A Case Study for Hypermedia Cartography: Radial Growth in Trembling Aspen at Waterton Lakes National Park

Christopher R. Weber
Barbara P. Buttenfield
National Center for Geographic Information and Analysis
Department of Geography
State University of New York at Buffalo
Buffalo, New York 14261

Dennis E. Jelinski
Department of Forestry, Fisheries and Wildlife
Institute of Agriculture and Natural Resources
University of Nebraska-Lincoln
Lincoln, Nebraska 68483-0814

Abstract

Hypermedia software developments afford new opportunities for cartographic visualization. There is a burgeoning inquiry into effective techniques and formats within the hypermedia realm Users may now work with visualizations proactively, initiate data queries and steer the presentation in a manner consistent with the associative power of the human thought Hypermedia formats provide advantages of both the distillation of the data and the portrayal of the authored relationships between data chunks. This research describes the creation and implementation of one such visualization. Forty years of radial growth in trembling aspen tree populations from Waterton Lakes National Park, Alberta, Canada are depicted in macro and micro scales. Meta-information about the display and its contents is provided through hyperlinks to graphics, text, embedded animation, and photos.

Keywords: Hypermedia, multimedia, animation, spatiotemporal, cartography, aspen, biogeography.

Introduction

> "Geographers have long practiced and preached that several journeys across a physical landscape were necessary for a full, multi-viewed understanding of the earth as a home of man. ...if we want true learning and understanding in the spatial domain then there is definitely a place for a hypermap" (Laurini and Thompson 1992, p. 681).

Traditional map production generates single static maps offering data that have been distilled for the map reader through a highly focused, authored view of the world (Monmonier 1991). Animated maps provide multiple views of subject matter or present a dynamic portrayal of spatiotemporal data. These have been extant for well over 10 years, though these constructions still present a highly authored view. Comprehensive reviews of this method and its contribution to cartography to date can be found in Cambell and Egbert (1990) and in Weber and Buttenfield (1993)

To overcome the sequential view of the world presented in animation, Monmonier (1991) has proposed a concept called *Atlas Touring*. This format involves the presentation of several maps as well as statistical diagrams and text blocks, organized into *graphic scripts* composed of *graphic phrases*. Each phrase is "a computer generated sequence of focused graphics tailored to the data and intended to explore a distribution, a spatial trend, a spatial-temporal series, or a bivariate relationship" (Monmonier 1991, p. 4). To utilize this format effectively, Monmonier has called for *experiential* maps which allow the map reader to freely explore the scripts within the atlas. It has been proposed that integration of viewer perspectives into the mindset of the cartographer, researcher, or domain expert, is possible by adopting presentation formats which enable *proactive* user involvement, as opposed to *interactive* involvement (Buttenfield 1993, Buttenfield and Weber, 1993). In this manner, map readers may generate their own views and steer the ordering and duration of graphic script equivalents within an atlas format.

Hypermedia software development and multimedia computer platforms provide cartographers with the capabilities for such presentations. Furthermore, due to cascading costs, such systems are fast becoming the norm rather than the exception (Donovan, 1991a). This has resulted in ready access to these new technological standards and working environments. The implications for both cartography and GIS are vast and the topic of much research (see for example Armstrong et al 1986, Koussoulakou and Kraak 1992, Buttenfield and Weber 1993).

This research reviews the design, construction and iterative refinment of a hypermedia animation using forty years of radial growth data from trembling aspen populations from Waterton Lakes National Park, Alberta Canada. The hypermap can be viewed at macro and micro scales, has embedded metadata, proactive user steering, as well as granularized help and encyclopedic reference functions These features are accessed through "hot" icons within the map itself, through hypertext, and through iconic buttons. The document utilizes animation, pictures, graphs, charts, and text Most importantly, the visualization of tree growth data allows viewers to see trends which are counter-intuitive to the climate and soil conditions existing within the park. Without the visualization, these trends are perceptible only through sophisticated statistical analyses. Alone or combined with the original field research account, the visualization reveals the existence of spatial patterns that would not be immediately apparent in a tabular or static map display.

