...INTRODUCTION

As computer systems make dynamic interaction with maps more practical and map animations less cumbersome to create, the cartographic perspective on time must change. Time has typically been treated as an attribute to be mapped, with aspects such as length, date of occurrence or change in location over time being depicted much as we might show aspects of vegetation, atmospheric pressure or environmental risk (e.g. Vasilev, 1991). The representation of time as an attribute does not require time, something that Mladenov made clear more than a century ago with his now famous flow map of Napoleon’s march into and out of Russia. In a dynamic cartographic world, although we can now represent time with time, we may achieve only modest gains by so doing. Conceptualising time only as an attribute limits the potential of dynamic map displays. Time can also be conceived of as a cartographic variable to be manipulated, much as we manipulate size, colour hue and space itself. It is this addition of a powerful variable to our limited cartographic tool kit (Bertin’s seven graphic variables) that is likely to make the most substantial impact on maps as a visualization tool in GIS.

Whether static or dynamic, all cartographic representation depends on a limited graphic language which derives from a set of graphic primitives first explored by Bertin (1981). For non-animated maps, Bertin identified seven primitives: size, value, texture, colour, orientation, shape and location in space. Although other authors have added to or modified this list slightly, most cartographers accept the contention that there is a limited set of fundamental graphic variables, illustrated in Plate 13, from which all map representations are built. Bertin specifically excluded movement and time from the system he developed because he felt that a completely different cartographic environment results when these factors are included – a shift from ‘graphic system’ to ‘film’. As demonstrated by Delaine et al. (1991), however, Bertin’s system of graphic variables seems to hold up in a dynamic environment and this dynamic environment further expands Bertin’s static set.
...Dynamic variables

Our research team at Penn State University initially identified three fundamental dynamic variables: duration, rate of change and order (DiBiase et al., 1991b). Here I will add a fourth to that list: phase. As with Bertin's static variables, for which combinations of shape, arrangement, orientation, and so on can result in various spatial patterns, combinations of these fundamental variables can result in temporal patterns. For present purposes, however, we will focus on the basic temporal primitives.

Duration

For static maps, Szego (1987) considered a variety of issues related to how space and time interact and can be conceptualised cartographically. He labelled an instant in time a 'situation'. Traditional static paper maps depict situations. In mapping single situations, duration is independent of the processes of cartographic display. Instead, it is controlled only by how long a viewer wants to look at the map. We can animate an otherwise static map by explicitly controlling duration. When we do so, each situation becomes a frame of the animation (Figure 13.1). A sequence of frames with no change from frame to frame will be termed a scene. Szego refers to a coherent sequence of situations (animation frames) as an 'event'. Because duration is a quantity which can be precisely controlled with most animation software, duration of a scene or of a frame can be used to depict ordinal or quantitative data. If animation is applied to a static situation, short duration scenes within events might correspond to insignificant features and long duration scenes to significant features. Applied to dynamic processes, on the other hand, short duration scenes throughout an event imply smooth movement while long duration scenes suggest abrupt movement. The duration of individual frames of an event, or number of frames per unit time, determines the animation's temporal texture. This is referred to as 'pace' in some commercial animation software packages.

Rate of change

For events, defined as two or more related situations depicted as animation frames, we obtain a second dynamic variable, the rate of change. From one frame to the next, any of the static visual variables can change, as can the dynamic variable of duration (Figure 13.2). Change in the location variable results in apparent motion and change in any other static variable draws attention to a location and, if change continues throughout an event, can suggest that an attribute at a location is changing. The rate of change can be constant or variable.

Rate of change

![Figure 13.2 The impact of different rates of change in position and in attributes for a five scene animated sequence.](image)

Change in duration of frames in an event can suggest increasing or decreasing importance, or can imply accelerating or decelerating location or attribute change. When attribute or location change is depicted between frames, relative...
duration of frames can interact with the magnitude of this change. For example, many constant but short duration frames per unit time, with a constantly decreasing change in position of a map symbol, will give the impression of a smooth slowing movement. Frames of geometrically decreasing duration with constant changes in position, on the other hand, will produce an impression of slow abrupt movement gradually giving way to accelerated, explosive, continuous movement.

