[CV-04-017] Spatiotemporal Representation

Abstract

Space and time are integral components of geographic information. There are many ways in which to conceptualize space and time in the geographic realm that stem from time geography research in the 1960s. Cartographers and geovisualization experts alike have grappled with how to represent spatiotemporal data visually. Four broad types of mapping techniques allow for a variety of representations of spatiotemporal data: (1) single static maps, (2) multiple static maps, (3) single dynamic maps, and (4) multiple dynamic maps. The advantages and limitations of these static and dynamic methods are discussed in this entry. For cartographers, identifying the audience and purpose, medium, available data, and available time to design the map are vital aspects to deciding between the different spatiotemporal mapping techniques. However, each of these different mapping techniques offers its own advantages and disadvantages to the cartographer and the map reader. This entry focuses on the mapping of time and spatiotemporal data, the types of time, current methods of mapping, and the advantages and limitations of representing spatiotemporal data.

Keywords: animated maps, change maps, dynamic variables, map design techniques, mapping time, representing change, small multiples, space-time cube, spatio-temporal data

Author & citation

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Explanation

1. Definitions

- **animated map:** a map that uses display time to illustrate change in location, attributes, or existence over real time
- **attribute change:** changes to the character or quality of an event or object change over time

- **change maps:** maps that illustrate the difference between two time slices by subtracting the older time slice from the newer
- **congruency principle:** the ability of some graphics to represent abstract concepts that are cognitively suggestive between cognitive space and real space; in terms of time, this means using display time to represent time as is possible through the use of animation.
- **cyclic time:** time as reoccurring time entities such as hours in the day, days of the week, and months in the year
- **dance map:** locations of events and the transitions between are symbolized
- **duration of scene:** how long each scene in an animation is displayed for viewers
- **existential change:** the appearance or disappearance of events or objects
- **linked views:** a dashboard-type view with both statistical graphics and maps where the component graphics are linked and the map user can brush over locations in the display to see corresponding connections between the data illustrated in each pane
- **locational change:** expansion, contraction, and movement of objects
- **magnitude of change:** how much change takes place across the display during one scene transition
- **mental interactivity:** an affordance of small multiple maps that allows the map reader to visually compare the spatial pattern differences between different snapshots
- **ordinal time:** time as relative, ordering events in relation to one another
- **rate of change:** the rate at which an animation plays through the scenes
- **small multiples (chess maps):** a series of static maps that show spatiotemporal data at various time stamps
- **space-time cube:** based on work by Hägerstrand on time geography, where locations are represented on the x and y axes and the z-axis is reserved for representing the temporal attribute
- **space-time matrix:** based on Berry’s conceptualization of time, where by the x and y axes correspond to a location and attributes, and the z-dimension represents time slices relating to the location and its attributes
- **spatiotemporal:** phenomenon, data, maps, etc., that depict both space and time together
- **time as distance:** time as friction for overcoming space
- **time geography:** a subdomain of geography commonly associated with Hägerstrand calling for geographers to study processes (i.e., change over time), not simply spaces
- **TRIAD model:** Peuquet’s model of time illustrating the interaction between “what”, “when”, and “where”
- **universe time:** time as a timeline with only forward progression

2. Introduction to Spatiotemporal Representation

“Whatever spatial process under scrutiny, inclusion of the temporal element in the data is required so that change can be represented, cause and effect relationships can be derived from observational data, and ultimately understanding of the nature and structure of the processes involved can be advanced” (Peuquet 1994, 441).

The quote above by Peuquet notes the importance of including the temporal aspects of geographic data to derive information on relationships and processes related to geography. The addition of the temporal aspect of representing spatial information on maps largely grew out of time geography, a subdomain of geography resulting from a call for geographers to study processes (i.e., change over time), not simply spaces. This idea that geography is the study of space and time is now pervasive in all subfields of geography. Time geography often is credited to Hägerstrand, who famously used time as a variable for the study of spatial processes. He asked us to ponder “what it means for a location to have not only space coordinates but also time coordinates” (Hägerstrand 1970, 10). In addition, Hägerstrand was famous for his use of the space-time cube to illustrate and represent dynamics of how individuals interact with the world. In the space-time cube, locations were represented on the x and y axes and the z-axis was reserved for representing the temporal attribute. Today, the representation of spatiotemporal data is vital to the study of geography and specifically by making spatial and temporal interactions and processes visible through the visual. In the following, the term spatiotemporal is used to describe phenomenon, data, maps, etc., that treat both space and time together.

