Degree-of-Interest Trees: A Component of an Attention-Reactive User Interface

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ABSTRACT
This paper proposes Degree-of-Interest trees. These trees use degree-of-interest calculations and focus+context visualization methods, together with bounding constraints, to fit within pre-established bounds. The method is an instance of an emerging "attention-reactive" user interface whose components are designed to snap together in bounded spaces.

Categories and Subject Descriptors
H.5.2 (Information Interfaces and Presentation): Graphical user interfaces. I.3.6. (Methodology and Techniques): Interaction techniques.

General Terms
Human Factors

Keywords
Degree-of-Interest Trees, DOI Trees, focus+context, information visualization, attention-reactive user interfaces, fisheye displays, hierarchical display, tree

1. INTRODUCTION

Current technology makes it feasible to bring increasingly large amounts of information to bear in computer applications. This paper explores one instance of a general strategy for constructing interfaces for high-information applications. The strategy is the Attention-reactive User Interface (AUI). Such an interface consists of two parts. One part is a method for continuous prediction of the user's instantaneous Degree-of-Interest (DOI) over items in the field of information. The other part is a dynamic visual display of the information that uses the DOI calculation to reduce the time cost of information access or to manage attention. DOI calculations could be used to allocate display resources, decide which elements to display, change representation, highlight, or take initiative in a mixed-initiative dialogue (see Figure 1).

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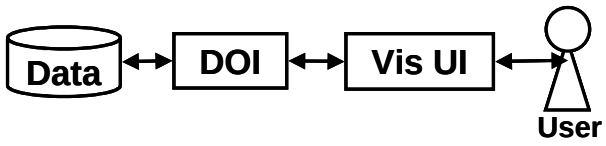


Figure 1. Attention-Reactive User Interface.

The instance of this paradigm we explore here is a method for dynamically interacting with hierarchical information in trees. Hierarchical displays are important not only because many interesting collections of information, such as organization charts or taxonomies, are hierarchical in form, but also because important collections of information, such as Websites, are *approximately* hierarchical. Whereas practical methods exist for displaying trees up to several thousand nodes, no good methods exist for displaying general graphs of this size. Hence, tree-based displays are more important than just as displays of hierarchical data.

Good visualizations of hierarchical information would (1) allow adequate space in nodes to display information, (2) allow users to understand the relationship of a node to its surrounding context, (3) allow users to find elements in the hierarchy quickly, and (4) fit into a bounded region. This last requirement is desirable in order to insure information fits on a display or that it can compose together with other display elements in an application without the need for scrolling.

For purpose of illustration, we shall use the display of organization charts as our example of hierarchical data, keeping in mind that the same techniques work for many different types of trees. Organization charts are trees (at least the ones we shall discuss first are) and have nodes that display several properties per node.

2. PREVIOUS WORK

There is a considerable literature on the use of trees for information visualization and on the layout of trees. The algorithms of tree layout from a graph drawing point of view have been summarized in Di Battista, et al [1]. Forms of trees from an information design and information visualization point of view have been surveyed in Bertin [2], Card et al [3], and Herman et al [4].

2.1 Simple Static Layouts

Much work on tree layouts assume trees will be static and concentrate on methods to layout trees that meet aesthetic criteria such as minimal line crossings, placing nodes at the same tree depth at the same level, and compactness. The simplest way to lay out trees is to lay them out *uniformly* (see Figure 2). The

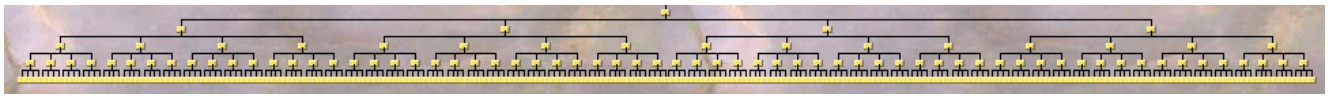


Figure 2. Small tree of 341 nodes, uniformly laid out.

number of nodes at the leaves of all the subtrees is computed and multiplied by an amount of space per node plus spacing between nodes and between subtrees. This method works for small trees, but any attempt to portray a tree of moderate size, say 1000 nodes, will start to approximate the appearance of a horizontal line, since the width increases exponentially while the height increases only linearly.

2.2 Compressed Static Layouts

More sophisticated methods of tree layouts have been developed that are spatially compact. The slide portions of deeper subtrees underneath shallow subtrees. For example, the classic *Reingold-Tilford layout* [5] and its later refinements, creates a top-down, reasonably compact tree that satisfies various aesthetic criteria, such as symmetry and the same shape of common subtrees. Tree space can also be compressed by the use of *recursive tree* layout algorithms. For example, *H-trees* lay out the first few branches as an H with later branches forming an H off those. *Ball-trees* lay-out the branches as spokes from a root with later branches as spokes from the tips of these (see Herman et al [4]).

2.3 Containment Trees

The tree layout algorithms discussed so far use node and link diagrams to represent trees. Trees have also been represented by containment, for example, as a set of nested circles. One class of particularly interesting containment trees is the *TreeMap* [6]. A TreeMap is a technique in which lower subtrees are contained within higher nodes of the tree. Space is divided, say vertically, into a number of sections equal to the number of branches at the top level. Each section is then divided horizontally according to the number of branches at the next level down in the tree. Division of the space continues vertically and horizontally until it is too small to divide. The algorithm does not allow room for the content of non-terminal nodes, but the technique can be modified so that each division has extra space for node contents. One advantage of TreeMaps is that they stay within predetermined space bounds, but there is little room for node content, especially of non-terminal nodes, and aspect ratios of the nodes vary widely, obscuring simple relationships Recent attempts to order or squarify the visualizations [7] have mitigated this effect.

2.4 Interactive Tree Layouts

The techniques discussed so far share several problems for use as components of information visualization systems. First, they do not scale sufficiently. The tree in Figure 2 has only 341 nodes, but is already nearly unreadable. Even using one of the compressed tree layouts will not adequately extend the number of nodes that can be handled. Second, much of the literature on tree layouts does not consider trees in which the nodes themselves contain significant information and require a significant amount of the layout space. Third, many of the techniques for tree layout are not bounded in space. They can therefore not be used easily as modular components of information displays. Interactive trees handle the first two of these problems by displaying only a portion of the nodes at one time. A typical interactive technique is that of the Apple Hierarchical Filing System. Each level in the tree can be expanded individually by clicking on a small triangle. Thus the user can expand portions of the tree that are to be compared on the screen, while keeping other portions of the tree compressed by eliding nodes below the compressed subtree root. The tradeoffs are that considerable manual manipulation must be performed by the user to constantly adjust views, and there is no guarantee the tree will fit, leading to more manual manipulation of scroll bars. Since the user cannot see large portions of a large tree, the user may have a difficult time navigating the tree or understanding the larger shape of the tree.

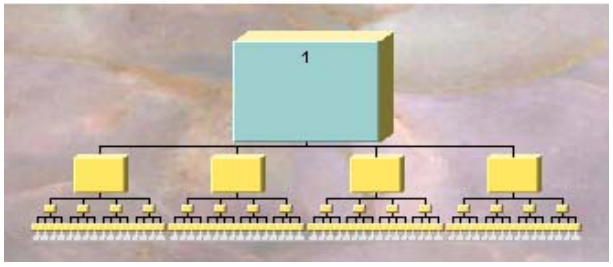


Figure 2. Display of a uniform tree of 4 levels, 4 branches each level, focus on Node 1 (number in the figure represents the node number).

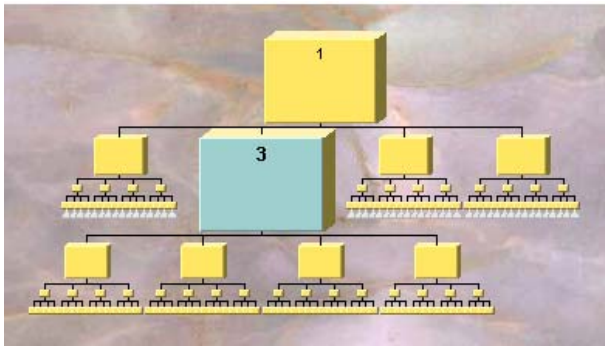


Figure 3. Same table with focus on Node 3.

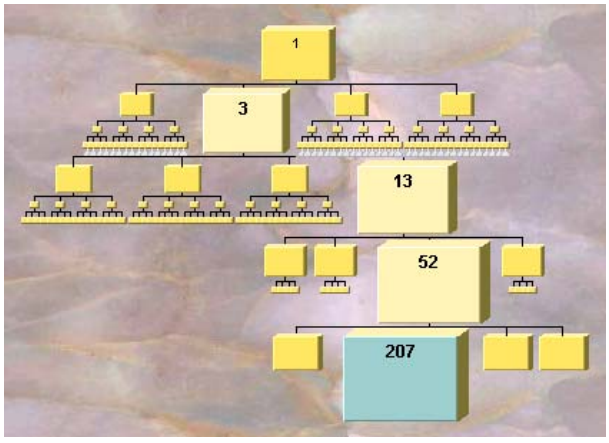


Figure 4. Same tree expanded down to a leaf node.