Order

Time is inherently ordered. Matching animation frame order with temporal order of the phenomenon depicted is the most obvious way that order can be used as a dynamic variable. With dynamic maps, however, we can use time order to represent, in a symbolic way, any other order. This is just the same as using an ordered set of grey tones or circle sizes to depict ordered income or population categories or as area is ordered in a cartogram to represent population or some other relevant feature (Figure 13.3). An example of temporal order used to represent something other than time can be found in Slocum et al. (1980). They use presentation order of categories on choropleth maps to emphasise the spatial distribution of each category.

**Figure 13.3** Temporal order of animation scenes can be matched to chronological order or to any other order of interest

**Phase**

Although my colleagues and I identified three fundamental dynamic variables (Dilts et al., 1992), a fourth was implied by Szeto (1987) in his account of maps that depict space-time phenomena. Szeto describes the concept of phase as "a rhythmic repetition of certain events". For him, phase is something to be mapped rather than a variable to be used in mapping, but when maps become dynamic, this situation changes. Map animation tools allow the length of time between repetitions of an order, of a spatial pattern, etc. to be controlled.

One could argue that phase is a composite of duration and rate of change or order, but, like texture as a static graphic variable, it seems to produce a basic perceptual response that justifies its identification as a distinct dynamic variable. A particularly important application of phase to static animation is its use in colour cycling, one of Gerstner's (1990) nine metaphors of animation. Colour cycling is usually applied to linear features to suggest movement through those features (Figure 13.4).

**Figure 13.4** Phase applied to colour cycling within a line symbol

...APPLICATION OF DYNAMIC VARIABLES: ANIMATING STATIC MAPS

Conceptually, the lowest level of map animation involves sequencing of spatially and temporally independent scenes to create what Gerstner (1990) termed a 'slideshow'. In this, the animation presents a series of dissimilar still images such as maps and other information such as graphs or text. The presentation duration of each image can be controlled to indicate relative emphasis and we can take advantage of order to establish logical links between adjacent presented scenes. The prototypical slideshow, however, does not usually use the dynamic variables in this symbolic way and the map base, if there is one, is likely to change abruptly from one slide to the next.

If a sequence of images is spatially dependent, then three categories of application can be identified for the dynamic variables: (1) depiction of existence at particular locations, (2) depiction of attributes at locations, and (3) depiction of change in existence, attributes or location. As will be described below, animating static maps involves a spatially linked sequence of scenes that are temporally independent, while animation of dynamic maps involves a spatially linked sequence of scenes that are temporally dependent.

The concept of animating static maps is interpreted here as the use of animation to depict things other than dynamic processes; the use of time to represent features other than time. Both change in position of the observer and change in
position of an object in attribute space seem to fit in this category. In addition, animation can be used in a more traditional symbolic way, on otherwise static maps, to highlight features that do not change. To describe how animation can be applied to static maps, we must begin by considering the three application areas of dynamic variables cited above.

EXISTENCE

'From neon signs in Las Vegas to the blue light atop an ambulance, flickering lights are used in our society to gain attention.' (Travis, 1990) The advantage provided by a dynamic symbol on an otherwise static map is that human vision is particularly sensitive to change, therefore the symbol is noticed and figure-ground is enhanced. We are most sensitive to flicker at about 30 degrees in the periphery of central vision, so that flashing symbols allow us to notice the presence or existence of important map features before we focus directly on them.

Just as any non-locational static variable applied to a particular location represents the existence of some object or feature at that location (e.g., a star shape representing a capital city), dynamic variables can have this simple symbolic function. Switching between constant duration scenes in which a static graphic variable applied to a symbol or set of symbols is varied from scene to scene is the most basic case of using dynamic variables to highlight existence. In this case, there is no spatial or temporal change from scene to scene. Such a procedure has been demonstrated for point features that depict earthquake locations (Dibiase et al., 1992) and for area features used to highlight geographic homogeneous areas (Moenmester, 1992). In a typical GIS context, individual data layers on composite maps might be blanked on and off to allow a viewer to visually isolate them without removing the other data layers from view.