3. Conceptualizations of Time

Numerous conceptualizations of time have been offered in geography and GIScience. In geography, three models stand out: Berry (1964), Sinton (1978), and Peuquet (1994). These conceptualizations are similar in that they presented a three-dimensional conceptualization that focused on the location of attributes and the addition of a third dimension of time. Berry’s conceptualization (1964) was the first to present the **space-time matrix** (Figure 1). In Berry’s model, all things can be located in both space and time. Space is represented by the x-axis, attribute by the y-axis, and time is the z-dimension. Sinton’s (1978) model was similar and simplified all geographic information into three basic components: (1) time, (2) location, and (3) attribute. Similarly, Peuquet’s (1994) model called the **TRIAD** conceptualized space and time as the interaction across “what”, “where”, and “when” (Figure 2).

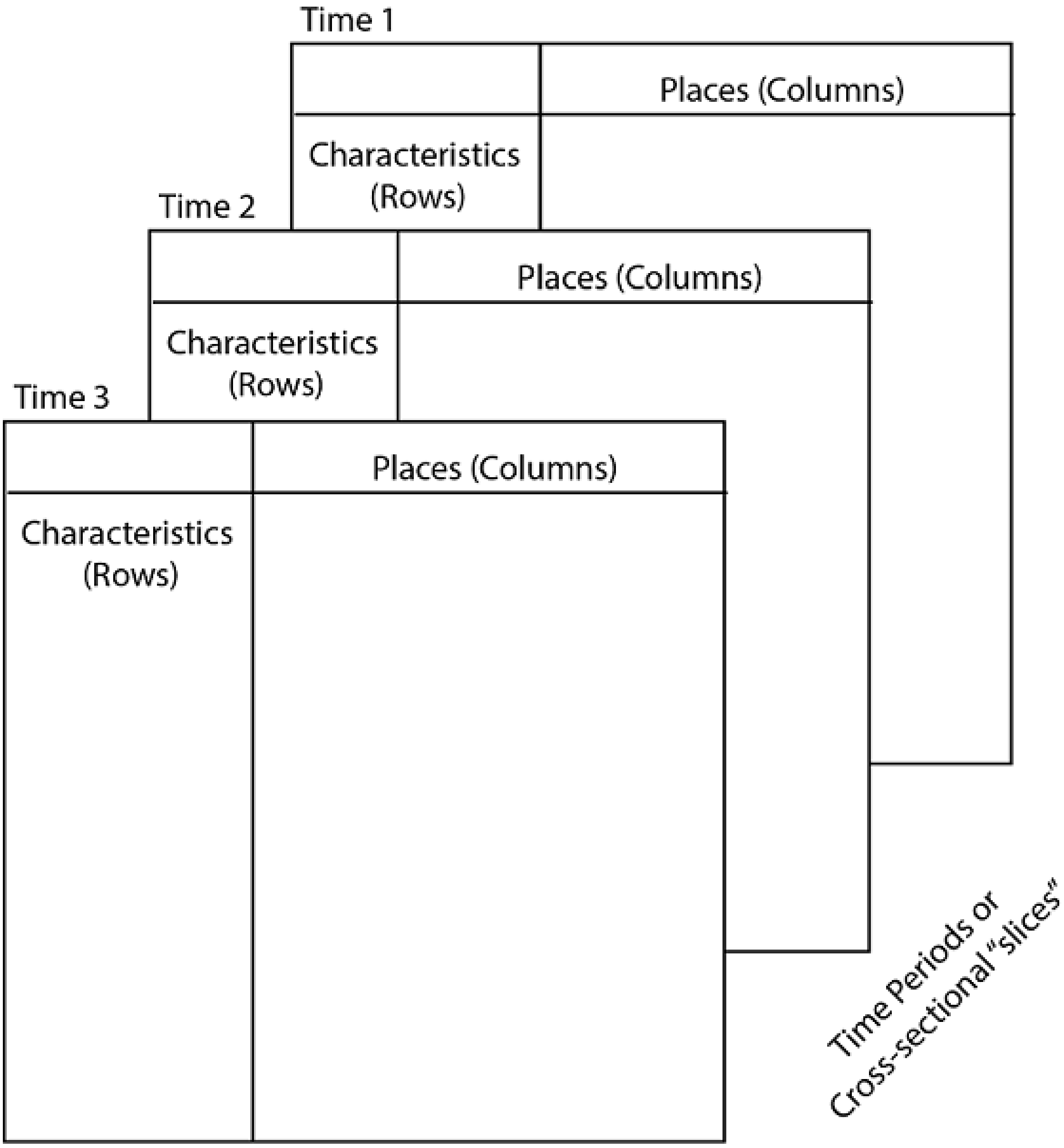

Figure 1. Berry's Space-time matrix. Source: author design, after Berry (1964).

