Animation and the Role of Map Design in Scientific Visualization

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ABSTRACT. Scientists visualize data for a range of purposes, from exploring unfamiliar data sets to communicating insights revealed by visual analyses. As the supply of numerical environmental data has increased, so has the need for effective visual methods, especially for exploratory data analysis. Map animation is particularly attractive to earth system scientists who typically study large spatio-temporal data sets. In addition to the “visual variables” of static maps, animated maps are composed of three basic design elements or “dynamic variables”--scene duration, rate of change between scenes, and scene order. The dynamic variables can be used to emphasize the location of a phenomenon, emphasize its attributes, or visualize change in its spatial, temporal, and attribute dimensions. In combination with static maps, graphs, diagrams, images, and sound, animation enhances analysts’ ability to express data in a variety of complementary forms.

Introduction

By necessity, every map is a selective representation of reality. One conscientious response to this limitation is to map each geographic data set in several different ways, in the hope of "lying less by telling more of the truth" (Monmonier 1991). This "multiple map" approach conflicts with the central thrust of map design research, which seeks monocular, optimal design solutions. The new approach is born not only of a concern for graphic integrity, but also of an emerging feasibility provided by maturing computing technologies. Map animations, for example, are now both easier to create than in the past and easier to modify.

For earth science researchers, the ability to envision data in a variety of forms is a necessity. The rate of environmental change effected by human activity appears to be accelerating. Quantitative data about the environment, once in short supply, now exceed our capacity to learn from them. Converting these data to graphic form and searching visually for patterns and anomalies is an effective way to prompt scientific insight. Appearances can be deceiving, so analysts need to be able to generate alternative views quickly to evaluate the stability of apparent patterns. Cartographers who can suggest a range of appropriate graphic expressions for a given data set are poised to collaborate in a scientific enterprise whose scope, resources, and reliance on graphics is unprecedented.

Since much environmental data are both spatial and temporal, map animation is potentially useful in earth science research. Here we attempt to fathom that potential. After first discussing the role of visual methods in science, we consider principles and applications of cartographic animation. We identify what appear to be the three design elements or “dynamic variables” of map animation and explore the variety of uses to which they may be put. We describe one novel application in which a time-series animation viewed in nonchronological order revealed an unexpected and fruitful alternative view. The article concludes with a consideration of how the effectiveness of map animations may be evaluated.

Visualization in Science

Visual representations of data and concepts are indispensable materials in the construction of scientific knowledge. Applications of visual imagination in problem solving are documented throughout the history of science (Shepard 1988). Sociologists who observe contemporary scientists at work remark on "the extraordinary obsession of scientists with papers, prints, diagrams, archives, abstracts and curves on graph paper. No matter what they talk about, they start talking with confidence and being believed by colleagues, only once they point at simple geometricized two-dimensional shapes" (Latour 1990).

Graphics and imagery are particularly useful to investigators seeking to understand physical phenomena represented numerically.1 The supply of numerical data has increased explosively with the implementation of computational models and high-resolution remote sensing devices. The demand for effective graphic methods for data analysis and presentation has increased concomitantly. Collectively, these methods have come to be known as “visualization.”

The term visualization is applicable to two distinct but related activities: visual thinking and visual communication. Scientists are engaged in visual thinking when their intent is to produce new knowledge and their method involves creating and interpreting graphic representations. When their intent turns to distributing existing knowledge in an unambiguous graphic form, they are engaged in vis-
ual communication. Visual thinking is exploratory; visual communication is explanatory. Since exploratory and explanatory graphics are created for different purposes, they are likely also to differ in form. For instance, a semiloga-
arithmically scaled, three-dimensional scatter graph printed with a dot matrix printer may be perfectly informative to an analyst, but perfectly confusing to an unfamiliar viewer. In both cases, however, viewers are likely to profit by ob-
serving the graph from several points of view rather than from only one.

One way to compare the various forms of graphics sci-
entists use is to align them along a continuum from realistic to abstract (MacEachren and Ganter 1990). Photographs and imagery, whose spatial dimensions correspond with those of the physical object being depicted, are more realistic than graphs, whose spatial dimensions represent nonspatial quantitative data or diagrams in which spatial relations are topological. As a category, maps settle somewhere between the extremes by combining real-world spatial relations with abstract symbols. Within the category, of course, maps vary widely in form. Reference maps and most thematic maps designed for communication to diverse audiences carefully preserve spatial relationships of the observable landscape. Spatially abstract cartographic forms—such as cartograms, isochrone maps, and multidimensional scaling solutions—are relatively unusual in the public realm of conference presentations and professional and popular journals.

The potential value of spatial abstractions (particularly area cartograms) in visual thinking, however, may not be appreciated fully, as Dorling (1991) eloquently demonstrates. Becker and Cleveland (1991) also argue that inadequate attention has been devoted to visualizing scientific data in spatially abstract forms. A general strategy for cre-
ating multiple representations may be to decrease, rather than increase, realism. As Muehrcke (1990) states, "it is abstraction, not realism, that gives maps their unique power." Later in this paper we show how the dynamic variables introduced by animation enable analysts to use time in abstract ways that complement spatially abstract maps in enhancing visual thinking in geography.

