2: Any Hasse graph can be generated by a unique canonical sequence of productions from CGS [6].

Theorem 3: For every Hasse graph there is a unique decomposition into quotient graphs that are identified as linear, primitive or independent [5,6].

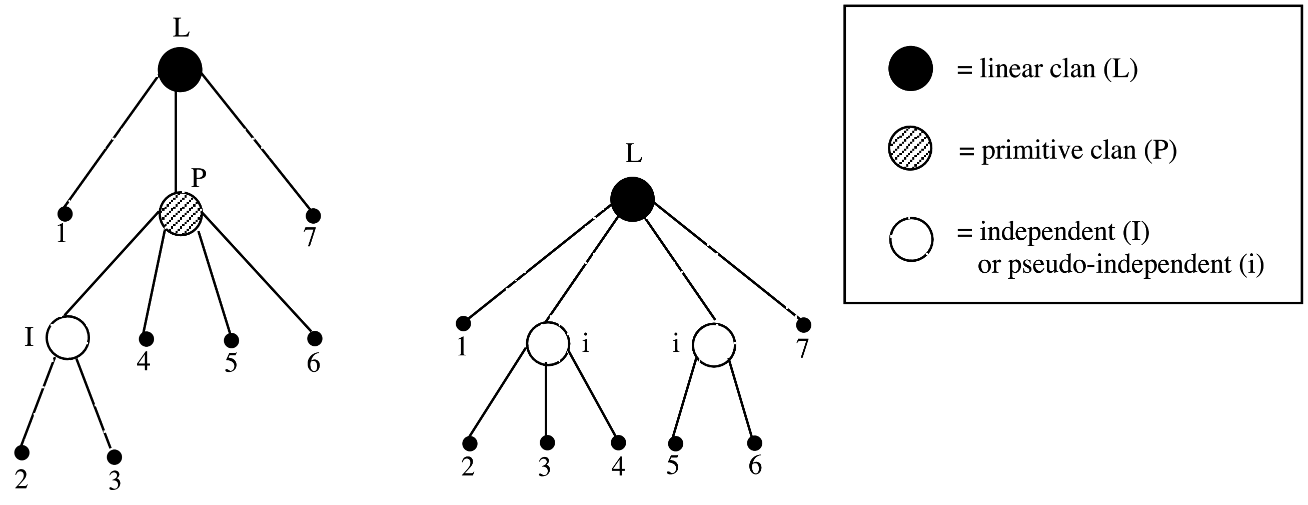
Theorem 3 guarantees the existence of a unique parse tree from the clans of a graph. In the graph layout algorithm, the parse tree is used to specify the graph node locations. A bounding box attribute for each tree vertex, *x*, specifies the length and width of a rectangle containing the graph nodes in *x*'s subtree. The length and width are computed for each linear and each independent clan from the attributes of the clan's children. The children of a linear clan are displayed vertically and the children of a horizontal clan are displayed horizontally in our example layout.

Decomposing Primitives

Primitive clans represent a special challenge. They do not fall into the clear-cut categories of vertices that should be laid out horizontally or laid out vertically. In addition, primitive clans can be arbitrarily large, and there can be indefinitely many of them. While this poses no special challenge to parsing, and every directed graph can be parsed into clans from the three clan types, arbitrary graph generation is a problem since a list of all primitive graphs must be included in the production possibilities to create any specific graph. Our approach is to eliminate primitive clans by decomposing them further into a hierarchy of *pseudo-independent* and linear clans. By adding edges from all the source nodes of a primitive to the union of the children of the sources, linear clan L is formed. L is composed of a clan of the source nodes (which is identified as pseudo-independent) and the remainder of the primitive clan. The procedure then recursively parses the remainder of the primitive. This method extracts series-parallel constructs from primitive clans and represents the serial and parallel structures in the parse tree. The pseudo-independent clans are treated as independent clans for layout purposes since their nodes are not connected. The parse tree of any completely decomposed graph is a bipartite tree where the internal vertices are classified as either linear or (pseudo-) independent. For a connected graph, the root vertex is always linear. In Figure 1, the primitive {2,3,4,5,6} decomposes into a linear connection between the independent clans {2,3,4} and {5,6}. The fully decomposed parse tree is shown in Figure 3(b). The bipartite parse tree can be decorated with layout attributes that can be synthesized to produce an aesthetically pleasing drawing.