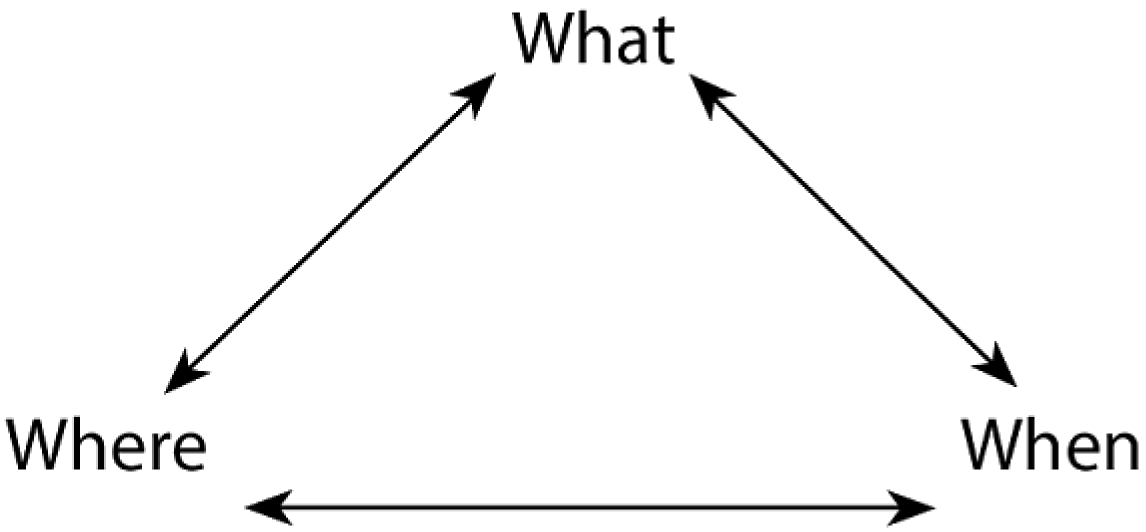

Figure 2. Peuquet’s TRIAD model. Source: author design, after Peuquet (1994).

Andrienko and her colleagues (2003) identified the types of changes that can occur in spatiotemporal information (Figure 3): (1) existential, (2) location, and (3) attribute. **Existential changes** are those types of changes dealing with appearance or disappearance of events or objects. **Locational changes** include expansion, contraction, and movement. **Attribute changes** are those where aspects of the character or quality of an event or object change over time. Andrienko et al. (2003) also identified the different types of data analysis tasks with regards to spatiotemporal data: (1) elementary and (2) general tasks. Elementary tasks are those which are focused on individual time moments, while general tasks refer to time intervals. The difference is in the amount of time one is evaluating. Gleicher et al. (2011) identified a taxonomy of different complex comparisons types. While different in their goals, both elementary and general tasks support identifying the time at which something happened or identifying what happened at a particular time (Andrienko et al. 2003).