Background

> "There is a new profession of trail blazers, those who find delight in the task of establishing useful trails through the enormous mass of the common record. The inheritance from the master becomes, not only his additions to the world's record, but for his disciples the entire scaffolding by which they were erected." (Bush 1945, p. 108)

The concept of hypermedia was first introduced by Vannevar Bush in 1945. He envisioned a *Memex* system which would allow for a mechanized associative linking of the vast amounts of information available in the mid 20th century. Memex would free investigators from being bogged down in the ever-growing mountains of research produced by increased specialization into fringe disciplines. Not only would the record of human achievements continue to be enormously extended, it would be accessible

Today, the term hypermedia refers to information structures in which various nodes containing information are associated through direct links much the same way as information is associated within the human mind. It is an automated as opposed to mechanical realization of Bush's vision. Hyperstructures are thus beyond the sequential style of composition found in most books; they are akin to the neural structure of a thesaurus (Laurini and Thompson 1992). Authors of hypermedia documents present information not only as disparate chunks found in the nodes themselves, but also through the structure of the node links which reflect the author's conceptualization of the relationships between the node topics These data nodes are commonly referred to as *hypernodes* and the associative links as *hyperlinks.*

The data residing at a hypernode may appear in various forms including animation, audio, text, video, CD-ROM, static graphics and spreadsheets Thus, hypermedia structures may be multimedia in nature by incorporating divere media within a single structure (Barker and Tucker 1990). Hyperlinks may reflect a hierarchical structure within the data, a consensus of association developed through multi-user input, or perhaps a domain specific ordering which guides experts between intuitively linked nodes For instance, in a GIS, hypernode linkages may be constructed to allow the circular sequence· map layers, landuse, agriculture, erosion, rainfall, cloud cover, greenhouse effect, carbon dioxide levels, pollution, industry, landuse, map layers

Types of links include *inferential* and *organizational* hyperlinks which may be constructed to connect the data to hardware and non-hypermedia programming languages. *Implication* links can connect hypernodes in inference trees. *Execute* links can be sliders or buttons which are used in high level programming interfaces for steering computation. *Index* links may connect to a relational database. *Is-a* links may set up semantic network structures, and has-a links can describe properties of hypernodes. A complete discussion of hyperlink types and their relationship to semantic networks, neural networks, and relational data structures may be found in Parsaye et al (1989).

Because of the seemingly unlimited possibilities presented by mental association of subject matter, navigation through hypermaps and hyper-databases becomes problematic. Properly structured, maintained, and security governed hyperdocuments should rely upon several modes of navigation There may be a novice mode for newcomers to the realm, and an expert mode for users familiar with the data domain (Laurini and Thompson 1992). Co-authorship may also be possible, through editable text and importation of additional data. This is demonstrable in the hypertext help functions familiar to users of Window's™ (Microsoft Corp. 1992) products

The cartographer developing a hypermedia document must decide whom to target as viewers and what information and meta-information they should have access to. Design considerations for the graphical symbols representing hyperlinks along with their visual placement, and the organization of hyperlinks within hyperdocuments are pressing issues for developers Hyperlinks should be designed and placed so as to provide the user with information about the probable nature of the destination hypernode. The very existence of links in hypermedia conditions the user to expect purposeful, important relationships between linked materials (Landow 1991). Hyperstructures should stimulate the user to explore through stylized iconography and color schema which highlight active hyperlinks. It has been suggested that query capabilities should include devices that allow users to see where they have been, to see new paths to a destination they have previously visited, to review paths taken to a particular hypernode, and to put the user into a previous context (Oren 1987) These design considerations should prevent users from becoming lost or disoriented when perusing a document A review of the psychological implications of becoming lost in hyperdocuments can be found in Harpold (1991)

Hypermedia lends itself to easy and rapid prototyping The lure of its capabilities for popular use has insured authoring of transparent interfaces and scripting languages by product developers. Hypermedia documents can be in themselves high-level, flexible representations that require minimal familiarity for new users to adopt (Woodhead 1991) Their effectiveness for data portrayal and learning is becoming apparent. Yager (1991) contends that hypermedia / multimedia solutions enhance audience immersion and that multi-sensory presentations speed and improve understanding, and increase attention spans. The ability of pictures to enhance recall of textual information has been demonstrated (Kozma 1991). For spatio-temporal data, "there is a statistically significant difference between the time it takes to answer a question (at any reading level) looking at an animated map [shorter time] and the time it takes to answer the same question looking at a static map [longer time] displaying the same spatio-temporal phenomenon" even though the quality of answers is not significantly different (Koussoulakou and Kraak 1992, parenthetic comments by this author) Lastly, Beer and Freifield (1992) report that the US Department of Defense finds that learning assisted by hypermedia / multimedia is cost effective. Interactive videodisc instruction takes a third less time, costs about a third less and is more effective than conventional methods of learning even though the initial outlay costs are high.