2.2 Extension to Cyclic Graphs

A simple transformation is required to apply the graph decomposition method to cyclic graphs. Cycles can be found in a depth-first graph traversal. To break a cycle, the arc that identifies the cycle is given the reverse orientation. When the layout is ready, its orientation will be corrected.



(a) parse tree **(b) parse tree with primitive removed**

Figure 3. Parse trees

2.3 Spatial Analysis

The parse tree of the graph can be given a variety of geometric interpretations. For example, a rectangle or bounding box with known width and length can be associated with each clan. Synthetic attributes can be associated with the parse tree hierarchy to show the embedding of the bounding boxes. For illustrative purposes we choose attributes we call *natural* that give a balanced layout, both vertically and horizontally.

2.3.1 Bounding Boxes

A simple two-dimensional algebra defines the synthetic attributes that specify the bounding boxes. The intrinsic attributes of singleton DAG nodes (or equivalently parse tree leaves) describe unit square bounding boxes. Linear clans require an area whose length is the sum of the lengths of the component clans and whose width is the maximum width of the component clans. Independent clans require an area whose width is the sum of the widths of the component clans and whose length is the maximum of the lengths of the component clans.

Definition: Denote the *bounding box attribute* of node N in parse tree T by (L.N,W.N). We define the *natural* values of the attribute to be: (1) (L.N, W.N) = (1,1), if N has no children; (2) (L.N, W.N) <-- ($L.C_1$+...+$L.C_k$, Max($W.C_1$,...,$W.C_k$)), if N is a **linear** node with children $C_1...C_{k;}$

(3) (L.N, W.N) <--- (Max($L.C_1$+...+$L.C_k$,$W.C_1$,...,$W.C_k$)), if N is an **independent** node with children C_1 ...Ck.

As an example consider the parse tree in Figure 4. The bounding box dimensions are indicated by the (i,j) pairs.