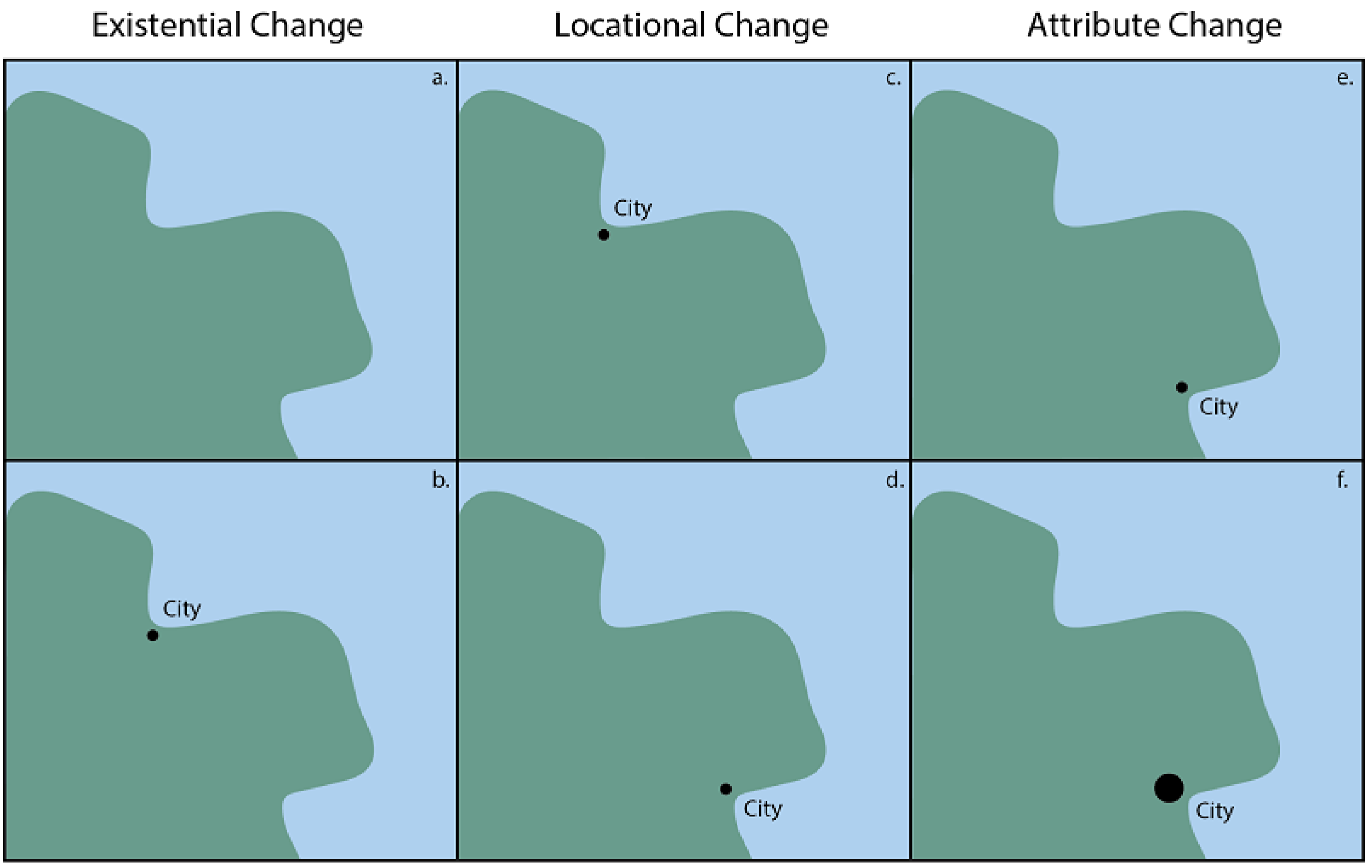

Figure 3. Types of Change (Andrienko et al. 2003). Existential change (a to b) is when something appears or disappears. In this case, the city was established. Locational change (c to d) is when the location of something changes, in this case, the city moved. Attribute change (e to f) is when attributes related to something change. In this case, the city grew in population. Source: author.

Scholars in geography and GIScience have also identified different types of time. Isard divided time into (1) universe time, (2) cyclic time, (3) ordinal time, and (4) time as distance. **Universe time** treats time as a timeline with only forward progression. **Cyclic time** instead describes reoccurring time entities such as hours in the day, days of the week, and months in the year. **Ordinal time** conceptualizes time not as discrete and systematic moments, such as minutes or seconds, but as an order applied to events in relation to one another. Finally, **time as distance** might be represented by a surface where every cell represents a value of time to drive to a particular location. In terms of maps, this might be a time travel map. Similarly, Vasiliev (1997) conceptualizes time as (1) moments, (2) duration, (3) structured (4) time as distance (5) and space as clock.

4. Mapping Time in Cartography and Visualization

available data, and available time to design the map are vital aspects to deciding between the different spatiotemporal mapping techniques. However, each of these different mapping techniques offer their own advantages and disadvantages to the cartographer and the map reader (Table 1).

Table 1. Types of Spatiotemporal Maps

Type of map	Example	Description	Advantage	Limitations
Single static maps				
Time as a surface	Isochrone maps (see Figure 4)	Each cell indicates time and then travel time is aggregated to create contour lines of equal travel times.	Map readers can easily make generalized estimates about time in a place. Presents time in a concise generalization. Useful for illustrating travel time.	Readers may be unfamiliar with this technique. Assumes one starting point for travel time.
Focused measurements	Peak year maps (see Figure 5)	Measurement of the center of population is measured at specific times in history (e.g., following the US Census)	Ideal for showing where one particular attribute was measured. Focus map reader on location and direction.	Does not help the map reader understand the extent or pattern of a particular phenomena.
"Dance maps" or maps of diffusion or movement	Road trip map (see Figure 6) and Minard's 1812 map (see Figure 8)	Locations of events and the transitions between are symbolized	Show transitions and changes in locations of particular events in one graphic	May be difficult to create with a traditional GIS if adding additional attribute information (e.g., recreating Minard's map which includes causalities as well as locations and times)
"Change maps" - also called "difference representations"	Difference between two time slices (see Figure 7)	Where the visual variable represents the direction, rate, or absolute amount of change between two time periods	Easy to measure the difference in one attribute between two times. Often used for illustrating demographic changes. Ideal for showing change in attributes.	Can only show the difference between two time periods and no more.
Multiple static maps				
"Chess maps" - often referred to as "small multiples"	Multiple maps that show outcomes of elections every four years (see Figure 9)	Multiple maps where each map shows the geography as it was during a particular time slice or event.	Easy for all map readers to understand and simple to create in a traditional GIS or graphic design software. Allows for map reader to compare between time slides which are not necessarily sequential. Allows for what Fabrikant et al. (2008) call mental interactivity. Supports tasks where the goal is juxtaposition for visual comparison.	Takes up a lot of page or display real estate. Often must be simplified to readable at a small size or shown at a coarse temporal resolution.
Cartographic-cross classification arrays	Multiple maps represent changes in time as well as in attributes.	The display of different maps can include several time slices as well as different attributes.		
Single dynamic maps				