Historically, the role of graphics in scientific analysis has been minor in comparison with its prevalence in science communications (Schmid 1983). This disparity is changing. The unique potency of graphics in revealing unexpected patterns in data sets and thereby prompting new research questions has been forcefully argued by Tukey (1977) and Tufte (1990). Tukey coined the phrase "exploratory data analysis" to describe the inquisitive and open-minded at-
titude he feels is a prerequisite for scientific insight. In prac-
tice, the exploratory approach involves interaction between an analyst or group of analysts and a data set mediated by a transformable graphic representation, where the analyst is motivated by an ill-defined problem and guided by some conception or theory. The potential fruitfulness of the ex-
ploratory approach is enhanced as the flexibility of inter-
active computer graphics systems improves.

In 1987 the National Science Foundation Panel on Graph-
ics, Image Processing, and Workstations recommended im-
plementation of a federally funded initiative called Visualization in Scientific Computing (ViSC) (McCormick et al. 1987). The panel defined visualization as "a method of computing... [that]... embraces both image understand-
ing and image synthesis." Three problems were cited to
justify the proposed initiative: the need to interpret the deluge of data produced by observational instruments and computer models, the inadequacy of static verbal media for scientific communication, and the desire "to steer, or dy-
namically modify, computations while they are occurring."

The ViSC report christened a new era in science's con-
tinuous dependence on visual methods in which dynamic representations are no longer limited to the imagination, but can be shared through computer graphics. By providing an inclusive definition and an ambitious set of goals, the report lent coherence to diverse but related developments in computer science, medical imaging, physics, chemistry, engineering, astronomy, and the earth sciences.

Visualization in Earth System Science

In response to concern in the international scientific com-
munity about such potential environmental threats as global warming, ozone depletion, and acid rain, the U.S. Global Change Research Program was initiated in 1990. One ob-
jective of the program is to improve the current state of knowledge of how the earth system works. "Earth system science" was proposed by an advisory committee of the National Aeronautics and Space Administration (NASA) as an integrative, multidisciplinary approach to understanding "the entire Earth system on a global scale by describing how its component parts and interactions have evolved, how they function, and how they may be expected to con-
tinue to evolve on all time scales" (Earth System Sciences Committee 1988).

A major source of funding for basic earth system science research is NASA's planned 15-year, $11 billion Earth Ob-
serving System (EOS). At Penn State, the global change research of 23 geoscientists, meteorologists, and geogra-
phers is coordinated by Penn State's Earth System Science Center (ESSC). The center is one of 29 EOS interdisciplinary teams funded by NASA. Our visualization efforts are geared to supporting ESSC research on the global water cycle, biogeochemical cycles, earth's history, and human impacts on the earth system.

The ultimate goal of earth system science is "to predict those changes [in the Earth system] that will occur in the next decade to the next century, both naturally and in re-
sponse to human activity" (Earth System Sciences Commit-
te 1988). Numerical climate modeling is a primary method for obtaining such predictions. The most sophis-
ticated climate models—called general circulation models (GCMs)—have been defined as "a prognostic system of equations representing the physical and dynamical processes which control climate" (Manabe 1983, cited in Meehl 1984).

GCMs uniquely afford earth system scientists "the capa-
bility of bringing together information from empirical stud-
ies of the real climate and results from simpler climate models to simulate the total climate system as realistically as possible" (Meehl 1984).

The predictive power of GCMs is limited by the com-
plexity and colossal scope of the climate system. "No com-
puter is fast enough to calculate climatic variables everywhere on the earth’s surface and in the atmosphere in a reasonable length of time” (Schneider 1987). Global GCMs, therefore, are limited in spatial resolution to grids hundreds of kilometers on a side. The behavior of many phenomena that operate at scales below model resolution must be assumed or ignored. Substantial uncertainties are introduced with such assumptions, undermining the credibility of model predictions.

An additional problem with GCMs is that their voluminous outputs of numerical matrices are difficult to interpret: “the artificial climates generated by these models are typically as complicated and inscrutable as the earth’s climate” (North et al. 1981, cited in Meehl 1984). Modelers depend primarily on visual representations—particularly interpolated isoline and unit vector maps—to interpret these data. Model performance is commonly verified by visually comparing predicted maps of current atmospheric conditions with maps derived from observations. Visualization techniques, thus, are equally valuable to both advocates and critics of numerical modeling as a way to predict changes in the earth system.

Marshall et al. (1990) have identified three different ways in which visualization techniques can be employed in the modeling process: tracking, steering, and postprocessing. Tracking means monitoring the performance of the model as it is running, where the flow of model calculations is represented as animated graphs or maps (or both). Tracking is a passive form of real-time visualization; no interactive manipulation of model parameters is involved. Tracking rewards the patient analyst with “live” visual feedback of model performance, potentially revealing anomalous blips that may warrant further investigation. Incorrectly calibrated runs can also be detected and aborted, saving valuable computing time.