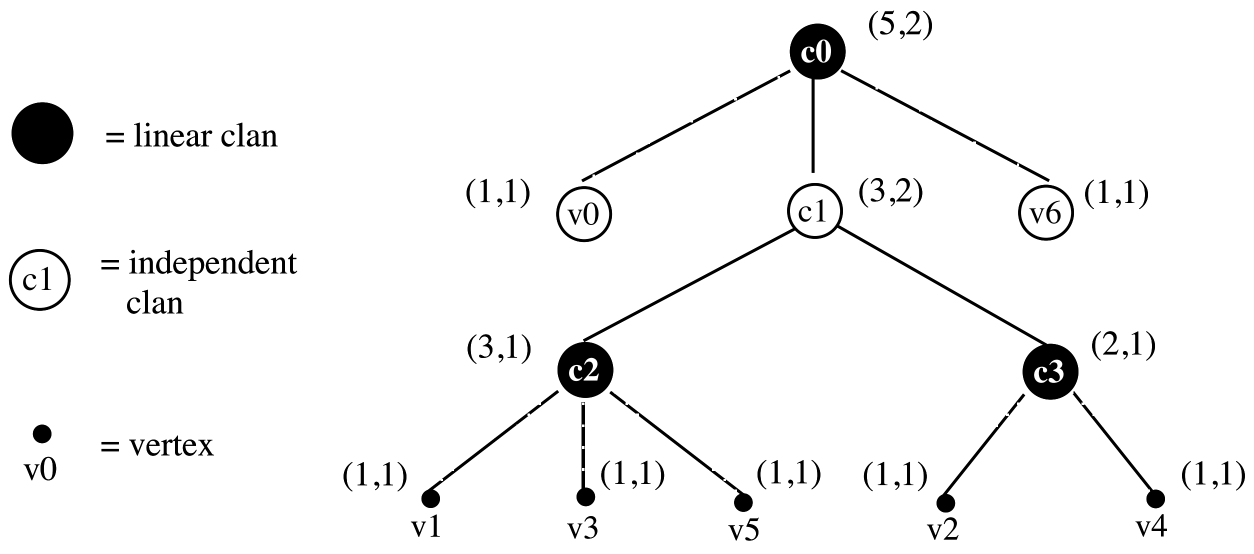


Figure 4. Parse tree with labeled bounding box labels

2.3.2 Node Placement

To achieve an aesthetically pleasing layout, the nodes are centered within the bounding boxes. For child C of linear node N, the actual rectangle in which the node is to be centered has length L.C and width W.N. For child D of independent node I, the rectangle in which D is to be centered has length L.I and width W.D. In Figure 4, for example, clan c3 is centered in a (3,1) bounding box and vertex v0 is centered in a (1,2) bounding box. Figure 5 shows the node layout for the parse tree of Figure 4.

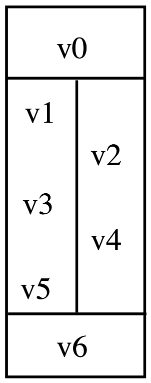


Figure 5. Bounding boxes

2.3.3 Clan Expansion and Contraction

Since clans are defined as groups of nodes with identical connections to the rest of the graph, clans can easily be contracted to a single node. Any node not in the clan that was connected to a clan source or sink will be connected to the contracted node. By allowing segments of the graph to be contacted, the user can simplify graphs for viewing by contracting those parts which are not relevant to the investigation. Contracted nodes can be expanded to show the original clan configuration. Similarly, it is possible to display only the clan, ignoring the rest of the graph.

One of the major differences between the graphs drawn by the naturally attributed CG and hierarchial systems [12][2] is that the nodes in CG's graphs are spaced in a balanced way both vertically and horizontally. Hierarchical drawings partition nodes into levels, and all nodes of the same level are placed on the same horizontal axis. Nodes tend to bunch toward the top of the graph is these systems. By using our graph decomposition technique, CG is able to determine balanced vertical spacing as well as balanced horizontal spacing.

3.0 Drawing Arcs

An important consideration that went into the formulation of the arc drawing algorithm was the question of which pairs of vertices can have arcs between them. The answer lies in the definition of linear and independent clans. The vertices of a linear clan can have arcs between them even if the vertices are not consecutive in the clans. Within independent clans no two vertices may be connected by an arc. For these reasons, the algorithm need only consider routing arcs between vertices within a common linear clan.

There are two major problems to be solved in routing arcs: reducing edge crossings and "long arc problems". Producing optimal edge crossings is NP-hard, even for nodes in only two levels [4]. CG modifies the Barycentric ordering technique of Warfield [13] to be applied to clans, as well as individual nodes.

The long arc problems include reducing arc lengths whenever possible and the proper routing of arcs that connect nodes not placed on adjacent levels. To avoid visual conflicts, long arcs may have to be routed around nodes from intermediate levels. Bends in the arcs are often necessary for this routing, but may cause visual confusion. Bends should be minimized.

3.1 Routing Long Arcs

Before nodes assume their final position in the layout, their location is determined by considering placement that will shorten long arcs when possible or straighten arcs for those that cannot be shortened. To describe the method, several definitions are required. The *level of node* x*,* $l(x)$*,* in DAG G is the length of the longest path from a source to x. The *height of node* x*,* $h(x)$*,* is the length of the longest path from a sink of the graph to x. The *height of* DAG G*,* $H(G)$*,* is the maximum of the node heights or, equivalently, the maximum of the node levels. The *length of arc* (x,y)*,* $L(x,y) = l(y) - l(x)$. An arc, (x,y),is called *long* if $L(x,y) > 1$. Otherwise, it is called *short*.