Type of map	Example	Description	Advantage	Limitations
Sequenced symbols (accretion)	Symbols on the map change over time	Maps where the symbols are dynamic, while the basemap remains largely unchanged. These maps may be animated or simply allow the map reader to page through a map sequence as an attribute changes over time.	These are simple dynamic maps which are easy to read. These maps are simple to create than the Multiple Dynamic Maps listed below.	Map readers may experience a variety of cognitive limits such as overload of their comprehension abilities or change blindness.
Temporal sequence of views	Sequencing of different views over time			
Symbols suggesting motion	Pulsating directional symbols to show movement			
Space-time cube	Map of daily life and interactions throughout the day (see Figure 10)	Using Hagerstand's (1970) space-time cube, time is illustrated in the z-dimension and the x and y are reserved for location. When viewed from the top, the map simply represents a path. When viewed at an angle, this representation allows the map reader to see the path and time.	Shows spatio-temporal information in three dimensions (space, time, attribute). When created with interactivity, the map user is able to explore all aspects of the three-dimensional cube and the attributes, locations, and times are illustrated.	Difficult to read without interactivity, and even with interactivity map users may struggle to identify specific changes in location or attributes over time.
Multiple dynamic maps				
High-interaction graphic analysis	Scatterplot, geographic, and temporal brushing with linked viewed that can include maps, scatterplots, and other graphics (see Figure 13)	As the user mouses over one aspect, the user gets "details-on-demand" and highlights the linked information in other views.	Map reader has control of how they interact with these maps. Readers are able to discover unknown patterns or complex comparisons including juxtaposition, superposition, and explicit encoding.	Time consuming to create. Requires the map user to be entirely engaged.
Map animation	Change in carbon dioxide emissions over the course of a year (see Figure 11)	Animation in which spatiotemporal information changes over time on a map.	Illustrate time with time (Tversky et al. 2002) which has been shown to increase understanding. More software that can create animations regularly becomes available. Can be used to show existential, location, and attribute changes albeit with different visual variables. Attract attention through movement (Lloyd 2005).	Time consuming to create. Cartographer has to make many decisions about the timing and design of these maps (DiBiase et al. 1990; Griffin et al. 2006). Map readers may experience numerous cognitive limitations that make reading these maps difficult, depending on their design (Harrower 2007).

4.1 Single Static Maps

Many maps depict time by illustrating changes over time on a single map. Single static maps are useful for displaying locational or attribute changes across space. In single-static maps, cartographers can use the traditional visual variables to create a variety of different map types: including representing time as a surface in an isochrone map (Figure 4), or showing changes in distribution such as a peak year map (Figure 5), changes in location and movement in a **dance map** (Figure 6), or changes in attributes in **change map** (Figure 7).

Minard’s map of Napoleon’s advance and subsequent retreat from Russia in 1812 has famously been used as one premiere examples of a single-static map (Tufte 1983, Kraak 2014). This map illustrates multivariate phenomena in a single image (Figure 8). Minard’s map is still a challenge to recreate today with modern GIS given the inclusion of existential, locational, and attribute change in a single graphic. In addition, some of these types of maps might be difficult for map readers to understand. For instance, change maps and isochrone maps are not typical map types with which map readers are familiar.

Figure 4. Isochrone map of time it takes to get to Paris. Carte des communications rapides entre Paris et le reste de la France /dressée par E. Martin ; E. Chevaillier, del. Source: [University of Chicago Map Collection](#).