ATTRIBUTES

Dynamic variables can also be used to symbolise an attribute of a feature being depicted. An innovative use of duration to depict an attribute is Fisher's use of duration to indicate uncertainty in Chapter 19. In one of his applications, duration is used to represent the likelihood that the cells on a gridded soils map have a specific soil type. The more likely that the soil in a grid cell is in a particular category, the longer that cell appears in the hue associated with that type. The resulting map appears quite stable in regions of soil classification certainty and appears chaotic where certainty is low. As he demonstrates, duration of sounds as well as graphic variables can be used to represent attributes of locations.

Colour cycling as noted above is an effective use of phase (of hue and/or value ordering) both to highlight and depict the attribute of direction. The best known use of this technique is on television weather programmes to portray location and direction of the jet stream. Colour cycling has an advantage over moving symbols on a complex map because, as symbols are static, with only an illusion of movement, no attention need be given by the animator to the potential collision of symbols. Like actual movement, colour cycling is a particularly strong mimetic symbol because human vision tricks us with the sensation that we are perceiving motion even though the symbol location remains static. We intuitively associate this apparent symbol movement with physical movement.

An extended symbolic application of colour cycling, beyond that used on typical television weather maps, would be to vary the rate of colour cycling as a direct indication of flow magnitude. Tobler's (1981) fiscal flow maps, for example, can be effectively animated in this way (Figure 13.5). On such a map the Gestalt principle of 'common fate' predicts that viewers should be able to group common apparent movements in speed and direction and separate regional patterns if they exist.

Figure 13.5 One application of phase is the production of colour cycling

A common feature of the dynamic symbolisation of feature attributes cited above is that each could be shown with static symbols on a single static map. None depict change in either space or time, although colour cycling implies it. As with the use of viewing time to depict existence, the dynamic symbols have apparent figure-ground and attentional advantages. They can be used to give particular emphasis to limited aspects of a map and, perhaps more importantly, to change that emphasis over time. For exploratory visualization applications, it is this potential dynamically to alter emphasis that makes animated static maps an important development in visualization for GIS.

CHANGE

Change depicted with dynamic maps can be of three types involving change in the position of the observer in relation to geographic space, shown with viewpoint change, change in position and/or attributes of an object within geographic space, shown with time series and change in position of an object...
within attribute space, shown with re-expression (DiBase et al., 1992). Time series are obviously applicable to dynamic spatio-temporal processes and are perhaps the first application thought of when map animation is considered. With time series maps, the sequence of scenes is temporally dependent. For example the depiction of change in AIDS incidence per county over time requires that scene order be matched to chronological order. When using dynamic variables to depict change in observer position, on the other hand, the sequence is temporally independent. No particular ordering of scenes is required because what is viewed is not changing over time. Viewpoint change is, however, spatially dependent. Change in location or scale from scene to scene will be perceived as observer movement so it must occur in a logical, spatially sequential, order. Change in attribute space is both temporally and spatially independent. The sequence of scenes is matched neither to chronological order nor position order, but to the order of some attribute at places for a particular time. This use of time to represent orders other than chronological is comparable to the use of space to represent variables other than space advocated by Dorling in Chapter 11. As with use of animation to depict existence or attributes at locations, depiction of change in viewpoint and change in attribute space can be considered an application of animation to spatio-temporal maps.