Theorem 4: In DAG G, if $l(x) + h(x) = H(G)$, then there exist a path from source z_1 to sink z_k, $z_1,...x=z_i,...z_k$, such that $L(z_j,z_{j+1})= 1$ for $1 \leq j < k$.

We say a node x is *specified* if $l(x) + h(x) = H(G)$. The vertical positioning of a specified node is determined since it is contained in a path whose arcs are all of length 1. Short edges are routed directly to vertices while long arcs are routed through false vertices embedded in clans between the two vertices. Since bends are hard to follow and distracting to the eye, our strategy guarantees that transitive arcs will have at most two bends. Furthermore, no edges will cross long arcs except possibly at either end of the arc.

3.1.1 Recognizing Long Arcs

A long arc is incident to node x iff there exists node y such that (x,y) ∈E or (y,x) ∈E and |l(y)-l(x)| > 1. If the the long arc, (x,y), is a transitive arc, it is replace by a dummy node z and arcs (x,z) and (z,y). When the augmented graph is parsed, z is a component in an independent subclan of the clan containing x and y. The example graph in Figure 6 illustrates this situation. The only transitive arc is (a,d). Here, node z and arcs (a,z) and (z,d) are added, and arc (a,d) is deleted. The augmented parse includes new independent clan, {b,c, z} with components {b,c} and {z}. The augmented parse tree is shown in figure 6d. Since the only role of z is that of place holder for the dummy node, a reasonable modification of the attribute grammar would be to give the dummy node a smaller width. The layout in 6(e) illustrates the case where the bounding box of z is assigned the dimensions (1, 0.5).

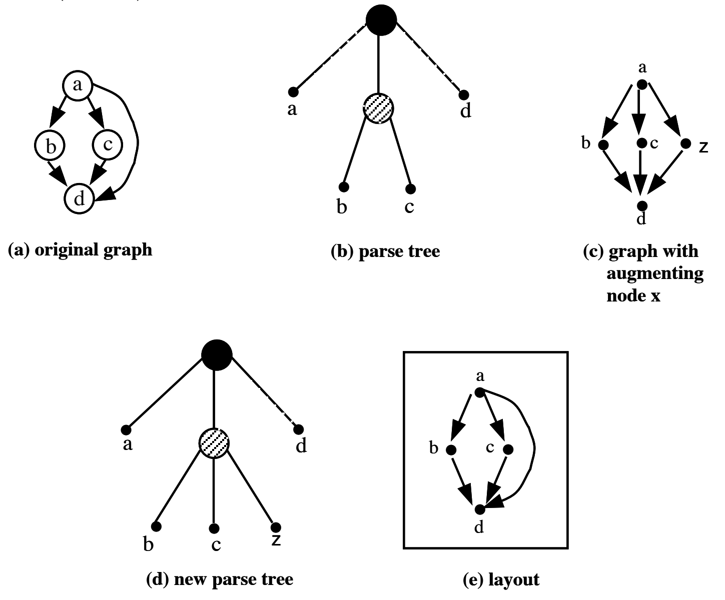


Figure 6. Routing transitive arc

3.1.2 Positioning Nodes Incident with Long Arcs

For non-transitive long arcs incident at x, if $l(x) + h(x) < H(G)$, then some flexibility exists for adjusting the vertical positioning of x. The vertical positioning will be modified in one of three ways: (i) x will be centered between predecessor and successor, (ii) x will be placed one level below its predecessor, or (iii) x will be placed one level above its successor. If there is a successor of x and a predecessor of x that are both specified, then x will be placed midway between, separating two long arcs. If only a successor or a predecessor, y, is specified, x will be moved as close as possible to y. These modifications are made by inserting dummy nodes into the parse tree, completing the normal layout, routing the edges through the dummy nodes and then removing the unnecessary nodes. The dummy nodes are included with x in a linear clan. The addition of the linear clans insures the nodes with be placed in vertically adjacent positions. Specifically, the parse tree transformations will be:

(i) if all predecessors, w, and all successors, z, of x are satisfied, let $d = \min \left\lfloor \left\lceil l(z) - l(w) - 2 \right\rceil / 2 \right\rfloor$, where the minimum is taken over all w,z adjacent to x. Node x is replaced in the parse tree by a linear with $l(z) - l(w) -1$ nodes: d dummy nodes are placed to the left of x and $l(z) - l(w) - d - 2$ dummy nodes are placed to the right of x. Figure 7 illustrates the process. In the figure, arc (a,z) is a transitive arc. The graph is augmented with node x to remove the transitive edge. Now arcs (x,z) and (e,z) are long. Furthermore all predecessors and successors of x and e are satisfied. Node x in the parse tree is replaced by a linear clan with $d = (5-0-2)/2 = 1$ dummy node to the left of x and $l(z) - l(a) - d - 2 = 2$ dummy nodes to the right of x. Similarly, e is replaced by a linear clan with 2 nodes.

(ii) if there exists a y such that y is specified, $(x,y) \in E$, and $l(y) - l(x) > 1$, let $d = \min[l(y)-l(x)-1]$, where the min is taken over all y adjacent to x. Replace node x in the parse tree by a linear node with d + 1 children: d dummy nodes to the left of x. Figure 8 illustrates this solution. Here (a,z) is a long arc that is not transitive. d = 3, and parse tree node a is replaced by a linear clan with 3 dummy nodes followed by x. (See Figure 8(c)). Note that neither the dummy nodes nor the potential edges between them are required for the layout.