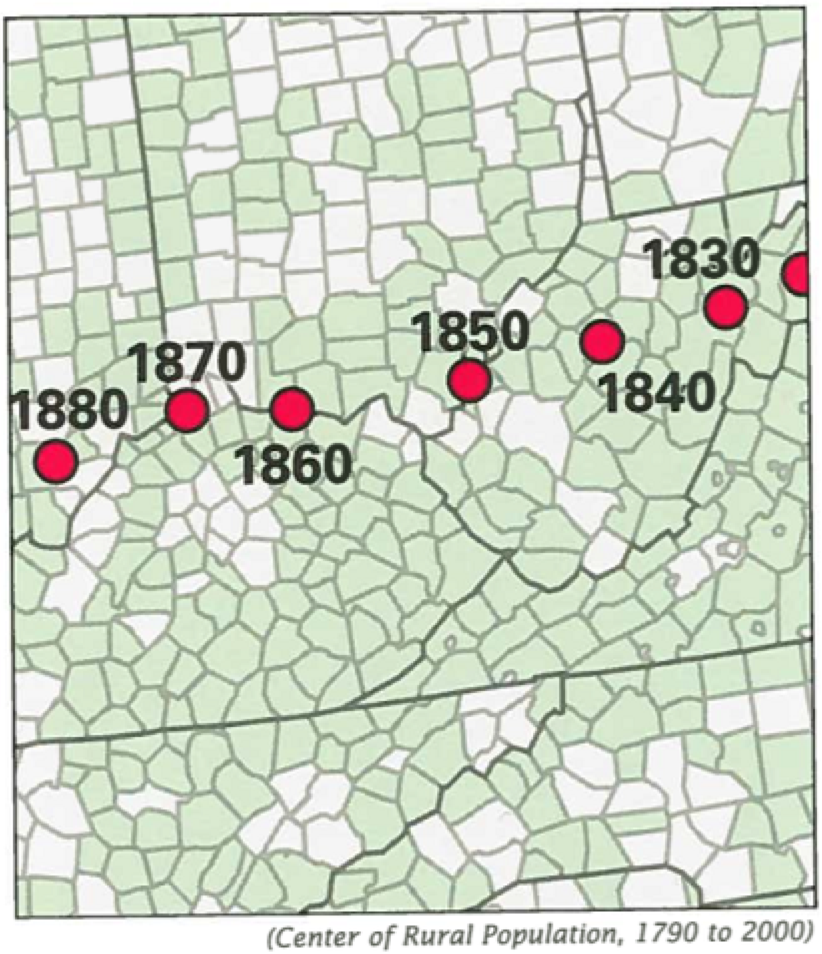

Figure 5. Center of Rural Population. Dots are located at the mean center of rural population for each U.S. Census from 1790 to 2000. Source: U.S. Census Bureau.