Steering is an active form of real-time visualization. It surpasses tracking by allowing the modeler to effect changes in model performance by manipulating its graphic representation. From the modeler’s point of view, steering is “the most exciting potential [use] of visualization tools” (McCormick et al. 1987). The technique is so computationally intensive, however, that its full potential may not be realized for some time. Marshall et al. (1990), for example, report having to compromise model resolution to steer a turbulence model for Lake Erie, even in their Cray Y-MP8/864 and Stellar GS1000 supercomputing environment. Their model could be run at 2 km resolution and visually steered in real time using two-dimensional maps and graphics; however, to obtain near-real-time interaction via a three-dimensional visual display, model resolution had to be reduced to 5 km.

Postprocessing means visualizing the numerical output of a model after a run has been completed. Typically, model data are piped from host supercomputers to specialized graphics workstations for both exploratory analysis and subsequent production of presentation graphics. At this stage the model visualization process becomes most interdisciplinary, with specialists in computer graphics, programming, and visual information design collaborating with modelers using high-speed networks.

Tracking, steering, and postprocessing present opportunities to enhance the modeling process by coupling visual thinking with numerical analysis. The expertise that cartographers bring to the visualization enterprise may prove most valuable at the postprocessing stage, since they are already accustomed to mapping data supplied by others.

**Cartography in Visualization**

In one sense, visualization is nothing new to cartographers. The goal of optimizing maps as vehicles of visual communication has motivated most cartographic research since 1950 (Petchenik 1983). The role of maps as “forms of abstract thinking” was emphasized by Muehrcke (1980). Visualization is not a new method of computing, but rather “an act of cognition, a human ability to develop mental representations that allow us to identify patterns and create or impose order” (MacEachren et al. 1992).

Advances in computing and instrumentation have made a difference, however. The quantity of geographic information that will become available in the 1990s is unprecedented; image data from EOS remote sensing satellites, for example, is expected to accumulate at a rate of one terabit (10^12 bits) per day (Soften 1990). Concern for representing the quality of rapidly expanding archives of geographic data has become urgent (Buttenfield and Beard 1991). Perhaps most importantly, the steadily improving performance/price ratio associated with graphics workstations is allowing more analysts to realize the potential of high-interaction exploratory data analysis of large, multidimensional data sets, such as those produced by GCMs.

What role might cartographers play in scientific visualization? The VISC report sorts participants into two groups: tool users (“experts from engineering and the discipline sciences who depend on computations for their research”) and tool makers (“visualization researchers who can develop the necessary hardware, software, and systems”) (McCormick et al. 1987). Visualization projects are driven by the research goals of tool users, but the cooperation of tool makers is often required because the tools (especially visualization software) are not developed fully.

As a group, cartographers offer expertise in several relevant specialties, including data classification, feature generalization, graphic symbolization, and formal evaluation of viewers’ interpretations of graphic displays. Many cartographers also have a strong grounding in a discipline science (geography), often working in close collaboration with physical and social scientists. Cartographers could participate in earth science visualization projects as both tool users or tool makers, depending on the proclivities of the individuals. Here we emphasize the use of visualization tools. In particular, we discuss how animation expands the graphic symbolization options available for visual thinking and communication, and how dynamic displays can be used to generate multiple alternative views in the spirit of exploratory data analysis.

Cartographic symbolization is, in essence, a problem of appropriately and creatively signifying geographic data with what Bertin (1983) has called the “visual variables.” Monmonier (1990) claims that “electronic graphics systems have

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Figure 1. The visual variables and their effectiveness in signifying the three levels of measurement of data (after Bertin [1983]).

Visual Variables
Selecting appropriate graphic characteristics for data displays is a challenging issue in visualization. Earth system scientists commonly seek synoptic views of multivariate data sets; for example, a geoscientist studying paleo ocean circulation patterns recently asked our advice in designing a global display combining statistical surfaces representing temperature, precipitation minus evapotranspiration, and ocean salinity. Modern visualization hardware/software systems provide abundant varieties of options for graphic symbolization, but little guidance on how to choose among these in visualizing particular data sets.

Ambitious expert systems research notwithstanding, effective graphic symbolization requires human creativity and judgment. Fortunately, all numerical data can be classified into one of four levels of measurement, and graphic symbols can be reduced to a short list of visual variables. A systematic approach to cartographic symbolization (that also applies to the design of other forms of scientific graphics) was devised by Bertin (1983), who recognized apparently logical relationships between the measurement categories of data and the visual variables.

Bertin identified seven visual variables in his *Semiology of Graphics*, first published in French in 1967. Adaptations of Bertin’s original list of visual variables commonly appear in cartography texts and design-oriented cartographic research articles. Bertin’s original list (Figure 1) includes position (the two dimensions of the graphic plane), size, color value, texture, color hue, orientation, and shape. The original list is not exhaustive; additional variables such as color saturation, arrangement, and focus have been identified by such other authors as McCleary (1983).

Bertin’s system was devised in the context of static graphics. Despite his warning that “the intervention of real movement ... would make us pass from the graphic system ... into film, whose laws are very different” (Bertin 1983), the system of visual variables and their “signifying properties” (logical relationships with the four levels of data measurement) seem applicable to the design of animated maps (DiBiase et al. 1991).