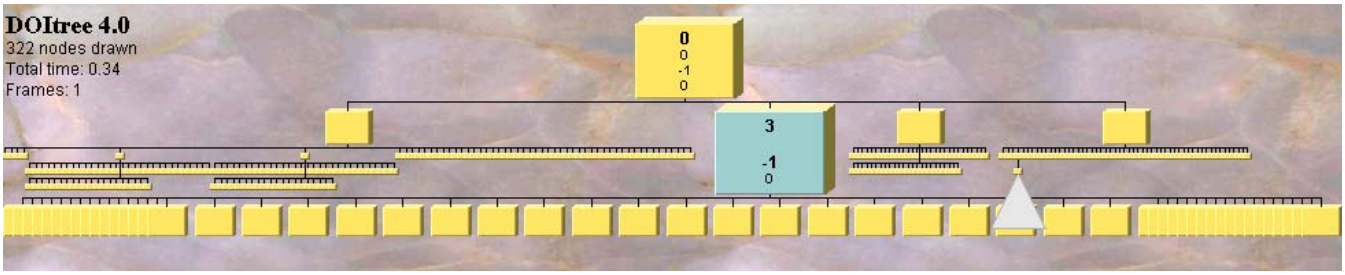


Figure 5. Tree showing overlapping of large branching factor of nodes under several nodes, when these have moderate DOI. There are 300 nodes under the triangular symbol.

2.5 Focus+Context Trees

Focus+context trees add automation for automatically choosing which portions of the tree to show at any instant. In this way, they reduce the time cost of navigating around the tree. Four main methods of expanding focus+context trees have been proposed. The first is *logical filtering* of nodes. Furnas [8] describes a class of *fisheye* techniques in which nodes are automatically displayed or elided according to the user's computed degree-of-interest (DOI) in them. The estimated

DOI of a node = Intrinsic Importance
– Distance from a focus node.

The *Intrinsic Importance* of a node is its distance from the root and the *Distance* of a node is the number of nodes that must be traversed by following parent and child links from the node of interest until reaching the subject node. Those nodes whose DOI lies below a certain threshold are not displayed. If the user indicates interest in some node, say by selecting it, this calculation is performed again and the display elides those nodes below threshold. In this way, the display of the tree follows the user's changing interest. The limitation of this technique is that there is no guarantee the displayed trees will fit in any display bounds. The technique is especially problematic when there are a large number of sibling nodes in a branch.

A second class of focus+context techniques uses *geometric distortion.* An example is the *hyperbolic tree* [9, 10]. A visual transfer function is defined that distorts space such that the area of interest is magnified at the expense of nodes of the trees some distance from this interest. Selecting a node moves it to the center (or side) of the display. Nodes further out are smaller and closer to each other. The display stays within fixed boundaries. But only a limited number of links out from the focus node can be seen. This technique is less suited for cases in which the DOI varies in discontinuous ways across the tree, although there can be a limited number of multiple foci. A variant of geometrical distortion is the *cone-tree* (Robertson et al, [11]). Cone-trees arrange the nodes in a 3-D tree. Selecting a node rotates a branch of the cone-tree, bringing related nodes into the foreground while sending other nodes into the background. This technique uses natural perspective and occlusion to achieve some of the effect of geometric distortion, but in a way that the user does not experience the geometric compression as distortion. Furnas' fisheye view technique can be combined with cone-trees, thus allowing the display of larger trees on the order of 10,000 nodes [12]. Because a cone tree is a 3-D display, some of the nodes occlude each other.

Another class of technique for expanding focus+context displays is *semantic zooming*. As the display is zoomed in and nodes are expanded past a certain threshold their content changes. Fox and Perlin [13] used this technique in their Pad system to expand a calendar, which can be seen as a sort of containment tree. Mackinlay et al [14] also used semantic zooming in calendars and other *spiral trees*. The tree is arranged in a 3D spiral. One node from the tree is expanded and its content semantically zoomed to reveal additional structure. The higher-level nodes are spiraled toward the center and made more distant from the user (using perspective to reduce their size). This tree layout has the virtue that it stays confined in fixed bounds, but the user only sees a limited subset of the nodes in the tree, essentially a view looking upward in the tree toward the root. Graham and Kennedy [15] used both semantic zooming and geometrical distortion to display biological taxonomies.

A final focus+context technique is to cluster nodes far from the point of focus. Those nodes near the point of interest are expanded into their constituent parts; those more distant are kept in an aggregate form. This technique was used in SemNet [16] and could be applied to trees.

3. DEGREE-OF-INTEREST TREE (DOI TREE) SOLUTION

Our Degree-of-Interest Trees (DOI Trees) solution combines all

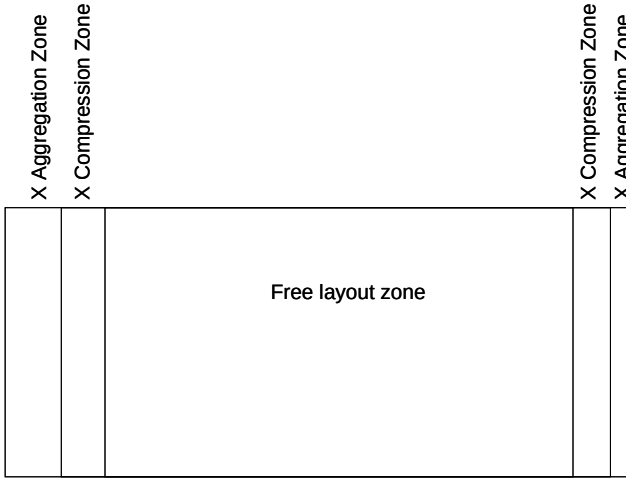


Figure 6. Compression and aggregation zones.

four focus+context techniques with a method to ensure that the tree stays within a predefined bounding box. DOI Trees combine (a) an expanded computation of users' DOI estimates with (b) logical filtering to elide nodes of low DOI, (c) geometric scaling of node size according to DOI so as to be able to hold different levels of information, (d) semantic scaling of the contents of the nodes with node size, (e) clustered representation of large unexpanded branches of the tree, and (f) animated transitions, designed to speed the user's rapid understanding of changes in the tree. New techniques are developed for many of these parts.

3.1 Degree-of-Interest Computation

The degree of interest calculation is expanded beyond that used by Furnas. Whereas Furnas's calculation assigns all siblings the same distance from the focus node and hence the same DOI value, our calculation treats the children of a parent node as ordered and assigns fractional DOI offsets to the children based on order distance from the focus node. The farther the sibling from the focus node, the more the fractional decrement in its DOI (but the decrement is always less than 1). This allows the visualization part of the program to decide which sibling nodes to compress and how to compress them. Whenever the user clicks on a tree node, that node becomes the focus node, DOI values are recomputed for each node of the tree, the tree is laid out again, and an animated transition moves to the next layout. Multiple-foci can be determined by values of the data or hits in a search.

3.2 Visualization of Tree

There are a small number of possible node sizes (we currently use three main sizes). The largest size is sufficient to display the entire full content of the node. For an organization chart, this would include a person's name, picture, organization, title, extension, room number, web page, and possible other information. A middle size node still displays enough information to identify a person including a few facts about him. A small node just displays the fact that a node exists in that position and hence shows tree structure (and a mouse target for tree expansion). In addition, nodes have multiple faces to allow the storing of additional information. A table maps DOI values into node sizes. Figure 3 shows the display of the uniform tree in the Figure 2 (with a branching factor of 4 at each node) when the focus is at the root. The larger node has automatically been selected for the focus node and its color changed. Smaller node sizes have been automatically selected by the algorithm for nodes with lower DOI. Optionally, a small "fade value" is assigned to cause nodes farther away that would be the same size to be a little smaller. This is equivalent to increasing the weighting on the DOI distance function.

In Figure 4, one of the nodes (node 3) on the next level down has been selected, changing the DOI calculation for the nodes. Now when the tree is displayed, node 1 is reduced in size, node 3 is increased, and nodes below the focus tree are increased in size, according to the computed DOIs for the nodes. The transition proceeds by a smooth animation from one state to another to keep the user oriented and unconfused.

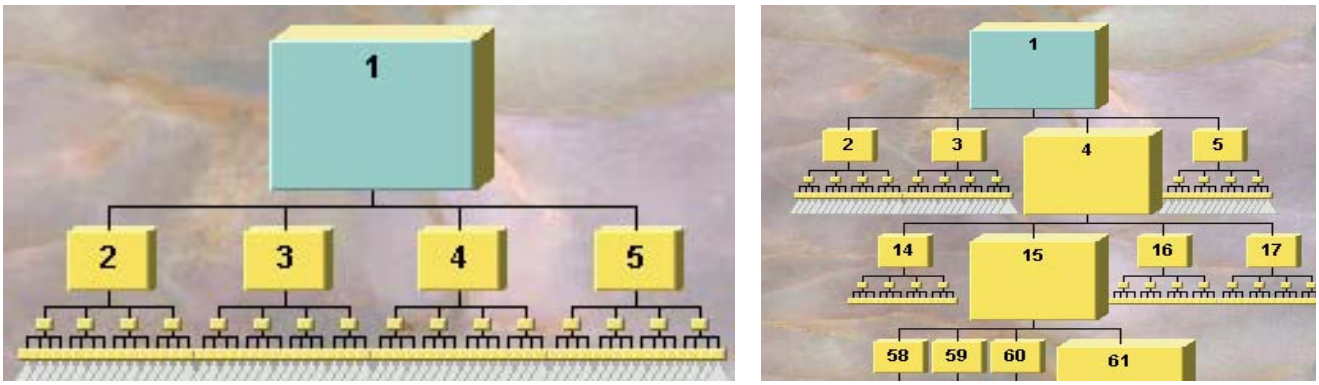
In Figure 5, one of the lowest nodes has been selected, either by selecting directly, or by selecting nearby nodes, causing the target node to get larger and be more easily selectable.