Viewpoint change can involve zooming and panning to change apparent distance from, and position over, a map. These techniques are usually used to examine a two- or three-dimensional spatial scene. One successful example of viewpoint change in a non-geographic context is its use in medical imaging as a diagnostic tool. Closer to a GIS context, user controlled changes in viewpoint have been the fundamental basis of flight simulators. In an environment resembling a flight simulator, Bishop (Chapter 8) uses changes in viewpoint to allow a viewer to traverse a realistic model of the natural environment and see the impact of an insect infestation throughout a forested region. In relation to global environmental problems, standard flat map projections provide an interrupted view with false edges. Viewpoint change in relation to a model globe can overcome this limitation by simulating the act of spinning a physical globe (Figure 13.6). Dorling (1992) found changes in viewpoint, which he termed ‘animating space’, to be quite successful as a way to explore spatially complex two-dimensional maps. Although the use of three-dimensional panning and zooming has proved to be particularly useful in medical visualization applications, flight simulators and Bishop’s landscape visualization applications, Dorling (1992) suggests that it may be less useful than two-dimensional changes in viewpoint as a tool for visualizing abstract spatial concepts. He also argues that for visualization of enumeration unit data of the kind typical in urban and regional GIS, the zooming capability of viewpoint manipulation may be even more critical than the ability to pan in complex paths over the surface depicted.

Time series data involve change over time in position or attributes of an object rather than in position of the viewer. They can be depicted by using viewpoint change directly to emphasize temporal order, that is, by change in temporal space. This use of time does not apply to animating static maps, but is described briefly here for completeness of the typology and is considered in more detail below. Time can be treated as a vector with viewing time matched to the duration between discrete time samples. It is this use of viewing time that has been most common in past animations (Figure 13.7). Frame order might be matched to order of time aggregates such as an hour, a week, or a month to produce what Moel lering (1976) termed ‘collapsed real time’. Gould et al. (1980) used this mapping of aggregate chronological time onto animation time to produce animated map movies of the incidence of AIDS in the western United States from 1981 through 1988. Kabel and Heidl (1992) have extended this analysis to the entire US from 1980 to 1991, with predictions through 1995. Time can also be treated as cyclic, with aggregate values depicted for positions in the cycle. An example relevant to GIS applications in emergency management.
Figure 13.7 Selected scenes from an animated map depicting continental drift

would be the depiction of traffic volume along a road network for composite days. Such a depiction would indicate the typical ebb and flow of traffic and could be used to route emergency vehicles so that peak traffic corridors at a particular time of day were avoided.

Re-expression includes at least three types of transformation relevant to time as a cartographic variable. These are the selection of a subset from time, space or both; reordering based on an attribute other than time; and emphasis based on non-linear mapping of a variable onto time (DiBiase et al., 1992). While temporal brushes (selecting a time subset) can be useful in exploring spatial-temporal processes, other forms of re-expression are applicable to non-temporal analysis and, therefore, represent additional cases of animating static maps. As noted above, order can be applied to depiction of any ordered variable. An interesting ordering example is Monmonier’s (1992) combination of order and duration simultaneously to “sweep-by-value” across a map and bar graph.

In this application, a choropleth map of the US showing percentage of female elected local officials appears on a computer screen together with a rank ordered bar graph of the percentages by state. The animation consists of frames having equal duration and constant percentage change from frame to frame. The viewer is presented with an evolving event in which bars on the graph and corresponding states are filled with a “signature” hue. In parts of the distribution for which percentage of female elected officials is similar, the presentation depicts a smooth filling in of the map and graph. For parts of the distribution in which numerically adjacent states have substantially different percentages, however, the map’s evolution appears to hesitate, then jumps quickly ahead in sudden disconnected steps. In a similar application, our Penn State research group has combined reordering and non-linear mappings onto time to help global climate researchers explore issues of global climate model uncertainty about temperature in Mexico (DiBiase et al., 1992). By sequencing temperature predictions by order of their uncertainty and increasing duration of scene presentation in proportion to that uncertainty, researchers viewing the animation uncovered an unexpected pattern of planting season uncertainty in global climate model predictions (Figure 13.8).