Animation in Cartography
Static maps are constructed from visual variables within two or three spatial dimensions. Time is required to per-
Figure 2. The dynamic variables. Large squares represent scenes; small squares represent a phenomenon in the scene. Duration bars indicate length of time each scene is displayed. Rate of change varies simultaneously with scene duration and the magnitude of change in a phenomenon’s position or attributes (a quantitative attribute is symbolized with gray tints). As an alternative to chronological order, scenes may be presented in attribute order (i.e., from greatest to least or vice versa).

Annual Reviews of Cartography and Geographic Information Systems (Krygier 1992); and interaction—the empowerment of the viewer to modify a data display. Here we focus on animation.

Thirty years of sporadic activity in map animation is documented in Campbell and Egbert (1990). The increasing practicality of computer-assisted techniques has led to renewed interest in cartographic animation, as evidenced by a recent spate of publications and presentations on the subject (Gersmehl 1990; MacEachren and DiBiase 1991; Tilton
1992; Cammack 1992; Weber and Buttenfield forthcoming; Peterson forthcoming; Karl 1992). "Animation is both implied and inherent in most of the problems that are being, or will be, addressed in the growing field of visualization" (Campbell and Egbert 1990). This is particularly true of earth system science, whose global change observations and predictions are almost always temporal in nature.

The look of an animated map is accounted for not only by the visual variables and typography, but also by other elements. The pace (fast-slow) and character (smooth-abrupt) of the illusory motion created in an animation depend on how a set of dynamic variables are used (Figure 2). Whether an animation is manipulated interactively, guided by a "graphic script" (Monmonier 1989b), or storyboarded in the manner of traditional cel animation, control over both the visual and dynamic variables is required to exploit fully the potential of cartographic animation. In practice, computer-assisted map animation typically involves a sequence of tasks accomplished in several specialized mapping, illustration, and animation packages. Commercial animation and multimedia software packages usually provide control over the dynamic variables, but terms and techniques are not standardized among software vendors.

Dynamic Variables

Duration

In the terminology of the Swedish cartographer Janos Szégo (1987), an instant in time in the history of the world is called a "situation." The representation of a situation is called a "scene" in animation terms and may take the form of a static map. The dynamic variable associated with a scene is duration—the number of units of time that a scene is displayed. The difference between displaying a scene as a static map and as part of an animation is that in an animation, scene duration can be treated as a design variable. All other characteristics of a scene are accounted for by variations in the visual variables. Changing the duration of a scene or scenes affects the "pace" of an animation; for example, longer scenes result in a slower-paced sequence.

Since duration is measured in time units, it could be used to represent other ordinal- or interval/ratio-scaled data. For example, an analyst studying simulated temperature patterns suspected to result from changes in a global variable (such as concentration of a well-mixed atmospheric pollutant) could set scene durations proportional to the magnitude of the global variable. Longer scenes associated with high values of the global variable would presumably be emphasized.

Rate of Change

Szégo refers to a coherent sequence of two or more situations as an "event." The representation of an event requires two or more scenes that may be superimposed on a single static map, laid out side-by-side in a set of small multiples, or sequenced in an animation. Animation becomes the preferable alternative as the number of scenes increases.

A second dynamic variable—rate of change—becomes available in the animation of an event. Rate of change is a proportion, \( m/d \), where \( m \) is the magnitude of change in position and attributes of entities between scenes and \( d \) is the duration of each scene. \( m \) varies with both (1) the dynamics of the original phenomenon and (2) the sampling interval used in generating individual scenes prior to animation. Like choosing a contour interval on the basis of the character of the terrain, \( m \) can be controlled by selecting a more- or less-frequent scene interval in whatever software is used to generate individual scenes. As \( m \) is increased (while holding \( d \) constant), the apparent rate of change of entities in the animation increases and the character of illusory motion becomes less smooth and more abrupt. If \( d \) is decreased (while holding \( m \) constant), apparent rate of change decreases. Figure 2 illustrates how the interaction of scene duration and magnitude of change between scenes can affect the continuity of an animation.

Order

A third dynamic variable is the order in which scenes are presented. The logic of chronological sequencing of scenes associated with a time-series data set is obvious; however, there are instances when ordering scenes by a metric other than chronology is logical and potentially fruitful in geographic analysis. For instance, Weber recently created an animated isotherm map of average annual temperature deviations (in degrees Fahrenheit above and below a 92-year mean) for the United States from 1897 to 1986 (Weber and Buttenfield forthcoming). The 92 scenes dissolve one into the next in chronological order. Weber and Buttenfield note that "(t)he animation affirms a general cooling trend over the past 35 years, as well as a temporal pattern of cooling in the East and warming in the West over the last 20 years." Reordering the scenes from greatest positive aggregate deviation to greatest negative aggregate deviation would have facilitated visual analysis of the stability of the apparent regional patterns.

Uses of Dynamic Variables

In the same way that many different forms of static graphics can be constructed from a few visual variables, several types of animated maps can be created from the dynamic variables. Grossman (1990) lists potential applications of dynamic maps in geographic-information-system-based environmental assessments, but considers only chronologically ordered sequences of static maps. Peterson (forthcoming) also recognizes several "nontemporal" uses, including sequential presentations of alternative classification schemes, generalization levels, or related variables. Karl (1992) suggests that new forms of animated maps may be revealed through experimentation. At present, we recognize three categories of dynamic maps: those that emphasize the existence of a phenomenon at a particular location, those that emphasize an attribute of the phenomenon, and those that represent change in a phenomenon's position or attributes.