With the continued evolution of operating environments and accompanying software which allow dynamic linking of various software packages, personalized hyperlinked GIS may arrive in the near future. Such modular architecture has been proposed for Spatial Decision Support Systems as an alternative to the proprietary data, display and report GISs commonly marketed (Armstrong et al. 1986). Hyper-authoring tools are also readily available to cartographers, especially for desktop computers. Implementation of hypermedia is fast becoming common on these platforms through multimedia extension standards in Microsoft's^{TM} Windows 3.1^{TM} running under DOS, and Apple's^{TM} Quicktime^{TM} running under the Macintosh^{TM} operating system Through these technologies, multimedia and hypermedia are predicted to provide the most popular interface tools for these systems within a few years (Donovan 1991a). Currently these systems allow for embedding of external code into multimedia and hypermedia software through Object Linking and Embedding and Dynamic Linking and Embedding (OLE and DDE in Windows 3.1^{TM}) and through External Commands and External Functions (XCMDs and XFCNs in the Macintosh^{TM} environment). Most importantly, these hyper-desktop environments allow for seamless integration of numerous software packages. Microsoft's^{TM} Office^{TM}, now in distribution, is an example of such an environment at work. Reviews of hypermedia authoring products may be found in Bove and Rhodes (1990), Donovan (1991b), Yankelovich et al. (1991), Bielawski and Lewland (1991), Chua (1991), Scisco (1992) and Kindelberger (1993).

There has been a recent surge of exploration into hypermedia by cartographers, and each production has a unique focus. The earliest of these, the BBC's "Domesday Project", was conceived as a geographical commemorative reflecting the United Kingdom of the 1980's (Openshaw and Mounsey 1987, Ruggles 1992). Its title reflects the 900th anniversary of William the Conqueror's survey of England in the year 1086 A series of Ordnance Survey maps at scales between 1:625,000 and 1:10,000 serve as the base reference for a collection of text, pictures, photos, and relevant data reflecting the culture of the United Kingdom, Isle of Man and the Channel Islands in 1986 The system allows for limited geographic data manipulation including statistical and Boolean comparisons of pairs of maps. The design challenge for this project was the encoding and rapid retrieval of approximately 54,000 pictures, 500 analog maps, and sufficient data and algorithms to produce digital maps from the database in real time. Storage requirements are one of the major hurdles facing multimedia cartographic displays. In this case the solution was a combination of data compression techniques and the selection of videodisk technology which can hold 320 Mbytes of digital data in the sound track in addition to the 54,000 video images.

The advent of Apple Computer's Hypercard^{TM} in the past decade and the potential of hypermedia for educational applications has fostered several pedagogical productions. Tau et al (1988) produced "Map Projections" for the US Department of the Interior Geological Survey This Hypercard™ stack is a tutorial on map projections, their transformations, and their uses. Black and white text and pictures serve as the visual media, though the software's scripting language allows for external commands to various media and multimedia hardware

Geoff Dutton has created two rather interesting Hypercard™ stacks The first is a demonstration of data-quality / data-uncertainty mapping principles which provide viewers with fuzzy boundary views of vector data based on probabilities of generalization during digitization (Dutton 1992). The second is an overview of Dutton's triangular tessellation system for the Earth (Dutton 1991) Like the Map Projections project, the graphics and text in Dutton's stacks are limited to black and white colors, though a smattering of sound bites from popular sources alert the user to transitions and aid in steering Additionally, Dutton has relied heavily on Hypercard's™ scripting language Hypertalk™ to avoid redundant storage problems and allow for flexibility in display parameters