4. UTILIZATION OF THE SPACE RESOURCE

Space on the display is a resource. Making the tree stay within its resource requires methods for monitoring and making adjustments to the tree visualization. Often, to stay within its bounding box, the tree visualization must be compressed. But if the space is being under-utilized, the tree might also be profitably expanded to take advantage of the additional space. Both compression and expansion are controlled by the users' estimated DOI for each node.

4.1 Compress to Fit

The fact that the basic DOI-based algorithm very greatly reduces the pressure on the space resource sets up the condition for algorithms that enforce space boundaries to be successful. There are two cases to consider: the tree not fitting in the X direction and the tree not fitting in the Y direction.



(a) **(b)**

Figure 7. (a) Tree from Figure 1 without Expand-to-Fit turned on. (b) Same tree with Expand-to-Fit expanding the node with the most subnodes.

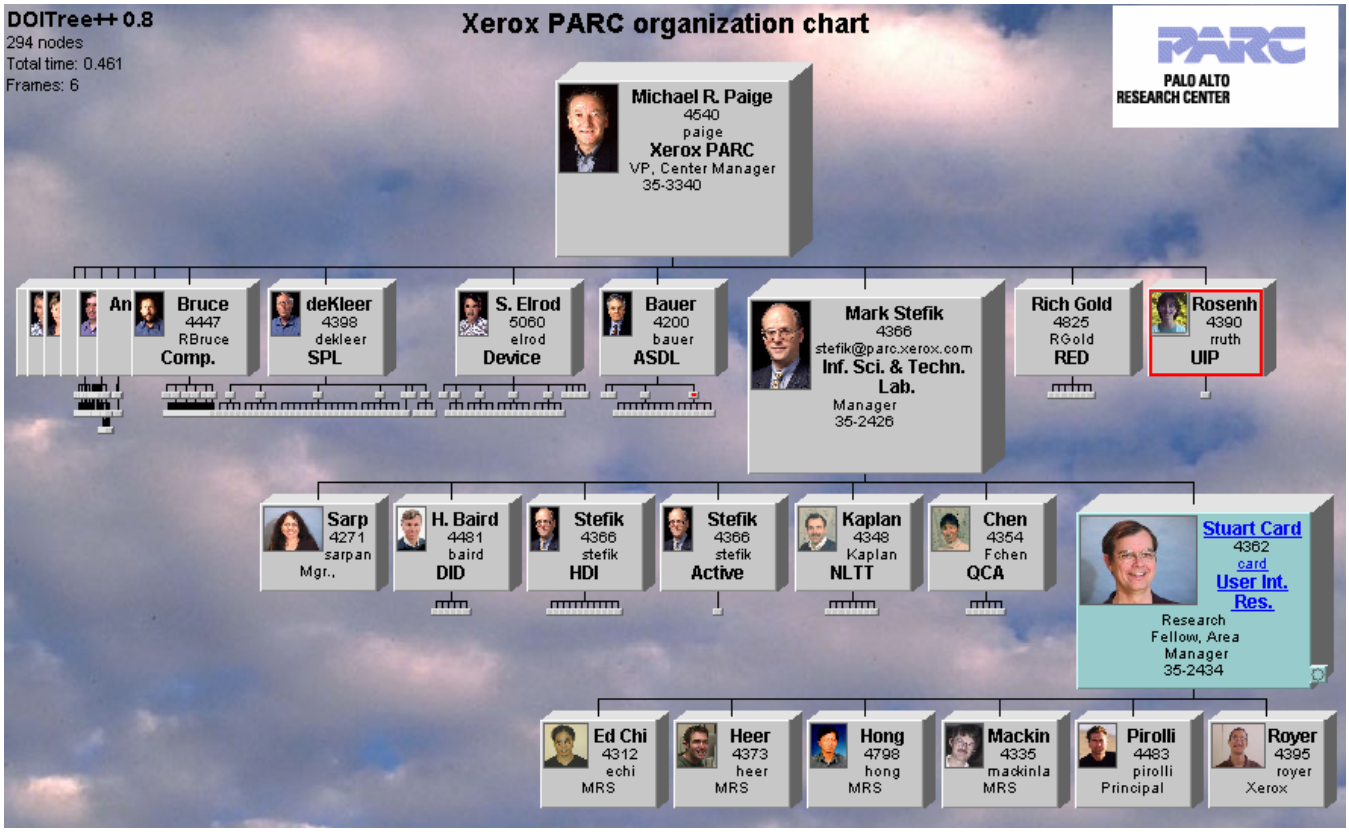


Figure 8. Organization chart with over 400 nodes accessible over WWW through Web browser.

Compression in X. The tree not fitting in the X direction is common and occurs either because of a large branching factor below one node or else because there is an accumulation of widths across several subtrees. In the latter case, the nodes below each box are laid out in the horizontal space available for each box. This pattern is visible in Figure 6. The nodes with the highest DOIs in a row have the largest node size. This node size establishes the Y height of a region in which to lay out the immediate descendents of a node. If there are too many Y descendents horizontally, they are folded into multiple rows according to a common organization chart convention (with a vertical line joining the rows, see Figure 11). If the branching factor of individual subtrees is large, then the nodes are overlapped as in Figure 6. If there are elided nodes below a threshold DOI value, then a triangular symbol proportionate to the log of the number of nodes is used.

To handle trees too wide for the bounding box, the box is divided horizontally into three regions (Figure 7): The regular free layout zone, a compression zone, and an aggregation zone. Typically, 70% of the screen is in the free layout zone, with 30% in the combined compression and aggregation zones. If necessary, the horizontal layout will be compressed (as in row 3 of Figure 6) for some of the nodes by overlapping them. As the mouse is moved over these nodes, they spring to the front, overlapping their neighbors, thereby allowing the user to peruse them. Space in the compression and aggregation zones is allocated according to the fractional DOI value of each node. By default, the value gets smaller as the node gets closer to the edge of the display. With large numbers of nodes, multiple nodes may occupy the same display location. Only one of the nodes will be displayed. If that node is selected as the focus node, it will be shifted to the free layout zone and surrounding nodes will then be visible. The use of DOI to do selective expansion and the use of folding rows greatly increases the size of tree that can be horizontally laid out. The use of compression and aggregation zones ensures that all trees can be fit within the space.

Compression in Y. It can also happen that a tree would be too deep vertically to fit within its space. Normally the tree is then scaled to fit within the Y dimension. If the scaling would result in nodes that are too small to display their contents, nodes are either elided lower in the tree or at the top, depending on the DOI and the position of the node of interest. First, if the nodes for a tree are less than a threshold DOI, then they are elided and replaced by an elision graphic, essentially representing the nodes as a cluster. Since nodes decrease intrinsic importance with distance from the root and in distance importance with distance from the focus node(s), the chain of nodes from the focus node through successive parent nodes to the root will have the same DOI value except that the fade feature will gradually make the nodes smaller as they approach the root node. Since the tree is scaled to fit within the window, this could cause all of the nodes to become very small for very deep trees. To deal with this problem a top portion of the tree is removed and replaced with an elision graphic.

4.2 Expand to Fit

Figure 12. Multi-focal result of a search. Besides showing the search hits, the tree context for the hits is also shown.

Sometimes the algorithms described so far might leave extra blank space on the display below the focus node. Therefore, an alternative version of the algorithm, switch selectable by the user, expands part of the tree into this space. The way it does this is that if there is still vertical space available on the display, the "most interesting node" is expanded.

This could (1) be the node with the highest DOI on the row, or it could (2) be the node with the largest number of descendents, or (3) it could be the node with the highest "information scent" as determined by key words typed by the user or (4) the words of greatest frequency in the nodes selected or (5) by other means. Figure 8(b) shows the tree of Figure 8(a) expanded according to the subtree with the most nodes.

4.3 Within-Node Compress to Fit—Semantic Zooming

Each node also represents an assigned space resource within which there are items to display. In our example organization chart application, these fields include attributes such as post name, post reported to, name, title, office extension, email, picture file URL, and home page URL. Just as we used compress-to-fit techniques for the layout, we can also use semantic zooming compress-to-fit techniques within the node:

1. *Data deletion.* Smaller nodes only display some of the data items.

2. *Word abbreviation.* Words and phrases are abbreviated if there is not room on the line where they are displayed. For example, Vice President becomes V.P. The system uses a text file of abbreviations plus some heuristics to generate abbreviations. Figure 9 shows the DOI Tree of an organization chart with the green node selected. The effect of data deletion and word abbreviations on the middle-sized nodes can be seen.