Emphasizing Location

The simplest dynamic maps are those that can be replaced by a single static graphic. A symbol whose visual characteristics noticeably and regularly change—such as point symbols that flash on and off to depict the locations of
catastrophic earthquakes since 1900 (Figure 3)—can be used to highlight the existence of a phenomenon at a particular location. In this instance a dynamic variable (duration) merely reinforces the visual variables (size, value, etc.) that comprise the point symbol. Because human vision is so sensitive to change, a flashing map symbol is more emphatic than a steady bright one. But because the map represents only a single situation (to use Szégo’s term again), it is essentially static. While adding emphasis to static displays may seem a trivial application of animation, using the dynamic variables to highlight selected subsets of complex distributions is an important feature of interactive data analysis environments.

Figure 3. Emphasizing location. Flashing point symbols highlight the distribution of the 27 most catastrophic earthquakes (those that caused 5,000 or more deaths) from 1900 to 1990.

Emphasizing Attribute

The dynamic variables and visual variables can also be combined to emphasize attributes or relationships among attributes of symbolized cartographic features. An early example is Moellering’s (1976) traffic accident animation, in which symbol duration was combined with symbol size to indicate severity of accidents at an intersection. More recently, Taylor (1982) and Slocum et al. (1990) have explored the potential of sequential presentation of choropleth map categories. This strategy involves generating several scenes from a single static map, where each scene depicts one category of attribute information. The derived scenes are then ordered from the lowest category to the highest or vice versa. Scene duration may either be programmed or controlled by the viewer. The technique is approximated in Figure 4, in which the earthquake data are quantized as four categories (classified by nested means) and presented in four corresponding scenes.

An interesting extension is to present several alternative classification schemes to reveal the stability of an apparent pattern or to compare patterns associated with the categories of related distributions. Monmonier’s (1992) “Women in Politics” atlas tour (an “atlas tour” is a programmed sequence of animated maps and graphs) includes several dynamic graphics that compare attributes of two related distributions. One is a bivariate “cross map” depicting the relationship between the percentage of elected local officials who are female and female participation in the labor force, by state, for the United States in 1987. The cross map presents sequentially four categories of correlation residuals (both variables below mean, female officials above mean, females working above mean, both variables above mean). Flashing symbols are used to help focus attention on corresponding patterns on a choropleth map and a scatter graph associated with the different data categories.

Visualizing Change

The two preceding categories account for uses of the dynamic variables to enhance essentially static representations. A third category includes uses of the dynamic variables to visualize phenomena that change through time and space. As Minard eloquently demonstrated more than a century ago with his now famous flow map of Napoleon’s Russian campaign of 1812, a skilled and imaginative designer can synthesize a complex event in a single scene (Tufte 1990). But Minard was looking back on a well-documented event; exploratory analyses involve the construction of virtual events (such as model-produced simulations) to reveal unforeseen spatio-temporal patterns. Animation and the dynamic variables it brings to visualization are obviously useful for envisioning such events.

At least three kinds of change can be visualized as dynamic maps: spatial change (fly-bys), chronological change (time series), and attribute change (reexpressions).

Visualizing Spatial Change: Fly-Bys

A fly-by is a sequence of views of a static surface or volume in which the viewpoint of the observer changes gradually. Figure 5 shows four scenes from a fly-by of the earthquake data projected on a sphere. Fly-by animation seems to be a more effective substitute for unwieldy physical models than static stereoscopy or visual enhancement of two-dimensional representations (Dorling 1991). A fly-by into a
Figure 4. Emphasizing attribute. The catastrophic earthquakes are categorized by the number of deaths attributed to each (nested means classification). Each scene highlights one category.

Figure 5. Visualizing spatial change: fly-by. The earthquake data are projected onto a sphere, which is rotated from a center point of 0° N, 70° W, to 50° N, 120° E.

1:1 scale visual model with which the viewer can interact has been called “virtual reality” (Rheingold 1991).

A well-developed application of fly-bys is found in flight/navigation simulators, where pilots’ apparent position and velocity over a landscape changes in response to their manipulation of the controls. Some of the best-known early examples of scientific visualization are a set of fly-bys over terrain models of Earth, Mars, and Miranda (one of the five
moons of Uranus) produced at the Jet Propulsion Laboratory (JPL) between 1987 and 1989. These roller coaster rides over realistic terrain models helped stimulate interest in the "new" field of scientific visualization among funding agencies, computer graphics vendors, research scientists, and the general public.

Interactive performance was sacrificed in the JPL simulations to achieve the realistic imagery that makes these promotional videos so impressive; the Mars fly-by, for example, required 37 days of computing time to render on two Vax minicomputers (DiBiase et al. 1989). The semi-realistic appearance of landscapes in advanced flight simulators is achieved by storing a library of high-resolution digital images that are displayed quickly in response to the pilot's actions. The tradeoff between real-time interactivity and three-dimensional realism is illustrated in Moellerings's (1978) videotape, in which a terrain model is manipulated directly in wireframe mode, then presented as an illuminated volume in a postprocessed fly-by animation.