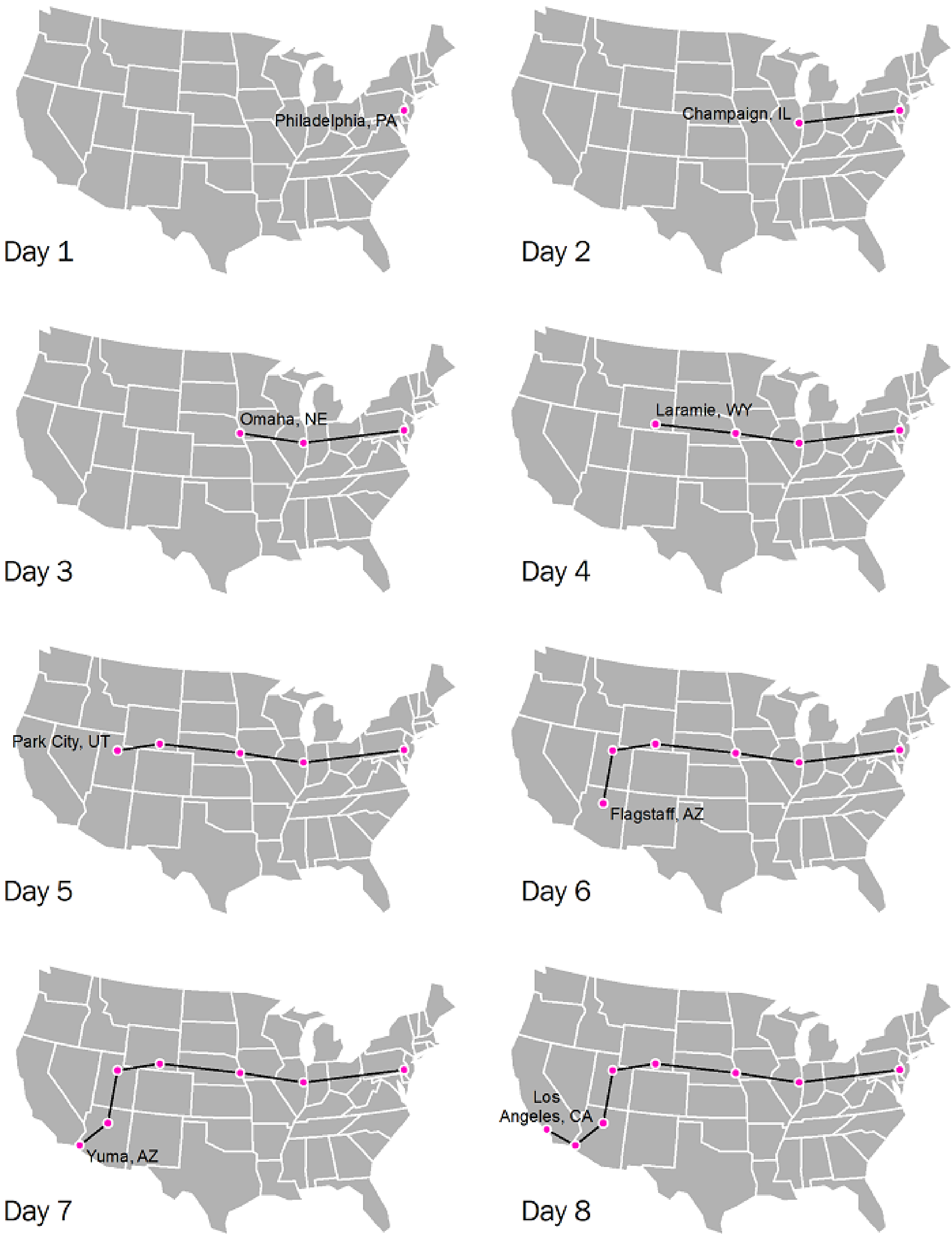

Figure 6. Dance map depicting a road trip across the United States from Philadelphia to Los Angeles. Source: author.

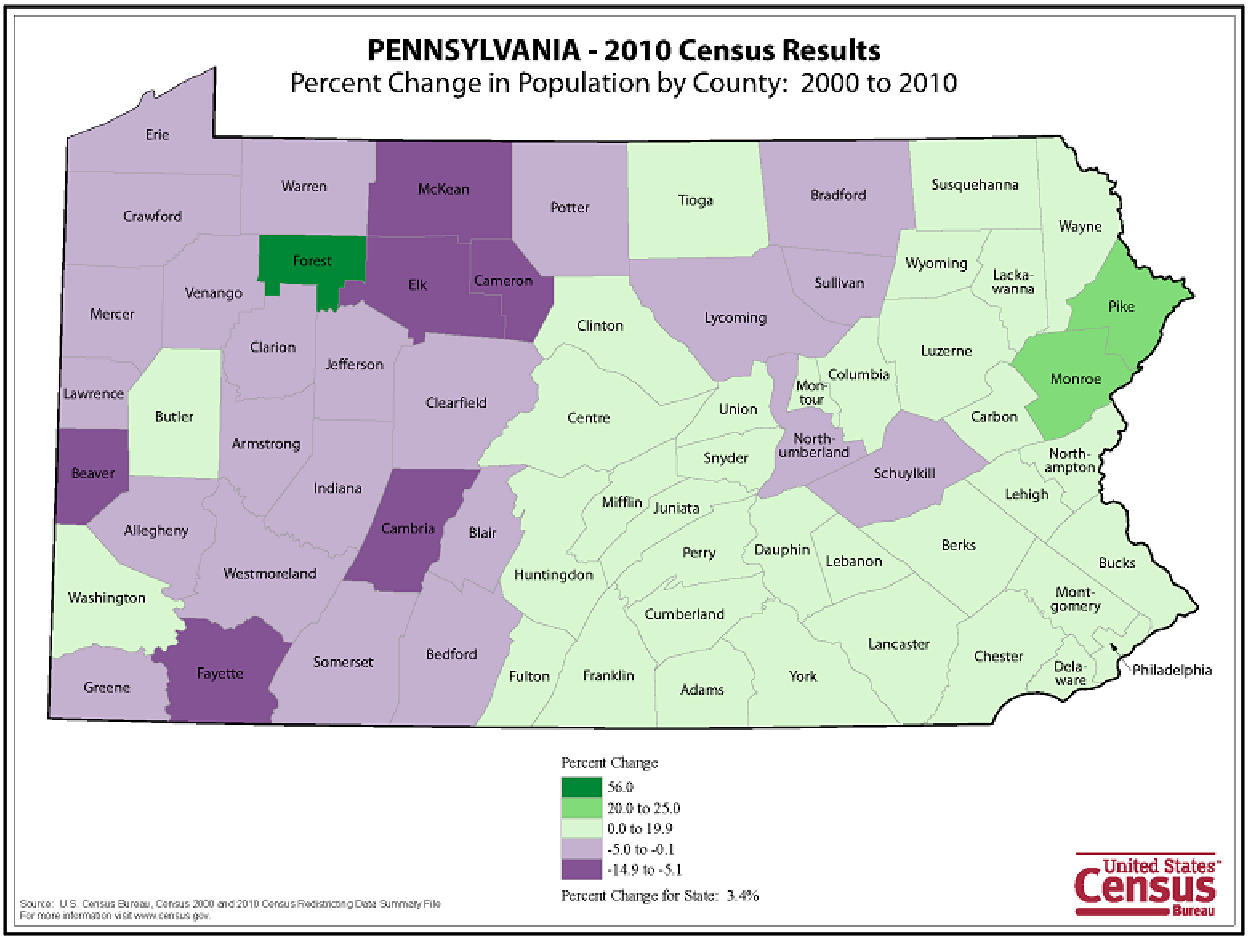

Figure 7.Census change map illustrating changes in population in Pennsylvania from 2000 to 2010. Source: U.S. Census Bureau.