3. *Node rotation.* The normal view of nodes shows them as 3D boxes. The 3D property is meant to suggest that the boxes have alternative faces. Stroking a box (by dragging the mouse horizontally over a box) makes the box appear to rotate such that another side of the box faces forward. This allows more data items to be associated with a node that are quickly accessible. Figure 10 shows the rotation of the nodes. Figure 10(a) shows a frame in mid-rotation; Figure 10(b) shows the completed rotation. In the figure, the picture has been expanded to fill the whole node side,

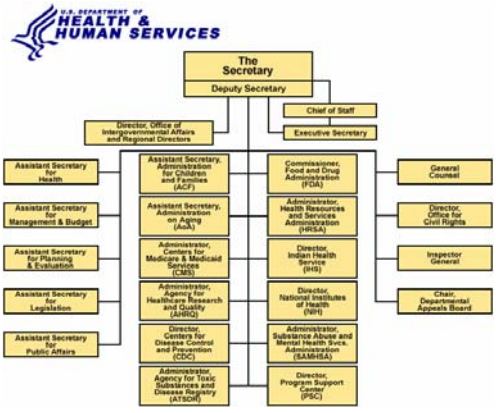


Figure 10. Organization chart showing folding convention. This tree layout is more difficult for producing understandable animated transitions for the user.

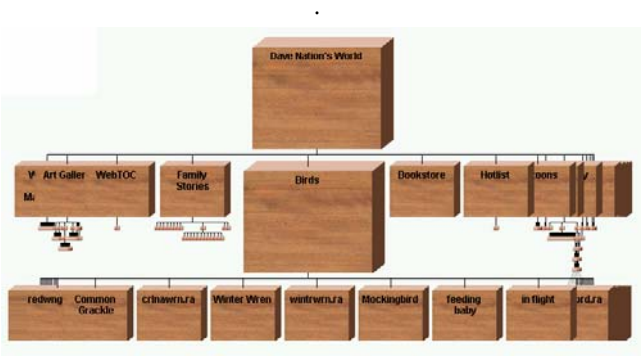


Figure 11. Visualization of Dave Nation's World website. Nodes expand and contract as user browses or searches website

to serve as a better cue—another form of semantic zooming. There are optimally three faces to a node—front, left, and right (more would be confusing).

4.4 Tree Transitions

User orientation in the tree is preserved by making the views of the tree animate into each other. The animation time is set at a desirable level, usually in the range of (0.5~1.0 sec) (see [17]). The average draw time per frame for recent frames is used to set the number of animation frames that can be drawn in this time. The in-between frames show a linear change in each node's size and position. It is important that the choreography of animated transitions be understandable by the user. In fact, the necessity for simple-to-understand transitions was found to limit tree layouts. For example, Figure 11 employs a folding convention often used in organization charts. Implementation of similar layouts convinced us that it is difficult to make tree transition animations with such layouts that are understandable to the user, except in the case where the stacked rows are of the smallest size nodes (e.g., as in Figure 6). Rapid-to-understand transitions are very important, because focus+context displays use system dynamics to substitute for being able to show the entire tree. The user must have the experience that there is a single tree that is being stretched and pulled as it is being explored.

5. SEARCH AND MULTIFOCAL DOI TREES

DOI calculations can be done based on computations other than the user's point of attention used above. An example is a user searching over a collection. This often results in multiple initial focal points from which to start the DOI calculation. The interest in a given node may be composed of DOI generated from multiple sources. In Figure 13, the user has searched for the name Stefik in the organization chart. The result reveals that Stefik appears three times and reports to himself twice. The chart shows these nodes, but it also shows them in context to the rest of the organization chart. The visualization makes it easy to find answers to questions like "to whom does Stefik report?" or "who is the lone person reporting to Stefik in one of his capacities?" or "who are all the research fellows and how are they distributed across laboratories?"

6. USES OF DOI TREES

DOI Trees have many uses. Here we list just a few:

Information Browser. Items in the tree could be linked to arbitrary URL pages or to programs, such as an email program. Hence, the tree could act as a browser across pages of WWW data (Figure 12). For some applications, such as the organization chart, the tree as a browser operates more quickly than a conventional WWW browser page. This is because a group of the pages can be on the screen together in their relationship.

Organization Chart. This is the application we have used as an example. In addition to displaying the organization chart and its use in finding people in the organization, the URL links on the nodes of the tree also serve as gateways to supporting data (Figure 9). This chart has over 400 nodes, is accessible over the Web, and combines all the information contained in ten separate organization charts (each of which fills a page). We also maintain a larger organization chart several times its size. By searching for a name or by browsing the chart, the details of the individual organizations are revealed. Furthermore, the chart serves as a gateway into the organizational home pages of the different organizations (accessed by clicking the appropriate link within the node) or personal home pages. It also could be used to access email to any of the individuals whose email is given on the chart by simply clicking the link.

Web site visualization. Another use is for views of Web sites, which have been coerced into tree form. Thumbnail miniatures of pages could be displayed in the nodes. Full size displays of the pages could be displayed beside the browser.

Web site statistics. The DOI of individual pages in the web site could be set to a function of the number of hits that page has received in the last month or week or hour or other time period. Thus, site sponsors could watch the activity of their web sites.

Databases. Databases that are expressible by trees could be displayed and searched. For example, the 7000-node taxonomic database used for competitive tests at CHI is shown in Figure 14. By following the higher-level groupings, the user has found the node "Ebola Virus."

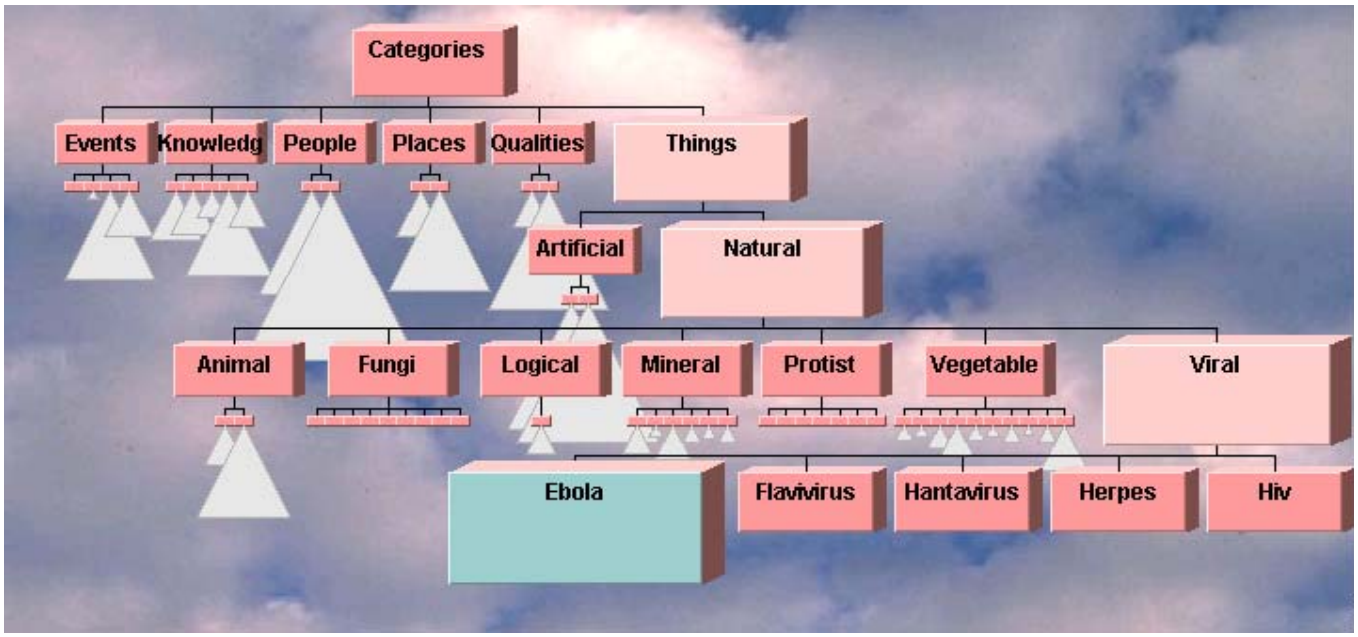


Figure 13. 7000-node taxonomic database. User has found the item Ebola.

Multilinked databases. Many databases that are not trees can also be displayed as DOI Trees. An example of such a database is given in Figure 15. The database is coerced into a tree. Additional, non-tree links are revealed as blue lines (as in the figure) when the mouse is moved over them. Because of the mapping into the tree, some nodes may be duplicated in the structure (these are colored pink in the figure). By using these techniques, complex structures that would be difficult to plot as generalized graphs are plotted as trees, but the other linkages can still be investigated.

Email streams visualization. Email streams could be represented as trees. The DOI for these streams could be generated based on the content similarity and tree closeness.