As earth system scientists acquire new generations of graphics-accelerated workstations, however, interactive fly-bys over detailed representations become increasingly viable. In a recent study of the role of clouds in global warming, researchers Veerabhadran Ramanathan and Bill Collins of the Scripps Institute of Oceanography visualized eight gigabytes of sea surface temperature and cloud cover data as a three-dimensional sphere using a Silicon Graphics Iris workstation. According to Collins, the researchers were able to change their viewpoint over the sphere in near real time by manipulating a trackball (Marshall 1992).

Visualizing Chronological Change: Time Series

Depicting change over time in the position or attributes of geographic phenomena from a constant viewpoint—change in chronological space—is the most obvious application of animation in both the social and physical sciences. Time-series sequences are ordinarily constructed from scenes sampled at intervals along the range of the series, viewed in chronological order at a constant rate.

Openshaw et al. (1987) produced a time-series animation of smoothed monthly incidences of childhood leukemia in England from 1967 to 1987 that reveals a remarkable periodic "bubbling-up" of cases in certain cities, a spatio-temporal pattern the authors interpret as contagious diffusion. Gould's animation of the diffusion of AIDS in Pennsylvania consists of 27 isarithm maps generated from quarterly county-level case data. Each scene is viewed for about three seconds, one map gradually dissolving into the next (MacEachren and DiBiase 1991).

The most elaborate scientific animation known to us—"Study of a Numerically Modeled Severe Storm" (Wilhelmson et al. 1990)—explores the physical structure of a simulated cyclogenesis event as it evolves during a two-hour period (condensed into segments approximately 20 seconds in length). The invisible structure of internal winds is artfully represented through the translucent shell of the storm with tracers, buoyant balls, and streamers. The video was produced during an 11-month period, requiring the equivalent of one person's full-time effort for more than a year. The animated portions of the 7.5-minute tape took about 200 hours to render on a graphics-accelerated Silicon Graphics Iris workstation (Wilhelmson et al. 1990).

Time series can also be created from scenes representing such time aggregates as an hour, a week, or a month. Weber's animated isotherm map, for example, used yearly aggregates from 1897 to 1986. Moellering termed the result of such an aggregation procedure "collapsed real time." Alternatively, time can also be treated as cyclic, with aggregate values depicted for positions in the circuit. A hypothetical example is mean weekly ozone concentration presented as a 52-week cycle derived for the period 1970 to 1990. In his traffic accident animation, Moellering (1976) used this procedure to create what he called a "composite week," during which accidents were displayed for 15-minute aggregates. Figure 6 suggests an aggregate time series in which the locations of 27 catastrophic earthquakes from 1900 to 1990 have been collapsed into five scenes.

Visualizing Attribute Change: Reexpressions

Third and perhaps least obvious is change in position of an object in attribute space. The term "reexpression" is borrowed from Tukey (1977) to denote alternative graphic representations whose structure has been changed through some transformation of the original data. Simple examples from graphing include transforming linear measurement scales to logarithmic and applying smoothing filters to unmask pattern in noisy point scatter. In the context of cartographic visualization, the analyst can choose strategic subsets of time-series sequences (brushing) and can alter the order (reordering) and rhythm (pacing) of sequences.

Brushing was first applied to scatterplot matrices by Becker and Cleveland (1987). They describe it as a high-interaction technique for analyzing multivariate data. In their implementations, a subset of elements on one scatterplot is highlighted by an analyst who selects it (possibly with a mouse-guided lasso tool), causing the corresponding cases on other scatterplots to be highlighted. Brushing thus allows the analyst to see the interdependence of subsets of data for a variety of variables simultaneously.

The technique was extended by Monmonier (1989a) to a geographic context. He suggested having linked scatterplots and a map on the screen together so that when points on one part of a scatterplot were selected, their geographic location would be highlighted. Conversely, when regions on the map were highlighted, points on the plots corresponding to these regions would be identified. In the context of animation, brushing allows the analyst to select and view changes in a subset of data in geographic, chronological, or attribute space.

Reordering is shuffling the scenes of an animation in a purposeful way. Time can be conceived as a vector that can be divided into ordered intervals. If time is employed as a measurement scale (as it is in dynamic mapping), any ordered (ranked) data distribution can be matched and exchanged with it. Slocum et al. (1990) exploited the dynamic variable order in the sequential presentation of classed choropleth maps. They created a series of scenes from a single choropleth map by isolating each data category, then presented the scenes in ascending order.

In Figure 7, the earthquake data—shown in chronological
Figure 6. Visualizing chronological change: time series. Twenty-seven scenes, each showing one catastrophic earthquake, are suggested here in five composite scenes.