An interactive flip-art animation entitled "A Cartographic Animation of Average Yearly Surface Temperatures for the 48 Contiguous United States: 1897-1986" (Weber and Buttenfield 1993) allows for temporal steering through interactive "hot" regions of the display screen, as well as user initiated viewing of meta-information. The hypermedia aspects of this project are not intricately developed. The notion of allowing the map itself to act as the interface was the experimental focus of the interactivity. Exposure of the animation to viewers around the U.S , and consideration of their comments, resulted in an iterative design process which significantly improved the quality of the display and the comprehensibility of the interactive links. The project continues to accept revisions in design. Voice-over and other sonifications are being considered. The topical motivation for the production adheres strictly to the title.

The "Interactive Multimedia Cartography Project" at the University of Wisconsin-Milwaukee (Tilton and Andrews 1993) is a closely structured hypermedia production in which a major focus is a new paradigm for user navigation through the hyperspace The database is a large one, and typically a user can become lost in such huge hyper-databases. Tilton and Andrews are exploring an alternative approach to navigation through display environments within which information is brought to the user and made available for analysis. The project is still under construction, and the efficacy of the navigation system has yet to be reviewed. The authors are utilizing Macromind™ Director™ software to control external C code and access videodisc stored of images.

"Hyperkarte" (Armstrong 1993) is an intentional pun on the popular software, though this particular hyperstack was written in Supercard™. This software alternative allows color images, animation, and a more refined stack production system than that afforded in Hypercard™. The motivation for the project is pedagogic The stack is a tutorial of dot and choropleth mapping techniques. At first glance the linkages between nodes appear to be based on a flow chart structure. Upon closer inspection, the "where am I" node allows radial access to all levels of the stack Because of the voluminous amount of conceptual information provided in the system, Armstrong has focused a good deal of attention on navigational aids One particularly effective solution is provided by "postage stamp" icons which pictorially preview the destination nodes of various hyperlinks

Hypermedia's penchant for interactivity and it's multimedia capabilities made it the ideal choice for this researcher's explorations into sonification for cartographic displays (Weber 1993) Embedded sounds were rated in map-task situations by subjects who mouse-clicked on and dragged "sound coins" to desired destinations on digital maps. Scripting commands were used to record subject responses to external files The topical focus of the research necessitated a flexible multimedia testing environment Macromind™ Director™ software again provided a convenient and malleable set of tools to complete this human-computer interface task, though the resulting product was not, in itself, a hypermedia production.

It can be seen that the development of hypermedia software and hardware has propelled the fulfillment of Vannevar Bush's dream. Educational productions are appearing in nearly every discipline including cartography. Hypermedia's rapid prototyping capabilities and multimedia interfaces are allowing the completion of high level research to be possible in less time and at less expense than ever before. Hypermedia's accelerating evolution is a result of its survival as a freely adaptable species Its continued survival will be a test of its ability to fulfill the expectations of researchers who see it as the connecting web of the information age. For the Waterton Lakes project, it certainly performed as expected

Building the Hyper Document

"Radial Growth in Trembling Aspen at Waterton Lakes National Park" was motivated by curiosity into the efficacy of hypermedia for cartographic display, and a need to efficiently visualize numerical ecological data (Jelinski 1987). The ultimate conceptualization and continuing refinement of the document is an interative process involving cartographers, ecologists, computer scientists and non-expert viewers.

Previous experience animating spatio-temporal data in flip-art form (Weber and Buttenfield 1993) indicated an efficient method of visualization, encapsulating 40 years of forest data. It was decided to reduce the storage volume by using a software scripting language (Macromind™ Director's™ Lingo™) to compute image frames in real time during the animation. Tree-growth data for cumulative yearly growth at a macro scale (the entire park) and at micro scales (individual aspen populations) is embedded in the animation within unseen text cast members Aspen populations at the macro level are represented by leaf icons whose size and color reflect the cumulative growth and yearly growth respectively. At the micro level, cloned tree stands are likewise represented by dynamic tree stand icons. In the visualization, dynamic icons change size from one year to the next giving the impression of continuous growth.