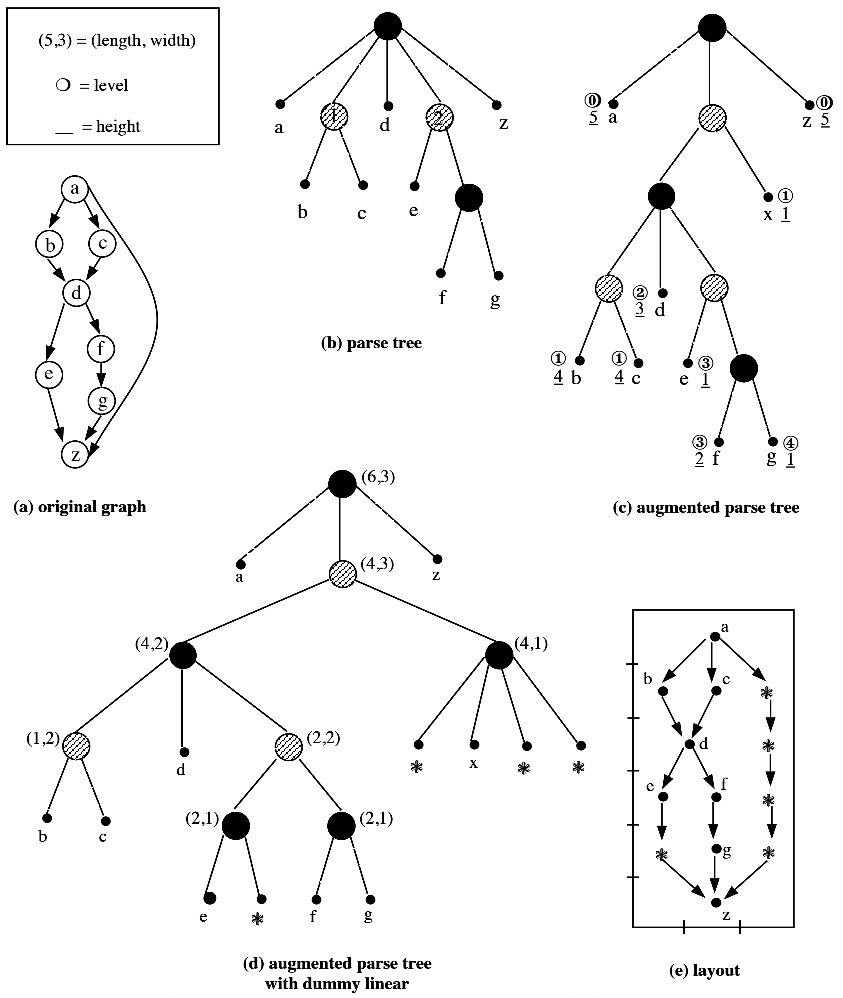


Figure 7. Layout for long transitive edge

(iii) if there exists a node y such that y is specified, (y,x) ∈E, and l(x) - l(y) > 1, let d = min[(l(y)- l(x)-2]. Replace node x in the parse tree by a linear node with d+1 children: node x is the left-most child and d dummy nodes are to its right. Though the parse tree changes and larger bounding boxes are assigned to these linear nodes, it is important to leave the bounding boxes of the ancestors unchanged. No additional space is required for the dummy nodes. They are placed in the graph only for the purpose of routing edges. Once all nodes and dummy nodes are placed, all arcs are short and their placement follows.