Figure 7. Visualizing attribute change: reexpression. Twenty-seven scenes, ordered from least to most catastrophic earthquakes, are suggested here in five composite scenes.
order in Figure 6—are reordered from least catastrophic to most catastrophic in terms of human fatalities (27 scenes were condensed to five for presentation here). Presenting a sequence of scenes in chronological order is intuitive, and we call chronological ordering of scenes in an animation a realistic use of time because it meets most viewers’ expectations. Because time is an independent variable in most time-series analyses, reordering by an attribute may yield meaningful alternative views in many time-series data sets.

Pacing is varying the durations of scenes in a purposeful way. For example, the earthquake sequences (Figures 6 or 7) could be paced such that the duration of each scene is proportional to the magnitude of fatalities or the Richter score associated with the scene. A paced animation may be considered a temporal cartogram.

We expect that reordering and pacing will prove useful in prompting analysts to seek patterns and anomalies in multivariate time-series data sets. In the case study that follows, we discuss apparent contributions of time-series and reexpressed map animations created for an ESSC research project.

Case Study: Climate Change in Mexico

Motivated by a concern that “climatic change may increase the risk of hunger ... and may stimulate migration to cities or the U.S. border,” Liverman and O’Brien (1991) use GCM simulations to assess the potential impacts of global warming on agriculture in Mexico. They compare temperature and precipitation values predicted by five global climate models (each assuming twice the current concentration of atmospheric CO\(_2\)) with observed values for 13 sites. The differences among model predictions are presented as a measure of the uncertainty inherent in such regional forecasting.

Figure 8 synthesizes the entire data set provided by Liverman and O’Brien from which we produced a series of animations. The graphs depict monthly mean observed temperature and precipitation data for 13 cities in Mexico, along with ranges of values predicted by the five GCMs for a two-times-CO\(_2\) scenario.

Our animations of Liverman’s and O’Brien’s data exemplify the postprocessing mode of numerical model visualization. We converted the observed and predicted temperature and precipitation data to graphic form using computer-aided design software on both DOS and Macintosh microcomputers. Our first animation (not illustrated here) consisted of a national-scale view of observed temperature and precipitation variations for all 13 sites. We used paired bar graph symbols or “temporal glyphs”) for each site, showing one monthly average temperature and precipitation value per site per scene.

The 12 scenes were then animated with commercial multimedia software for the Macintosh, viewed on-screen, and recorded directly to VHS tape with an accompanying narration. The sequence was animated such that scenes appear in chronological order and in equal duration, with one second of viewing time representing one month. The dynamic map loops through the year-long cycle to allow patterns to be noticed through repeated viewing. The 13 simultaneously changing graphs constitute the kind of complex display that Youngblood (1989) has termed a “parallel event stream.”

Figure 9 (see page 265) consists of actual scenes from another animation of the Liverman and O’Brien data—a time-series sequence that focuses on discrepancies among observations and predictions for Chihuahua. In these paired graphs the red and blue bars represent monthly mean observed temperature and precipitation values. Pointers move along the sides of the histograms to represent the range of predicted values by the five models. The black lines between the pointers show the mean of the model predictions. Temperatures predicted for a two-times-CO\(_2\) atmosphere consistently exceed contemporary observed temperatures at Chihuahua, but precipitation predictions vary conspicuously. Anomalies in precipitation predictions were well known to the authors and have been attributed to differing model assumptions.

Informal observation of the authors’ reactions lead us to believe that these time-series animations merely confirmed what the authors had already learned about the data from tables and static graphs. We speculate that this outcome is due to the authors’ ability to explore the relatively small quantity of numbers involved with conventional tools. Certainly the potential value of time-series animations increases as larger data sets confront the analyst. The following example, however, demonstrates how dynamic reexpression can reveal unexpected patterns even in familiar data sets by allowing analysts to explore them in unconventional ways.

Figure 10 (see page 266) shows the scenes of a reordered and paced sequence comparing predicted and observed temperatures for Puebla. The red bar represents monthly mean observed temperatures. The purple zone in the bar symbolizes the range of five GCM predictions for a two-times-CO\(_2\) scenario. The light purple bar depicts the mean of the model predictions. The scenes are ordered from months in which model predictions vary the least to those varying the most. The animation is paced such that durations of scenes increase with the magnitude of model variation. This dynamic reexpression reveals a trend of maximum uncertainty during the spring planting season of April, May, and June, a pattern that had previously gone unnoticed.

For Puebla, at least, this reexpression suggests that at the time of the year for which temperature predictions are most critical, model predictions can be relied on the least (unless, of course, you are convinced that one model is “right” and the others are “wrong”). The fruitful application of temporal abstraction to this already well-explored data set leads us to believe that the technique may be useful in other exploratory settings.

Evaluating Visualization Effectiveness

Visualization is expensive. Much training and experience are needed to operate the pricey workstations and specialized software entailed in earth science visualization. Map design researchers might play an important role in visualization by evaluating the cost-effectiveness of visualization techniques. Becker and Cleveland (1991), two of the leading figures in exploratory data analysis, assert that “issues of
visual perception are critical to understanding of scientific visualization.

A few research cartographers have begun to evaluate formally the effectiveness of animated maps. Slocum et al. (1990) compared subjects’ ability to recall patterns in static choropleth maps and animated maps in which map categories were presented sequentially. The study did not demonstrate any clear advantage to the sequenced maps, perhaps because animation adds little to the presentation of static information. The least equivocal findings in the study are anecdotal; subjects clearly preferred the animated maps over the static ones and offered numerous creative suggestions on how the animations might be improved.