The dynamic icons are positioned on 3-D terrain maps of the park at both scales. Orientations of these surface maps necessitated cartographic design decisions for each population map and the map of the park as a whole Thus, the positions of time lines, map legends, titles, interactivity buttons, as well as the surface map itself is customized for each scale of portrayal. A binding thread is necessary to thematically link each of the animated maps. A color sequence from yellow to deep green represents the relative yearly growth of populations and clone stands, and is diffused throughout the maps' designs. Hot buttons are dithered with this sequence and embossed with neutral gray borders. Hot text and hot labels are presented in a median green tone. Each map's time line, a histogram of cumulative yearly growth over the depicted 40 years, is "revealed" with present and past years in appearing in median green, and upcoming years remaining neutral gray.

Yearly growth classes are both chromatically intuitive and discernible from the legend. For each map, an information / help button labeled with a "?" links the viewer to granularized help displays. These displays describe the map region, the data being portrayed, and link the viewer to text and pictures describing trembling aspen in the study area. Instructions on how to use the interactive display are also available. In addition, the map legend is embossed by a button border. Clicking on it links the viewer to an explanation of its symbology and data classes. Lastly, at the site level, a "ZOOM OUT" button allows the viewer to return to the macro park level

In a structured hypermedia document, the design implies that a topical structure ought to be reflected in the placement of hypernodes and hyperlinks (Jonassen and Wang 1990). During the early stages of development, the hyperstructure of the aspens hyperdocument was basically a flowchart in nature. That is, micro site animations were accessible only by passing down from the macro park level, population statistics were viewable only through the overview map. No horizontal movement through the hyperspace was possible between micro site displays. Horizontal links were created to interconnect all site level maps (see the gray links in figure 1) and meta-displays These links are accessed through stacked at the edge of the display, labeled with abbreviated names of the study sites. The buttons retain their positions between views but change their labels which always appear alphabetically from top to bottom. This consistent web structure is intuitive and simple for users to comprehend.

Other details of the hyperstructure include links between help screens and field guide descriptions of the trembling aspen species, explanations of interactivity, stored data values, and a map showing the location of the park From the field guide, links provide color pictures of trees, leaves, bark and flowers, as well as a map of the species' range A common explanation of the study area legend is linked from each population node. Conceptual and semantic links interconnect similar information chunks. Users can browse supplementary information nodes from each animated portion. This is consistent with interactive conventions which allow expert users to rapidly glean information from the animated overview, and at the same time provide for interrupted and explanatory views for the novice user (Chignell et al , 1991)

It is important to stress that the iterative design process has played a crucial role in the document's construction. There is very little science to guide designers in creation of hypermedia (Laurel et al. 1990). The nature of the medium necessitates designs that reflect the features of the topic at hand, otherwise the associative value of hyperlinks would be lost. The granularity and content of hypernodes must be determined by the subject. The hyperlinks accessing these nodes must be designed with the subject in mind as well. Constant revision within a conceptual framework has allowed creative solutions to navigation and query problems for this document and have led to innovative cartographic solutions for data portrayal and interactivity

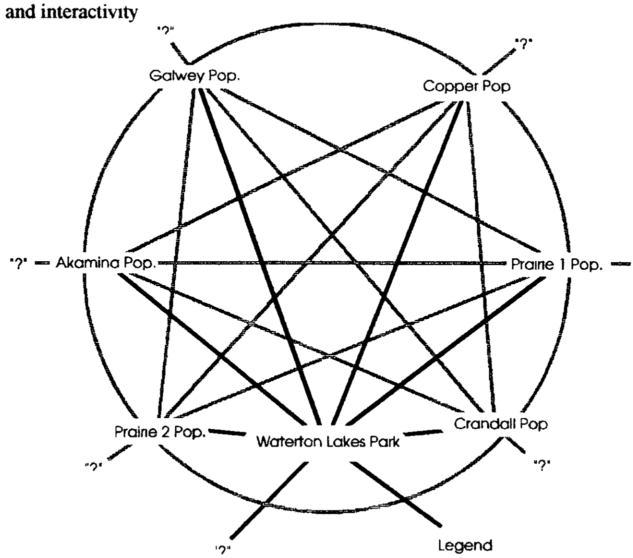

Figure 1: Part of the hyperstructure of "Radial Growth in Trembling Aspen at Waterton Lakes National Park" Gray links lie below black links if conceptualized in 3 dimensions.