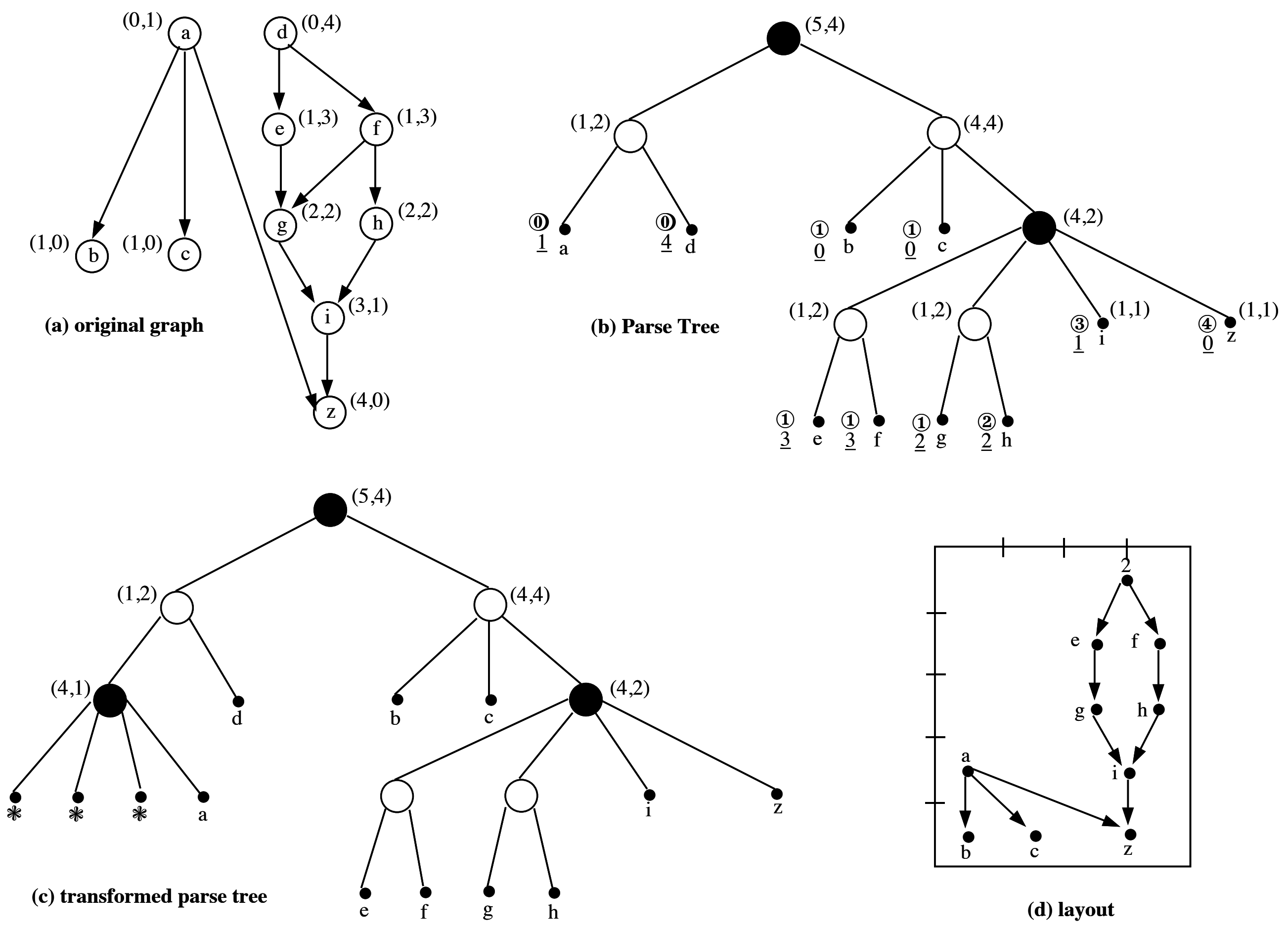


Figure 8. Layout to shorten long edge

3.2 The Barycentric Method and its Adaptation to Clans

The Barycentric method is a heuristic for reducing the number of edge crossings in two consecutive levels of a graph. Two values called the row barycenter and the column barycenter quantify the horizontal distance between adjacent vertices. Reducing these distances produces fewer edge crossings. The method traverses the levels of the graph and recursively computes the barycenter for adjacent levels starting with level zero. With each computation, the nodes on one level are permuted to reduce the row barycenter value. The process is repeated between top and bottom layers until no reordering occurs or a limit on the number of computations has been reached.

Adapting barycenters to clans involves replacing the adjacent levels of a hierarchy by adjacent independent clan components of linear clans. The process first inspects the smallest linear clans in the parse tree (those closest to the leaves). The barycenter method is used on non-trivial adjacent independent subclans of these linear clans. Once the proper ordering has been established for the nodes within that linear clan, that ordering remains fixed. The process continues with the quotient graph where the linear node has been contracted.

Identifying and using only the linear clans results in a significant reduction in the amount of computation required to perform the barycentric method. In the original barycenter method, the barycenters are computed on matrices of size r_i*r_{i+1} where r_i is the number of vertices in level i and the computation requires r_i*r_{i+1} multiplications and $(r_i-1)*r_{i+1}$ additions at each level for each iteration between the top and bottom levels. With the application to the parse tree, after the proper placement of the independent clans within a linear, there is only one node that represents the entire structure of the linear clan.

3.3 Smoothing Arcs.

The CG system eliminates sharp corners by using B-splines. When an arc connects an actual vertex with a dummy vertex, the spline technique described by Enns [7] and Farin [8] is used. See Figures 9, 10 and 11..

4.0 The Implementation

The CG system has been implemented on a Sun Microsystems SPARCstation running the SunOS 4.1.2 operating system. It was written in C++ and uses the InterViews toolkit developed at Stanford University. This toolkit provides an object-oriented interface to the X Window System. Using this interface, the system generates a drawing of a directed graph from a textual description. The windows in Figures 9, 10, and 11 contain the digraph displays generated by the

CG system. The vertices of the digraph are represented by circles, each of which contains the number of the vertex. Vertices can be selected by clicking on them with the left mouse button. This action highlights the vertex by reversing its foreground and background colors. When all the components of a clan have been selected, the user may then contract the clan. Figure 9 shows a layout and the results of contracting clans $\{1, 2\} \cup \{3, 4, 5\}$, and $\{6, 7, 8, 9, 10\}$.

The contracted clans can be selected exactly like the vertices. The expand button can then be used to expand selected clans to reveal their contents. This expansion and contraction of clans allows the user to concentrate on specific subgraphs while browsing the digraph.

Figure 9. Graph with 15 nodes and contractions

Figure 10. Random DAG with 33 Nodes

Figure 11. Random DAG with 31 nodes.

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