6.1 Data Source and Authoring

The data for DOI Trees can be derived from a database. They can also be read from tab-delimited files. Users can thus prepare and edit trees for DOI Tree display by using normal spreadsheets without any programming. The present embodiment of DOI Trees enables users to place arbitrary bitmaps as backgrounds to the tree and to the nodes. This allows the display of these trees to be readily adapted to presentation requirements of an organization.

7. DISCUSSION

The evaluation of dynamic visualizations such as DOI Trees is a subtle undertaking. Philosophically, we do not believe it is sufficient to do a simple system A vs. system B human factors evaluation on DOI Trees, because the results may depend on the task, the contents of the nodes, and perceptual properties of the visualization design, all of which need to be teased out. Our previous studies on the hyperbolic tree required lengthy studies using eye-movements and scales of semantic ambiguity (measured as information scent) in order to tease out issues of visualization design [18, 19] and visual attention [20]. We plan similar studies for DOI Trees, but they are beyond the scope of this paper. What we can say is that the current prototype is in use for organization charts at PARC, in use for other databases in the government, and under consideration for a web analytics product component. Users seem to be able to use DOI Trees easily. Several government agencies in the health and statistical services area have indicated interest. When we contacted the Xerox licensing office for licensing discussions on this system, we were amazed that they had already discovered it on the internal corporate Web and were already using it for their own applications. Thus, we believe it will not be hard to use the system for practical applications.

DOI Trees use predictions of the user's dynamically changing interest to change the display: If the user indicates interest by selecting one nodes, then the system predicts the user's relative interest in the other nodes through the DOI calculation. If the user indicates interest by a search for some term, then the system predicts interest in the other nodes through the DOI calculations from the nodes that hit. We are implementing other ways for the user to indicate a base interest, such as frequency of access. The purpose of having separate DOI and visual rendering calculations is so that new methods of indicating interest may be devised without having to redo the visual algorithms.

Nodes of most interest are filtered for visualization, geometrically enlarged, semantically zoomed, and shown in tree context of relevantly selected other nodes. Nodes predicted to be distant from the user's interest are shrunk, aggregated, or elided. Nodes in the display become the access portal to related information on the web or applications like email. DOI trees force the display to be contained within a constrained space, but they also choose extra nodes to display in order to fill that display.

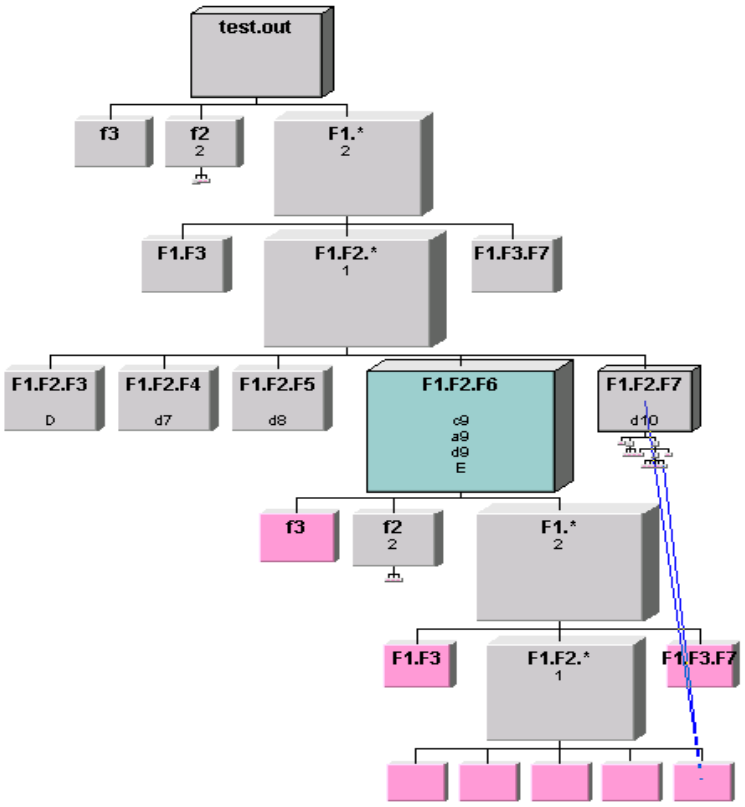


Figure 14. Tree derived from database with multiple links per node. One link type is used to form the tree. Others are visible when the mouse is placed atop them. (Node faces have had proprietary data removed).

These design features are in the service of higher-level goals. The principle goal is to reduce the average cost-structure of information to the user of a large information set. The DOI calculation and its subsequent use in visualization attempt to reduce the cost structure of the task using the information. For example, in Figure 12 the cost in time for finding who Stefik reports to or who reports to him in his many capacities is low. This is partly done by making user access to many of the other reporting relationships in the tree a little slower. That is to say, the DOI calculation is used to *bias* the interface in a way that accelerates likely actions. This differential cost of accessing information is what we mean by a cost structure and the paradigm of an attention-reactive user interface seeks to dynamically change these biases according to where the user's attention is (or should be—this paradigm can also be used to direct the user's attention to areas the system thinks are important). Although there is an access bias, notice the fact that DOI Trees still maintain an overview of the entire field of information, maintaining context and at least a minimum access to all pieces of information.

The second goal is to increase modularity between the DOI and the visual components by limiting the information exchanged between the DOI calculation and the visualization to a narrow interface. It should be possible to change either the DOI or visual component more or less independently Hence DOI Trees should make a good system building block.

The third goal is spatial modularity. By making the DOI Tree stay within its space bounds (which could be dynamically increased or decreased), it is easy to compose this display with other displays (for example, a panel showing detailed information about the current focus node). Thus, it would be easy to use this focus+context display as the overview part of a larger overview + detail display. Whereas a technique like TreeMaps stays within a bounded space, they have a more difficult time showing the contents of interest for nodes in large trees.

The last two goals make DOI Trees a modular system component to use in the construction of attention-reactive user interfaces for systems involving access to or sensemaking of large collections of information. The DOI Trees presented are particularly simple instantiations of the attention-reactive user interface idea. More complex dynamic calculations are possible that handle other sources of context or that take over automatically handling other overhead tasks for the user as the user's attention progresses.

8. ACKNOWLEDGMENTS

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A Focus+Context Technique Based on Hyperbolic Geometry for Visualizing Large Hierarchies

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A Focus+Context Technique Based on Hyperbolic Geometry for Visualizing Large Hierarchies.

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Abstract

We present a new focus+context (fisheye) technique for visualizing and manipulating large hierarchies. Our technique assigns more display space to a portion of the hierarchy while still embedding it in the context of the entire hierarchy. The essence of this scheme is to lay out the hierarchy in a uniform way on a hyperbolic plane and map this plane onto a circular display region. This supports a smooth blending between focus and context, as well as continuous redirection of the focus. We have developed effective procedures for manipulating the focus using pointer clicks as well as interactive dragging, and for smoothly animating transitions across such manipulation. A laboratory experiment comparing the hyperbolic browser with a conventional hierarchy browser was conducted.

Keywords:

Hierarchy Display, Information Visualization, Fisheye Display, Focus+Context Technique.

Introduction

In the last few years, Information Visualization research has explored the application of interactive graphics and animation technology to visualizing and making sense of larger information sets than would otherwise be practical (Robertson, Card and Mackinlay, 1994). One recurring theme has been the power of focus+context techniques, in which detailed views of particular parts of an information set are blended in some way with a view the of the overall structure of the set. In this paper, we present a new technique, called the hyperbolic browser, for visualizing and manipulating large hierarchies.

The hyperbolic browser, illustrated in Figure 1, was originally inspired by the Escher woodcut

shown in Figure 2. Two salient properties of the figures are: first that components diminish in size as they move outwards, and second that there is an exponential (devilish) growth in the number of components. These properties---``fisheye" distortion and the ability to uniformly embed an exponentially growing structure---are the aspects of this construction (the Poincar\'e mapping of the hyperbolic plane) that originally attracted our attention.

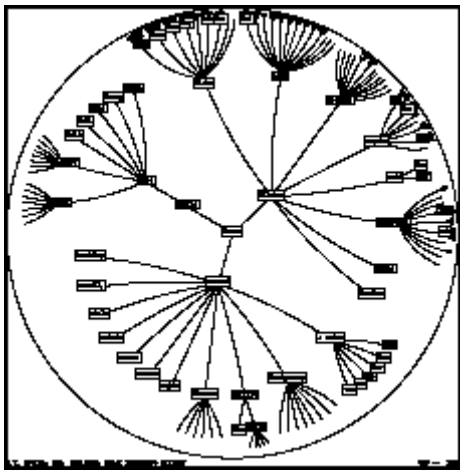
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Figure 1: An organization chart.