The Cartographic Perspective

One pressing issue in cartography today is interface design for computer displayed maps. Computer display real estate, and subsequently map quality, is often traded for interface accommodations Users of GIS and other computer mapping software are confronted with arrays of buttons, slider borders, blocks of text fields, and elusive pop-up menus. "Radial Growth in Trembling Aspen at Waterton Lakes National Park" takes a stab at the traditional screen interface by promoting the map itself as both the interface and the query language

Meta information about the trembling aspen data portrayed is accessed through hot labels Clicking on the portrayal itself (the dynamic icon) allows the user to take a closer look at the clones comprising a population. When the legend is activated, it becomes self-explanatory Clicking on the park map gives rotating 3-D views of the surface. The histogram time-line allows for pause and continue functions, as do each map title. Whenever possible, map elements or hot text provide control, query, and steering functions in lieu of buttons and GUI devices. Users are guided to interface controls through both color scheme and iconography

Traditional cartographic methods pose new questions when viewed in an interactive dynamic map user environment (Koussoulakou and Kraak 1992) The added dimension of spatio-temporal display has afforded the opportunity for bivariate and bi-functional map feature designs in this production The yearly and cumulative radial growth of aspen populations are both able to be depicted with a single icon whose visual variables of color and size serve separate purposes. As a comparison of 40 years of growth is the subject of interest, size for cumulative growth takes visual precedence over color which represents yearly incremental growth. This design is consistent with the hierarchy of visual variables as outlined in Bertin (1983). Position in time is portrayed through color highlighting of a temporal histogram whose remaining visual variables remain constant. Both data icon and histogram designs serve hypermedia steering functions.

Lastly, this animated product circumvents the GIS layer model of data depiction. In most previous animations described in the cartographic literature (see for example DiBiase et al. 1992, Monmonier 1992, Weber and Buttenfield 1993) flip-art and linearly structured animations have been constructed from map pictures whose data had been previously analyzed and portrayed through external systems "Radial Growth in Trembling Aspen at Waterton Lakes National Park" is a hybrid *real time -- real-time later* animation In a real-time animation, "all calculations necessary to produce a frame are immediately followed by its display. In the second situation (real-time later) the results of single frame calculations are written to a file, which is used later for display" (Koussoulakou and Kraak 1992, p. 102). The surface maps for this animation have been previously computed. So have the cumulative yearly growth data, but these are accessed and interpreted in real-time to control the size and color of dynamic icons at multiple scales. This circumvention of the frame-by-frame or flip-art format allows for tight encapsulation of the animation elements, continued expandability, and a subsequent ease of implementation with significant computer memory savings. The temporal growth attributes of each population mimics a primitive object-oriented spatio-temporal data structure. A model such as this could ultimately be used to create a general purpose cartographic animation system in which the user downloads base maps and spatio-temporal data, and then selects or creates dynamic icons for data display.

The Ecological Perspective

Understanding the dynamics of tree growth can be advanced with developments in computer visualization and especially animation. The power of the animation described herein is two-fold. First, the animation is a visualization tool that effectively assists in communicating patterns of growth. Because most forest trees are long-lived, and large sample sizes are required, the data sets become voluminous. Thousands of data values were used in this simulation. Animating radial growth helps clarify complex patterns of development and improves the scientist's understanding of the overall growth structure of the populations. Growth data can be represented at a range of hierarchical levels. The lowest level (individual tree) provides the greatest detail. However, one reaches the limits of knowledge for which lower level data can be useful. Emergent properties may only be visible from an animation of higher levels in the hierarchy (e.g., the growth "behavior" of clones or entire populations). The animation of radial growth in aspens also adds an additional dimension to visualization by dynamically assembling a series of still images or frames which allows the animation to be stopped at any point. The second powerful advantage of animating environmental data such as tree growth is that in addition to being useful as an explanatory tool, it can be used as an exploratory device. In this case it permits evaluation of the effect of environmental controls on the patterns of growth. In a heterogeneous environment such as Waterton Lakes National Park, the animation becomes an important exploratory tool for formulating hypotheses of cause-effect and the effect of environmental changes (e.g., how interannual changes in climate affect tree growth).