Figure 13.8 Graphing actual and predicted temperature using chronological order emphasizes the expected increase of temperature during the spring and summer months and the decrease in fall and winter

...APPLICATION OF DYNAMIC VARIABLES: DEPICTING DYNAMIC PROCESSES WITH TIME

As will be exemplified in more detail in the next chapter, a substantial portion of geographic research focuses on dynamic processes that vary over time as well as space. For visualization tools to be effective, therefore, they must depict the dynamic elements of the processes studied. Restricted to a static product, past cartographers have developed many clever representations of dynamic processes as snapshots of time, such as Smith’s Johnstown flood map reproduced in MacEachren et al. (1992). The introduction of time as a cartographic variable offers a more direct way to depict temporal change. Where temporal
patterns are expected, or simply possible, depicting time with time in dynamic animation, can uncover patterns that remained hidden in sets of static maps. A number of examples from global model outputs of such patterns are shown in the examples cited in Brodie et al. (1992).

In 1987, Norman J W Thrower reviewed the use of animated maps by the educational film industry and presented cartographers with the challenge of developing maps for this new dynamic environment. Because pre-computer map animation involved manual construction of dozens of individual map frames per second of animation, few map movies were actually produced.

Over the three decades since Thrower directed our attention to the potential of animation, most efforts have focused on producing map movies that were conceptually similar to those Thrower described, that is, they were depictions of time as an attribute using a flipbook procedure of sequenced frames. As early as 1970, computers were used to create the individual frames to be photographed (Tobler, 1970). Within a decade, Moeller (1978) developed a system in which simple map image frames could be derived computationally and displayed in real time on a computer graphics monitor. Moeller used available tools to demonstrate possibilities for both depicting a dynamic process of diffusion and for conducting a dynamic analysis of 3D time slices, the application of viewpoint change to terrain analysis. With the latter, for even moderately complex terrain surfaces the system required batch generation of image sequences that could then be played back in real time, or recorded on film or videotape for subsequent playback in a technique termed real-time-later (Dibley et al., 1991b). Recent microcomputer map animations have also relied heavily upon real-time-later sequencing of pre-created two-dimensional maps to represent dynamic processes (e.g. Gernsheimer, 1990; Gould et al., 1990). Microcomputer software tools such as Hypercard now allow flexible access to pre-created (real-time-later) 2D and 3D image sequences supplemented by static maps, other graphics and explanatory text (Marshall et al., 1990). Montmorin (1989a) has introduced the idea of graphic scripts, which are temporally sequenced multi-window graphic presentations, as a way to facilitate access to these maps, graphics, and text for exploring a spatial dataset. In investigating the potential of graphic scripts his ultimate goal is to automate the generation of a meaningful sequence of views of a multivariate spatial-temporal dataset. In addition to this real-time-later interactivity, technology at the microcomputer level has now progressed to the point where 2D and 3D images can be calculated and displayed on the fly, thus bringing the possibility of interactive manipulation of static-time displays to all GIS users. By linking (1992), for example, has developed a visualization environment that allows analysts interactively to control the pace and direction of two-dimensional dynamic depictions of election results for the UK during the period of 1995-97. When three-dimensional depictions using such ray tracing were produced, however, By linking found interactive manipulation to be impossible because a few seconds of motion could take many hours to render.

As technology has progressed from real-time-later playback through real-time-later interactivity to real-time interactivity, interest in linking map animation to process models has increased. Corresponding to the three modes of map animation cited, Marshall et al. (1990) identified three categories of visualization techniques involving the application of animation to simulation models called post-processing, tracking, and steering. Post-processing involves the use of visualization tools to explore the results of a model run after the run has been completed. With post-processing, interactive exploration of data generated at various stages of the model and animated time series of the model’s stages are possible. Based upon the success of our post-processing cartographic visualization efforts at Penn State thus far, my colleagues and I have argued that post-processing is the area of visualization where cartographers have the most to offer (Dibley et al., 1992). Our re-expression of global climate model data cited above provides a clear example of the extent to which visualization tools allow post-processing to go well beyond simply displaying model results.