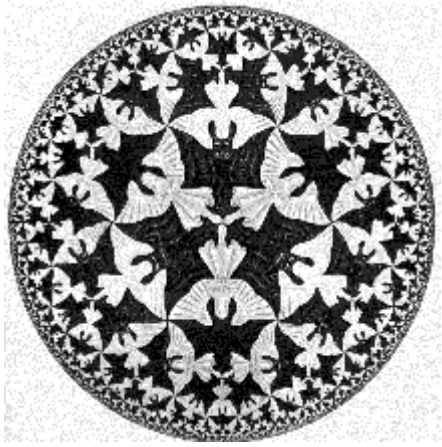
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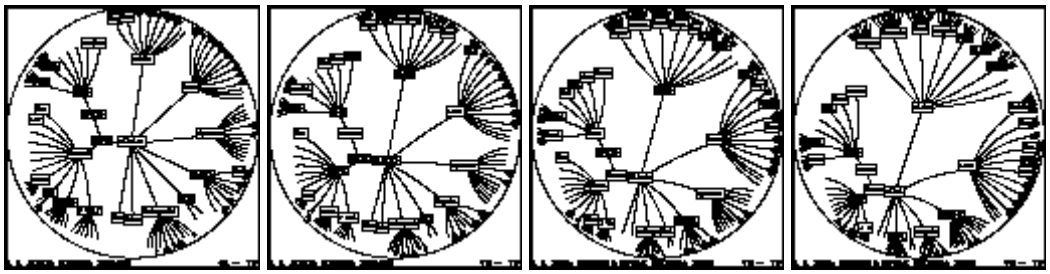
Figure 2: Original inspiration for the hyperbolic tree browser. Circle Limit IV (Heaven and Hell), 1960, (c) 1994 M.C. Escher Cordon Art -- Baarn -- Holland. All rights reserved. Printed with permission.

The hyperbolic browser initially displays a tree with its root at the center, but the display can be smoothly transformed to bring other nodes into focus, as illustrated in Figure 3. In all cases, the amount of space available to a node falls off as a continuous function of its distance in the tree from the point in the center. Thus the context always includes several generations of parents, siblings, and children, making it easier for the user to explore the hierarchy without getting lost.



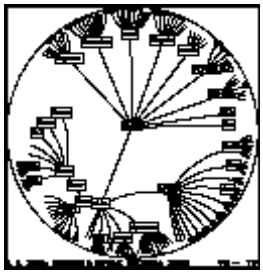
 Full Size Sequence Strip

Figure 3: Changing the focus.

The hyperbolic browser supports effective interaction with much larger hierarchies than conventional hierarchy viewers and complements the strengths of other novel tree browsers. In a 600 pixel by 600 pixel window, a standard 2-d hierarchy browser can typically display 100 nodes (w/ 3 character text strings). The hyperbolic browser can display 1000 nodes of which about the 50 nearest the focus can show from 3 to dozens of characters of text. Thus the hyperbolic browser can display up to 10 times as many nodes while providing more effective navigation around the hierarchy. The scale advantage is obtained by the dynamic distortion of the tree display according to the varying interest levels of its parts.

Our approach exploits hyperbolic geometry (Coxeter, 1965) (Moise, 1974). The essence of the approach is to lay out the hierarchy on the hyperbolic plane and map this plane onto a circular display region. The hyperbolic plane is a non-Euclidean geometry in which parallel lines diverge away from each other. This leads to the convenient property that the circumference of a circle on the hyperbolic plane grows exponentially with its radius, which means that exponentially more space is available with increasing distance. Thus hierarchies---which tend to expand exponentially with depth---can be laid out in hyperbolic space in a uniform way, so that the distance (as measured in the hyperbolic geometry) between parents, children, and siblings is approximately the same everywhere in the hierarchy.

While the hyperbolic plane is a mathematical object, it can be mapped in a natural way onto the unit disk, which provides a means for displaying it on an ordinary (Euclidean) display. This mapping displays portions of the plane near the origin using more space than other portions of the plane. Very remote parts of the hyperbolic plane get miniscule amounts of space near the edge of the disk. Translating the hierarchy on the hyperbolic plane provides a mechanism for controlling which portion of the structure receives the most space without compromising the illusion of viewing the entire hyperbolic plane. We have developed effective procedures for manipulating the focus using pointer dragging and for smoothly animating transitions across such manipulation.

We have implemented versions of the hyperbolic browser that run on Unix/X and on Macintoshes. We conducted an experiment with 4 subjects to compare the hyperbolic tree browser with a conventional browser on a node location task. Though no statistically significant performance difference was identified, a strong preference for the hyperbolic tree browser was established and a number of design insights were gained.

PROBLEM AND RELATED WORK

Many hierarchies, such as organization charts or directory structures, are too large to display in their entirety on a computer screen. The conventional display approach maps all the hierarchy into a region that is larger than the display and then uses scrolling to move around the region. This approach has the problem that the user can't see the relationship of the visible portion of the tree to the entire structure (without auxiliary views). It would be useful to be able to see the entire hierarchy while focusing on any particular part so that the relationship of parts to the whole can be seen and so that focus can be moved to other parts in a smooth and continuous way.

A number of focus+context display techniques have been introduced in the last fifteen years to address the needs of many types of information structures (Leung and Apperley, 1994) (Sarkar and Brown, 1994). Many of these focus+context techniques, including the document lens (Robertson and Mackinlay 1993), the perspective wall (Mackinlay, Robertson and Card, 1991), and the work of Sarkar et al, could be applied to browsing trees laid out using conventional 2-d layout techniques. The problem is that there is no satisfactory conventional 2-d layout of a large tree, because of its exponential growth. If leaf nodes are to be given adequate spacing, then nodes near the root must be placed very far apart, obscuring the high level tree structure, and leaving no nice way to display the context of the entire tree.

The Cone Tree (Robertson, Mackinlay and Card, 1991) modifies the above approach by embedding the tree in a three dimensional space. This embedding of the tree has joints that can be rotated to bring different parts of the tree into focus. This requires currently expensive 3D animation support. Furthermore, trees with more than approximately 1000 nodes are difficult to manipulate. The hyperbolic browser is two dimensional and has relatively modest computational needs, making it potentially useful on a broad variety of platforms.

Another novel tree browsing technique is treemaps (Johnson and Schneiderman, 1991) which allocates the entire space of a display area to the nodes of the tree by dividing the space of a node among itself and its descendants according to properties of the node. The space allocated to each node is then filled according to the same or other properties of the node. This technique utilizes space efficiently and can be used to look for values and patterns amongst a large collection of values which agglomerate hierarchically, however it tends to obscure the hierarchical structure of the values and provides no way of focusing on one part of a hierarchy without losing the context.

Some conventional hierarchy browsers prune or filter the tree to allow selective display of portions of the tree that the user has indicated. This still has the problem that the context of the interesting portion of the tree is not displayed. Furnas (1986) introduced a technique whereby nodes in the tree are assigned an interest level based on distance from a focus node (or its ancestors). Degree of interest can then be used to selectively display the nodes of interest and their local context. Though this technique is quite powerful, it still does not provide a solution to the problem of displaying the entire tree. In contrast, the hyperbolic browser is based on an underlying geometry that allows for smooth blending of focus and context and continuous repositioning of the focus.

Bertin (1983) illustrates that a radial layout of the tree could be uniform by shrinking the size of the nodes with their distance from the root. The use of hyperbolic geometry provides an elegant way of doing this while addressing the problems of navigation. The fractal approach of Koike and Yoshihara (1993) offers a similar technique for laying out trees. In particular, they have explored an implementation that combines fractal layout with Cone Tree-like technique. The hyperbolic browser has the benefit that focusing on a node shows more of the node's context in all directions (i.e. ancestors, siblings, and descendants). The fractal view has a more rigid layout (as with other multiscale interfaces) in which much of this context is lost as the viewpoint is moved to lower levels of the tree.

There have been a number of projects to visualize hyperbolic geometry, including an animated video of moving through hyperbolic space (Gunn, 1991). The emphasis of the hyperbolic browser is a particular exploitation of hyperbolic space for information visualization. We don't expect the user to know or care about hyperbolic geometry.

HYPERBOLIC BROWSER BASICS

The hyperbolic browser replaces the conventional approach of laying a tree out on a Euclidean plane by doing *layout* on the hyperbolic plane and then *mapping* to the unit disk (which is straightforwardly mapped to the display). *Change of focus* is handled by performing a rigid

transformation of the hyperbolic plane, moving the laid out tree in the process. Thus layout is only performed once. Space for displaying *node information* is also computed during layout and automatically transformed with each change of focus.

The implementation of points and transformations on the hyperbolic plane is briefly discussed in the appendix. The rest of this section presumes an implementation of the hyperbolic plane and discusses higher level issues.

Layout

Laying a tree out in the hyperbolic plane is an easy problem, because the circumference and area of a circle grow exponentially with its radius. There is lots of room. We use a recursive algorithm that lays out each node based on local information. A node is allocated a wedge of the hyperbolic plane, angling out from itself, to put its descendants in. It places all its children along an arc in that wedge, at an equal distance from itself, and far enough out so that the children are some minimum distance apart from each other. Each of the children then gets a sub-wedge for its descendants. Because of the way parallel lines diverge in hyperbolic geometry, each child will typically get a wedge that spans about as big an angle as does its parent's wedge, yet none of the children's wedges will overlap.

The layout routine navigates through the hyperbolic plane in terms of operations, like moving some distance or turning through some angle, which are provided by the hyperbolic plane implementation.