Summary

Traditionally, cartographic displays have been designed for static illustration. Reference and navigational maps illustrate the geography of a place at a single time. Thematic maps depict statistical measures for a single sample, or the results of modeling and analysis for a single iteration or set of model parameters. Geographical analysis has begun to address problems and issues that occur in more than a single time slice, and to demand software and hardware technologies that can provide visual tools to assist their research. The display elements traditionally used in geographical analysis are changing from the static map, chart, or table of numeric information to dynamic displays, for example, video, computer simulation, and map animation. With the developments in these display capabilities in hand, one is able to find answers to more complicated and more realistic research questions. The animation of aspen tree growth in Waterton Lakes National Park provides an example of the types of dynamic elements that should become commonplace in geographical analysis and in GIS software very soon.

Readers who are interested in obtaining a copy of the hypermedia document can find it at the anonymous ftp address *alpha2.csd.uwm.edu* with the user name *anonymous* and the password being your entire internet email address. The hypermedia document is one of several archived in the directory *pub/cartographic_perspectives* and is archived under the filename *aspecs.sea.hqx.*

Acknowledgements

This research forms a portion of research Initiative 8, "Formalizing Cartographic Knowledge" and Initiative 10 "Spatio Temporal Reasoning", funded by the National Center for Geographic Information and Analysis, supported by a grant from the National Science Foundation (SBR 88-10917); support by NSF is gratefully acknowledged.

Bibliography

Andrews, S , Tilton, D. (1993) Alternative Interface Designs for Hypermedia Cartography, Annual Meeting, Association of American Geographers, April 6-10, Atlanta, Georgia

Armstrong, M.P., Densham, P.J., Rushton, G. (1986) Architecture for a Microcomputer-based Decision Support System, *Proceedings of the Second International Symposium on Spatial Data Handling*, International Geographical Union, Williamsville, New York, 1986, 120-131

Armstrong, M.P. (1993) Hyperkarte, unpublished hypermedia map design program University of Iowa, Department of Geography.

Barker, J., Tucker, R.N. (1990) The Interactive Learning Revolution, Nichols, New York.

Bertin, J (1983) Semiology of Graphics, The University of Wisconsin Press, Madison

Bielawski, L , Lewland, R. (1991) Intelligent Systems Design, John Wiley and Sons, New York

Bove, T , Rhodes, C. (1990) Que's Macintosh Multimedia Handbook, Que Corporation, Carmel, Indiana

Bush, V. (1945) As We May Think, *Atlantic Monthly*, 176(1), 101-108

Buttenfield, B.P., Weber, C.R., (1993) Visualization in GIS, *Human Factors and GIS,* ed. D. Medyckyj-Scott and H Hearnshaw, London, Belhaven Press

Buttenfield, B.P. (1993) Proactive Graphics for GIS: Prototype Tools for Query, Modeling and Display, *Proceedings Auto-Carto 11*, Minneapolis, MN, 1993, 377-385.

Buttenfield, B.P., Weber, C.R., (1994) Proactive Graphics for Exploratory Visualization of Biogeographical Data, *Cartographic Perspectives*, 19(3), 8-18.

Cambell, C.S., Egbert, S.L (1990) Animated Cartography: Thirty Years of Scratching the Surface, *Cartographica*, 27(2), 24-46.

Chignell, M.H , Valdez, J F., Waterworth, J A. (1991) Knowledge Engineering for Hypermedia, *Multimedia Technology and Applications*, J A. Waterworth, ed , Ellis Horwood, New York.

Chua, T. (1991) Issues in Hypermedia Research, *Multimedia Technology and Applications*, John A Waterworth ed., Ellis Horwood, New York.

DiBiase, D., MacEachren, A.M , Krygier, J.B., Reeves, C. (1992) Animation and the Role of Map Design in Scientific Visualization, *Cartography and Geographic Information Systems*, 19(4), 201-214, 265-266.

Donovan, J W. (1991a) Multimedia Solutions Anticipating a Market, *BYTE*, December, 151

Donovan, J W (1991b) Multimedia Software Sampler, *BYTE*, December, 198-202.