Tracking involves real-time display while a model is running. Although some interactive control over what is being displayed is possible, tracking allows no manipulation of model parameters. It also does not allow the flexibility of analysis provided by post-processing because analytical procedures can take no longer than it takes the model to run. The main goal in tracking is to notice features that indicate the model is not proceeding as desired. For complex models that take considerable time to run, tracking allows the analyst to abort a run and begin again with new parameter settings without wasting time for the model to complete its run. A variation on tracking is the playback of real-time-later sequences of model runs that require substantial computation time. This is the equivalent of time-lapse photography and allows a very slow process model to be observed in human time.

Steering, as the term implies, allows the analyst to interact, not only with the data produced by the model, but with the model itself. Most importantly, steering allows change in parameters on the fly, in response to visual feedback about the model's progress. Marshall et al. (1990) present results of their research on visual steering of a turbulence model for Lake Erie. Even with a relatively small database and their Cray Y-MPS/64 and Stallard GS1000 supercomputer environment processing speed/resolution trade-offs were encountered. The model could be run for a 2km grid and visually steered in real time using two-dimensional maps and graphics. To obtain near-real-time interactive feedback with the model and a three-dimensional visual display, however, resolution had to be reduced to a 3km grid.

...Discussion

Geographers are seldom interested in a static view of the world, but until recently, that was what cartographic visualization tools provided. Successful static depiction of the world’s dynamic nature have often received high praise because of the ingenuity required to meld time and space on a static page. Animation has the potential to increase our success at relating time with space because it provides a new cartographic variable that can depict dynamic processes in an intuitive way and increase the possibilities of exploratory data analysis. Three characteristics of frames that can be depicted through manipulation of viewing time have been identified: feature existence, attributes of features and changes in feature existence or attributes. Change can be depicted with viewpoint changes, time series and re-expression. Although a sequence of views captured on videotape and shown to an audience works well for view-
point change and time series, for re-expression the impact will probably be best when visualization is interactive, controlled by the viewer rather than by the cartographer. For exploration of three-dimensional solid models such as geological structures, viewpoint change has proven to be particularly useful. With preprocessed models, tracking and steering, time series is probably the most applicable use of viewing time. It is for post-processing of models results, where time is available to ponder relationships at leisure, that dynamic re-expression is likely to make the greatest contribution.

Maps designed to support GIS-based visualization have very different goals from past maps. Rather than serving for the most accurate map or the single most effective display, visualization tools used in GIS must be flexible and allow exploration of data from multiple perspectives. When a scientist uses a GIS to explore topics such as forest fires, regional unemployment or traffic accidents, there is no predetermined message; only patterns, anomalies and relationships to discover. Identification of appropriate questions to pose will take precedence over information communication.

Particularly in cases where unexpected patterns and relationships may be as important, or more important, than seeing what was expected, time must be used in intuitively logical ways. In order to realize the potential of time as a cartographic variable, its relationship to non-temporal cartographic variables needs to be understood. It should prove useful to consider this new variable in relation to Berin's (1981) semiotics of graphics. Although Berin argues that his system for linking graphic variables with referents does not apply to dynamic maps, DiBiase et al. (1991a) have provided evidence to the contrary. Once we allow time to become a variable, we also create the potential for audio variables which require a finite time to be heard. There is now a need to delineate a set of audio variables for use in interactive exploratory analysis. Krygier (1991) and Fisher (Chapter 19) have begun to address this task.

Adding time to the cartographic toolkit has several specific implications for the role of maps in GIS. As an extension of GIS analysis, viewpoint change can be useful as a presentation tool to help the public understand the visual impact of a proposed highway decision or of a disease infestation in a forest. Time series are, of course, applicable to the direct depiction of spatio-temporal processes. Using viewing time to represent real time makes intuitive sense and should be easy for non-expert viewers to grasp in situations where there is only one chance to see the resultant maps as in animated map movies. Spatio-temporal processes can be uncovered when a GIS incorporates time as well as space in its data structure. For exploratory uses of GIS, addition of time to our toolkit of display variables will substantially extend our visual analysis capabilities. The ability to map non-temporal attributes onto duration, rate of change, order and phase makes multivariate visual analysis much more practical than when that analysis is limited to the seven to ten static graphic variables to which we are usually restricted.

...Acknowledgement

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