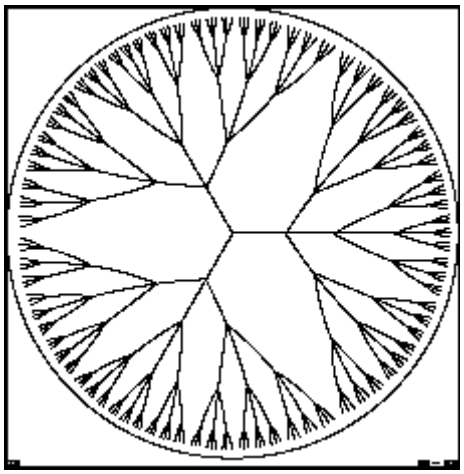
 Full Size Image

Figure 4: A uniform tree of depth 5 and branching factor 3 (364 nodes).

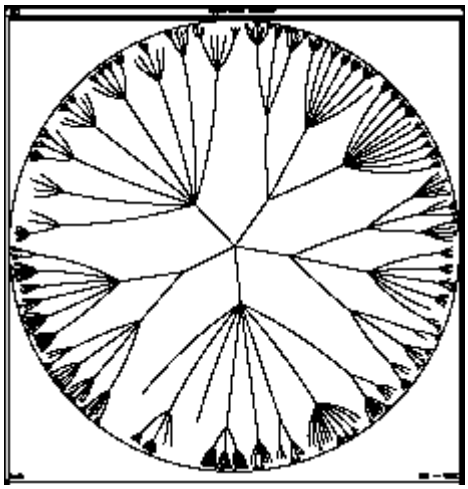
 Full Size Image

Figure 5: The initial layout of a tree with 1004 nodes using a Poisson distribution for number of

children. The origin of the tree is in the center.

Figure 4 shows what the layout of a uniform tree looks like. Notice how the children of each node span about the same angle, except near the root, where a larger wedge was available initially. To get a more compact layout for non-uniform trees, we modify this simple algorithm slightly, so that siblings that themselves have lots of children get a larger wedge than siblings that don't (the wedge size grows logarithmically). This effect can be seen in Figure 5 where, for example, the five children of the root get different amounts of space. This tends to decrease the variation of the distances between grandchildren and their grandparent.

Another option in layout (in contrast to all examples so far illustrated) is to use less than the entire 360 degree circle for spreading out the children of the root node. With this option, children of the root could all be put in one direction, for example to the right or below, as in conventional layouts. An example of this option, discussed below, appears in Figure 8.

Mapping and Representation

Once the tree has been laid out on the hyperbolic plane, it must be mapped in some way to a 2-d plane for display. (We can barely imagine the hyperbolic plane, not to mention see it.) There are two canonical ways of mapping the hyperbolic plane to the unit disk. In both of them, one vicinity in the hyperbolic plane is in focus at the center of the disk while the rest of the hyperbolic plane fades off in a perspective-like fashion toward the edge of the disk, as we desire. We use the conformal mapping, or Poincar\'e model, which preserves angles but distorts lines in the hyperbolic space into arcs on the unit disk, as can be seen in the takes lines in the hyperbolic plane to lines in the unit disk, but distorts angles. You can't have it both ways.

We tried the Klein model. But points that are mapped to near the edge by the Poincar\'e model get mapped almost right on the edge by the Klein model. As a result, nodes more than a link or two from the node in focus get almost no screen real-estate, making it very hard to perceive the context.

Change of Focus

The user can change focus either by clicking on any visible point to bring it into focus at the center, or by dragging any visible point interactively to any other position. In either case, the rest of the display transforms appropriately. Regions that approach the center become magnified, while regions that were in the center shrink as they are moved toward the edge. Figure 6 shows the same tree as Figure 5 with a different focus. The root has been shifted to the right, putting more focus on the nodes that were toward the left.

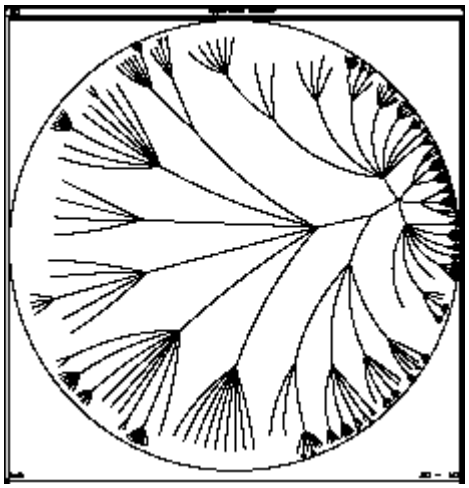
 Full Size Image

Figure 6: A new focus.

Changes of focus are implemented as rigid transformations of the hyperbolic plane that will have the desired effect when the plane is mapped to the display; there is never a need to repeat the layout process. A change of focus to a new node, for example, is implemented by a translation in the hyperbolic plane that moves the selected node to the location that is mapped to the center of the disk.

To avoid loss of floating point precision across multiple transformations, we compose successive transformations into a single cumulative transformation, which we then apply to the positions determined in the original layout. Further, since we only need the mapped positions of the nodes that will be displayed, the transformation only needs to be computed for nodes whose display size will be at least a screen pixel. This yields a constant bound on redisplay computation, no matter how many nodes are in the tree. And, the implementation of translation can be fairly efficient; we require about 20 floating point operations to translate a point, comparable to the cost of rendering a node on the screen.

Node Information

Another property of the Poincar\'e projection is that circles on the hyperbolic plane are mapped into circles on the Euclidean disk, though they will shrink in size the further they are from the origin. We exploit this property by calculating a circle in the hyperbolic plane around each node that is guaranteed not to intersect the circle of any other node. When those circles are mapped onto the unit disk they provide a circular display region for each node of the tree in which to display a represenation of the node. This can be combined with a facility that uses different representations for nodes depending on the amount of real space they receive. Figure 7 shows the same tree as Figure 1 with the display region of each node indicated.

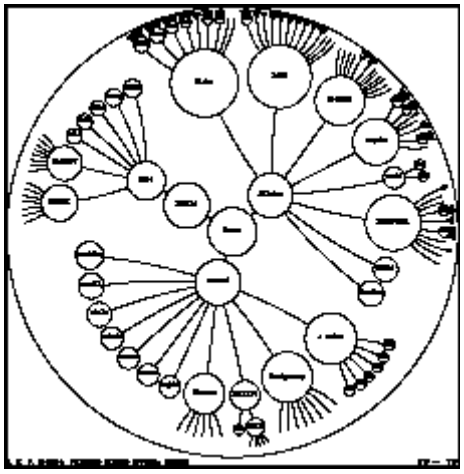
 Full Size Image

Figure 7: The display regions of nodes.

PRESERVING ORIENTATION

Orientation presents an interesting issue for the hyperbolic browser, because things tend to get rotated. For example, most nodes rotate on the display during a pure translation. There is a line that doesn't rotate, but the farther nodes are on the display from that line, the more they rotate. This can be seen in the series of frames in Figure 3. The node labeled ``Lowe'', for example, whose children fan out to the upper right in the top frame ends up with its children fanning out to the right in the bottom frame. These rotations are reasonably intuitive for translations to or from the origin. But if drags near the edge of the disk are interpreted as translations between the the source and the destination of the drag, the display will do a counter-intuitive pirouette about the point being

dragged.

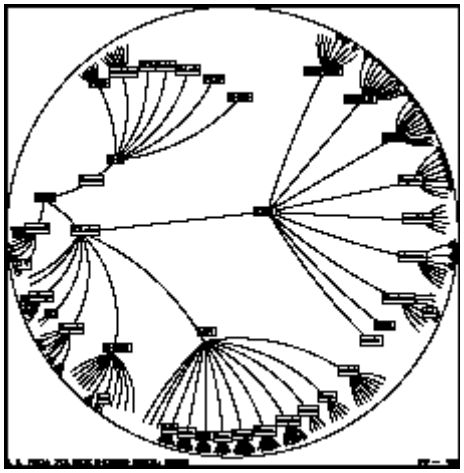
 Full Size Image

Figure 8: Putting children toward the right.

There is a fundamental property of hyperbolic geometry that is behind this and that also causes another problem. In the usual Euclidean plane, if some graphical object is dragged around, but not rotated, then is always keeps its original orientation---not rotated. But this is *not true* in the hyperbolic plane. A series of translations forming a closed loop, each preserving the orientation along the line of translation, will, in general, cause a rotation. (In fact the amount of rotation is proportional to the area of the closed loop and is in the opposite direction to the direction the loop was traversed.) This leads to the counter-intuitive behavior that a user who browses around the hierarchy can experience a different orientation each time they revisit some node, even though all they did was translations.

We address both of these problems by interpreting the user's manipulations as a combination of both the most direct translation between the points the user specifies and an additional rotation around the point moved, so that the manipulations and their cumulative effects are more intuitive. From the user's perspective, drags and clicks move the point that the user is manipulating where they expect. The additional rotation also appears natural, as it is designed to preserve some other property that the user expects. The user need not even be particularly aware that rotation is being added.

We have found two promising principles for adding rotations. In one approach, rotations are added so that the original root node always keeps its original orientation on the display. In particular, the edges leaving it always leave in their original directions. Preserving the orientation of the root node also means that the node currently in focus also has the orientation it had in the original image. The transformations in the examples presented so far all worked this way. It seems to give an intuitive behavior both for individual drags and for the cumulative effect of drags.