Dutton, G (1991) Zenithal Orthotriangular Projection *Proceedings Auto Carto 10*, Baltimore, MD, March 1991, 77-95.

Dutton, G. (1992) Handling Positional Uncertainty in Spatial Databases. *Proceedings Spatial data Handling Symposium 5*, Charleston, SC, August 1992, 2, 460-469

Harpold, T. (1991) Threnody. Psychoanalytic Digressions on the Subject of Hypertexts, *Hypermedia and Literary Studies*, Delany, P and Landow, G P ed.s, The MIT Press, Cambridge, 171-184

Jelinski, D E. (1987) Intraspecific Diversity in Trembling Aspen in Waterton Lakes National Park, Alberta: A Biogeographical Perspective, unpublished Ph.D. dissertation, Simon Fraser University, Department of Geography.

Jonassen, D., Wang, S. (1990) Hypertext, Learning and Instructional Design, *Educational Media and Technology Yearbook*, Libraries Unlimited, Inc., Englewood, Colorado, 16, 156-169.

Kindelberger, C. (1993) Multimedia -- The Next Big Wave, *URISA Journal*, 5(1) 121-133.

Koussoulakou, A., Kraak, M.J. (1992) Spatio-temporal Maps and Cartographic Communication, *The Cartographic Journal*, 29(2), 101-108.

Kozma, R.B. (1991) Learning with Media, *Review of Educational Research*, 61(2), 179-211.

Landow, G.P. (1991) The Rhetoric of Hypermedia: Some Rules for Authors, *Hypermedia and Literary Studies*, Delany, P. and Landow, G.P. ed s, The MIT Press, Cambridge, 81-104.

Laurel, B., Oren, T., Don, A. (1990) Issues in Multimedia Interface Design: Media Integration and Interface Agents, *CHI '90 Conference Proceedings*, Seattle, April 1-5, 133-139.

Laurini, R., Thompson, D. (1992) Fundamentals of Spatial Information Systems, Academic Press A.P.I.C. Series Number 37, Harcourt Brace Jovanovich Publishers, New York

Monmonier, M. (1991) Ethics and Map Design, *Cartographic Perspectives*, (10) Summer, 3-8.

Monmonier, M. (1992) Authoring Graphic Scripts: Experiences and Principles, *Cartography and Geographic Information Systems*, 19(4), 247-260, 272.

Openshaw, S., Mounsey, H. (1987) Geographic Information Systems and the BBC's Domesday Interactive Video Disk, *International Journal of Geographical Information System*, 1(2), 173-179

Parsaye, K., Chignell, M., Khoshafian, S., Wong, H. (1989) Intelligent Data Bases, John Wiley and Sons, Inc., New York

Ruggles, C.L.N. (1992) Structuring Image Data within a Multi-media Information System, *International Journal of Geographical Information Systems*, 6(3), 205-222.

Scisco, P. (1992) Multimedia Presents, *PC World*, May, 198-200.

Tau, R.A , Vigil, J.F., Buchholz, L. (1988) Map Projections, Open File Report 88-364, United States Department of the Interior Geological Survey.

Tilton, D., Andrews, S.K. (1993) Alternative Interface Designs for Hypermedia Cartography, Annual Meeting, Association of American Geographers, April 6-10, Atlanta, Georgia.

Weber, C.R., Buttenfield, B P. (1993) A Cartographic Animation of Average Yearly Surface Temperatures for the 48 Contiguous United States: 1897-1986, *Cartography and GIS*, 20(3), 141-150.

Weber, C.R. (1993) Sonic Enhancement of Map Information: Experiments Using Harmonic Intervals, unpublished Ph.D. dissertation, State University of New York at Buffalo, Department of Geography.

Woodhead, N. (1991) Hypertext and Hypermedia: Theory and Applications, Sigma Press, Wilmslow, England

Yager, T. (1991) Information's Human Dimension, *BYTE*, (12), 153-160.

Yankelovich, N., Meyrowitz, N., van Dam, A. (1991) Reading and Writing the Electronic Book, *Hypermedia and Literary Studies*, Delany, P., Landow, G.P. ed.s, The MIT Press, Cambridge, 53-79.