As the means to animate maps on widely available microcomputers proliferates, other new research questions arise. For example, what minimum duration is required for viewers to notice and interpret a feature, such as lettering? In a paced animation, what sequence of increasing durations results in the temporal analogue of the equal-value gray scale? What rate of change will most appropriately represent the motion inherent in a given time-series data set (Tilton 1992)? How does the order in which scenes or sequences are presented affect viewers’ interpretations of an animated map? What constraints are imposed on the use of the visual variables by the various dynamic media (such as videotape, videodisc, and cathode-ray tube)? How does motion affect figure/ground relationships? Do dynamic maps require more generalization than static maps?

Gilmartin’s (1991) survey indicates that approximately one-fifth of cartographic research published from 1964 to 1989 are “articles on communication and ... experimental studies of perceptual and cognitive aspects of map reading and design.” This tradition of “user-oriented research” prepares cartographers well for investigating the effectiveness of map animation.

As we have stressed throughout this essay, however, communication is often not the central issue in visualization. Scientists intend visualization to serve a range of purposes, from prompting unforeseen questions to convincing skeptical audiences that important questions have been an-

Figure 8. Comparison of observed temperature and precipitation values and ranges of values predicted by five global climate models for a 2 x CO₂ scenario. This static graphic summarizes the time-series animation discussed in the text (Liverman and O’Brien 1991).
swered. We are only beginning to consider how static and animated maps, graphs, and diagrams can be combined to foster scientific insight in exploratory analyses. As Mormonier (1989) concludes, "Cartographic research must turn away from its search for the single optimum map, and begin to deal with sequences of maps and the need to integrate maps with statistical diagrams and text."

For the scientist, the desired outcome of visual thinking is scientific insight—noticing meaningful patterns or anomalies in data. Insight becomes more likely as the potential for the so-called type I and type II visualization errors—"seeing wrong" and "not seeing" (MacEachren and Ganter 1990)—is minimized. The multiple representation approach is intended to minimize these errors by allowing the analyst to reveal hidden patterns and inspect their stability by generating several alternative views. To evaluate the effectiveness of this more-is-better strategy, there will be no substitute for observing and anecdotally reporting how scientists actually interact with complex displays in uncontrolled settings in the manner of the ethnomethodologists.  

Traditional perceptual research methods involving novice perceivers and well-defined tasks will not be adequate gauges of the efficacy of exploratory graphics. In the design of displays for exploratory analyses, we can assume expert, highly motivated viewers who are often engaged in ill-defined tasks, such as hypothesis formulation. For example, colleagues and students who viewed the parallel event stream animation in classroom and conference presentations found it confusing. Liverman and O’Brien, however, received it with interest, pointing to seasonal variations at individual sites and comparing patterns among neighboring sites.

Especially in exploratory visualization, seeing is an active, constructive process. Visual thinking, at its best, is a creative act. Finke (1990) has shown that creative problem solving can arise from playful combinations of "preinventive forms." Finke supplied subjects with a set of simple geometric shapes, asked them to combine the shapes in a variety of ways, and imagine practical uses for the combinations they devised. The dynamic variables may be the preinventive forms of animation.

Our revelation of maximum predicted temperature uncertainty during the planting season at Puebla, Mexico, was the unanticipated outcome of scene reordering motivated by simple curiosity. In addition to contriving more controlled experiments, we must actually engage in animation and visualization, applying the visual, dynamic, and audio variables in creative ways and observing carefully what scientists find useful.

**Conclusion**

Visualization provides cartographers with an opportunity to play a creative role in the "grand challenge" (National Research Council 1988) of global change research. In so doing we will collaborate with expert, highly motivated scientists who rely on graphics as windows on complex computational models and voluminous model-produced data sets. Cartographers' ability to express data and concepts in multiple complementary forms will be more valuable than our suggestions on how to select a single optimal form. Seeking higher levels of abstraction is likely to be a more fruitful approach than seeking greater realism in devising alternative representations. Map animation can be used to visualize spatio-temporal data in both realistic (chronological) and abstract (reordered and paced) forms. The effectiveness of temporally and spatially abstract animated maps in prompting scientific insight should be judged not only in isolation, but also in combination with static maps, graphs, diagrams, and sound.

**NOTES**

1. Cleveland’s (1985) survey of scientific journals indicates that graphs appear more frequently in physical science journals than in social science journals. DiBiase’s unpublished survey of three geography journals suggests that physical geographers rely more on graphics than human geographers: in 1988, 38% of the total page area of Earth Surface Process and Landforms was devoted to graphics, while only 18.5% of the page area of the Annals of the Association of American Geographers and 13% of Economic Geography was printed with graphics. The discrepancy has not been explained fully, but it seems likely that physical scientists’ greater reliance on quantitative data is one factor.

2. The five GCMs compared by Liverman and O’Brien include those developed by the Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies, National Center for Atmospheric Research, Oregon State University, and United Kingdom Meteorological Office.


**REFERENCES**


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