The other approach we have taken is to explicitly not preserve orientation. Instead, when a node is clicked on to bring it to focus, the display is rotated to have its children fan out in a canonical direction, such as to the right. This is illustrated in Figure 8 and also in the animation sequence in Figure 9. This approach is aided when the children of the root node are all laid out on one side of that node, as also illustrated in the two figures, so that the children of the root node can also fan out in the canonical direction when it is in focus.

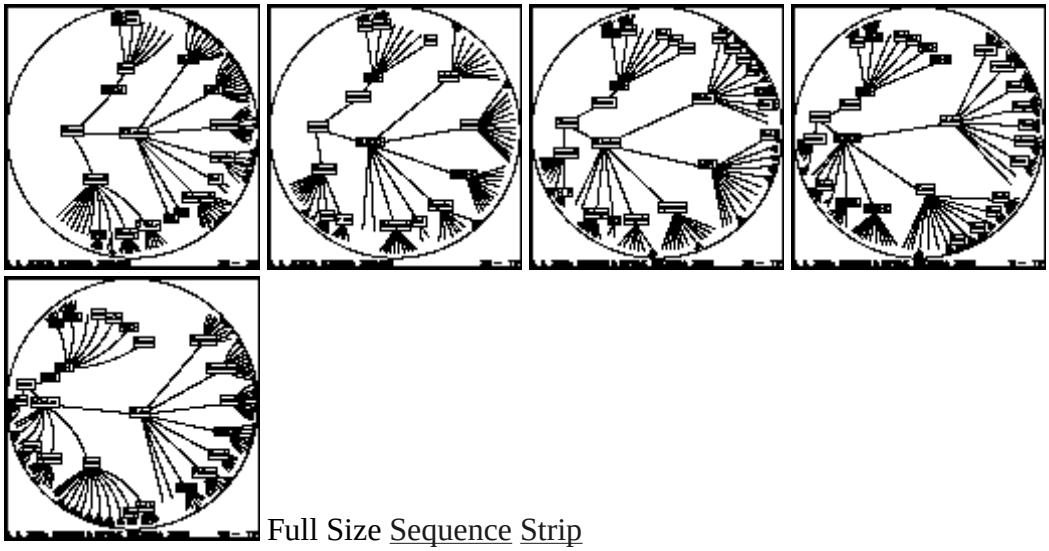

Full Size Sequence Strip

Figure 9: Animation with compromised rendering.

ANIMATED TRANSITIONS

As demonstrated by recent work on information visualizations, animated transitions between different views of a structure can maintain object constancy and help the user assimilate the changes across views. The smooth continuous nature of the hyperbolic plane allows for performing smooth transitions of focus by rendering appropriate intermediate views.

Animation sequences are generated using the so-called ``nth-root'' of a transition transformation, i.e. the rigid transformation that applied n times will have the same effect as the original. Successive applications of the ``nth-root'' generate the intermediate frames. The sequences in Figures 3 and 9 were generated this way.

Responsive display performance is crucial for animation and interactive dragging. This can be a problem for large hierarchies on standard hardware. We achieve quick redisplay by compromising on display quality during motion. These compromises provide options for use in a system that automatically adjusts rendering quality during animation, e.g. the Information Visualizer governor (Robertson, Card, and Mackinlay, 1989) or Pacers (Tang and Linton, 1993). Fortunately, there are compromises that don't significantly affect the sense of motion. Figure 9 shows an animation sequence with the compromises active in the intermediate frames. Unless specifically looked for, the compromises typically go unnoticed during motion.

One compromise is to draw less of the fringe. Even the full quality display routine stops drawing the fringe once it gets below one pixel resolution. For animation, the pruning can be strengthened, so that descendants of nodes within some small border inside the edge of the disk are not drawn. This tremendously increases display performance, since the vast majority of nodes are very close to the edge. But it doesn't significantly degrade perceptual quality for a moving display, since those nodes occupy only a small fraction of the display, and not a part that the user is typically focusing on.

The other compromise is to draw lines, rather than arcs, which are expensive in the display environments we have been using. While arcs give a more pleasing and intuitive static display, they aren't as important during animation. This appears to be the case both because the difference between arcs and lines isn't as apparent in the presence of motion, and because the user's attention during motion tends to be focused near the center of the display, where the arcs are already almost straight.

One other possible compromise is to drop text during animation. We found this to be a significant

distraction, however. And text display has not been a performance bottleneck.

EVALUATION AND FUTURE WORK

A laboratory experiment was conducted to contrast the hyperbolic browser against a conventional 2-d scrolling browser with a horizontal tree layout. Our subjects preferred the hyperbolic browser in a post-experimental survey, but there was no significant difference between the browsers in performance times for the given task, which involved finding specific node locations. The study has fueled our iterative design process as well as highlighted areas for further work and evaluation.

The two browsers in the study support mostly the same user operations. ``Pointing" provided feedback on the node under the cursor in a feedback area at the bottom of window. ``Clicking" moved a point to the center. ``Grabbing" any visible point allowed interactive dragging of the tree within the window. The 2-d scrolling browser provides conventional scrollbars as well.

The experiment was based on the task of locating and ``double-clicking" on particular nodes in four World-Wide-Web hierarchies identified by their URLs (the application intent being that a Web browser would jump to that node). Though this particular task and application were adequate for a rough baseline evaluation, there are problematic aspects. Typically, this task would better be supported by query-by-name or even an alphabetical listing of the nodes. Furthermore the WWW hierarchy (based on breadth-first flattening of the network) contained many similarly-named nodes and the hierarchy wasn't strongly related to a semantic nesting.

After pilot trials, we added to both browsers a feature to rotate the names of children of a pointed-to node through the feedback area and then jump to the current child. We also added a toggleable ``long text" mode in which all nodes beyond an allocated space threshold disregard their boundaries and display up to 25 characters. Despite the overlapping of the text, this leads to more text being visible and discernible on the screen at once (see Figure 10).

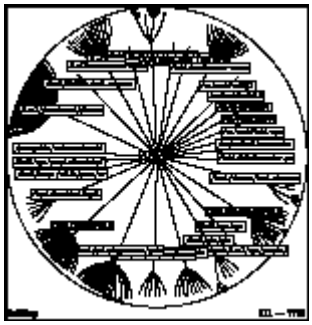
 Full Size Image

Figure 10: Hyperbolic browser in long text mode in World Wide Web hierarchy utilized in laboratory experiment.

The experiment used a within-subject design with four subjects, and tested for the effects of practice. We found no significant difference in time or number of user actions in performing the tasks across the browsers. There was a significant practice effect in which practice produced a decrease in the number of user actions required to perform the task for both browsers, but there was no practice effect on task completion time for either browser. These practice effects did not differ significantly between the browsers.

Our post-experimental survey showed that all four subjects preferred the hyperbolic browser for ``getting a sense of the overall tree structure" and ``finding specific nodes by their titles," as well as ``overall." In addition, specific survey questions and our observations identified relative strengths and weaknesses of the hyperbolic browser. Three of the subjects liked the ability to see more of the

nodes at once and two mentioned the ability to see various structural properties and a better use of the space.

The amount of text that the hyperbolic browser displays was a problem. The experimental task was particularly sensitive to this problem because of the length and overlap of URLs, and the ill-structured nature of the WWW hierarchy. Though the long text mode was introduced before the study, none of the subjects used this feature during the study, preferring to point at the parent and then rapidly rotate the children through the much larger feedback area.

Problem areas mentioned by one subject were that the hyperbolic browser provide a weaker sense of directionality of links and also of location of a node in the overall space (because shapes changed). Layout in a canonical direction as shown in Figure 8 addresses the first of these problems, but may worsen the second. In particular, for applications in which access to ancestors or to the root node is particularly important, this layout makes it easy to find and navigate toward these nodes.

A number of refinements may increase the value of the browser for navigating and learning hierarchies. For example, landmarks can be created in the space by utilizing color and other graphical elements (e.g.\ we painted http, gopher, and ftp links using different colors). Other possibilities are providing a visual indication of where there are nodes that are invisible because of the resolution limit, using a ladder of multiscale graphical representations in node display regions, and supporting user control of trade-off between node display region size and number of visible nodes (i.e.\ packing). The effective use of these variations are likely to be application or task dependent and so best explored in such a design context.

CONCLUSION

Hyperbolic geometry provides an elegant solution to the problem of providing a focus+context display for large hierarchies. The hyperbolic plane has the room to lay out large hierarchies, and the Poincar\'e map provides a natural, continuously graded, focus+context mapping from the hyperbolic plane to a display. The hyperbolic browser can handle arbitrarily large hierarchies, with a context that includes as many nodes as are included by 3d approaches and with modest computational requirements. Our evaluation study suggested this technique could be valuable, and has identified issues for further work. We believe that the hyperbolic browser offers a promising new addition to the suite of available focus+context techniques.

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APPENDIX: IMPLEMENTING HYPERBOLIC GEOMETRY

Note: If you have trouble linking to this Appendix, the following link is a scanned image of the Appendix content: Scanned Image of Appendix

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