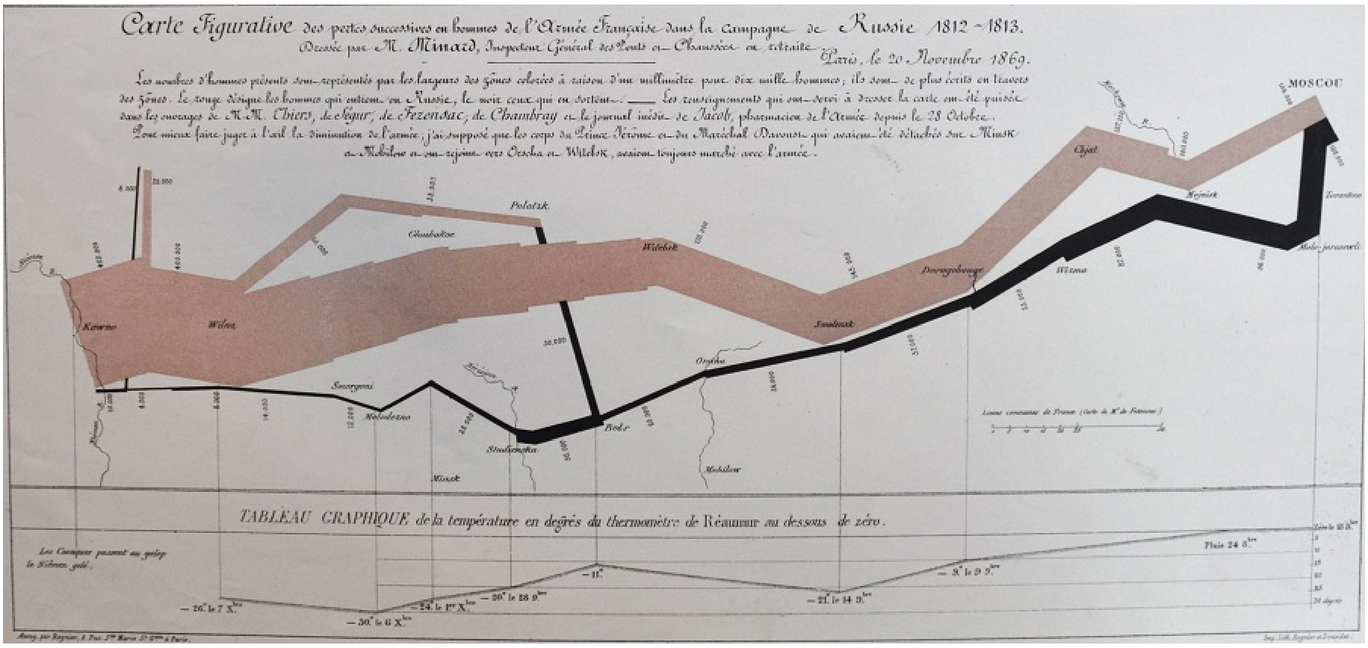

Figure 8. Minard's famous map of Napoleon's march to Russia and back in 1812. From the French: The Carte Figurative des pertes successives en hommes de l'Armée Française dans la campagne de Russie 1812-1813 ' or the Figurative Map of the successive losses of men of the French army during the Russian Campaign 1812-1813. [Source Library Lasage - Collection Ecole Nationale des Ponts et Chaussées / Minard - tableaux graphique et cartes figurative. Photo by Menno-Jan Kraak, see Mapping Time (2014).

4.2 Multiple Static Maps

Of the types of multiple static maps, small multiples are perhaps the most common type of spatiotemporal mapping technique. The term **small multiples** was popularized by Tufte (1983) but has been a long-used mapping technique in the cartographic realm. These sequenced static maps illustrate change over time through a series of static map snapshots. Monmonier (1990) terms these chess maps, as in the graphics used to describe the states or moments of a chess game over time. A popular example of this map type is shown in Figure 9, a series of small multiple maps illustrating the electoral college results to presidential elections over time.

Advantages of these maps are they are easy to create, especially in a modern GIS. The cartographer can simply plug-in thematic data for each moment in time for which they have data. These maps also allow map readers to visually compare between moments in time, even those which are not sequential. For instance, a map reader may want to compare the electoral college map from 1960 to the map from 1992. Fabrikant and colleagues (2008) called this **mental interactivity** by which the map reader can visually compare the spatial pattern differences between different snapshots.

There are also disadvantages to these types of displays. While these maps are easy for the cartographer to design, and easy for the map reader to understand, they often use a lot of display real estate. In order to fit many time slices onto the display of a computer or other devices, these maps need to be simplified to be readable at a very small size.

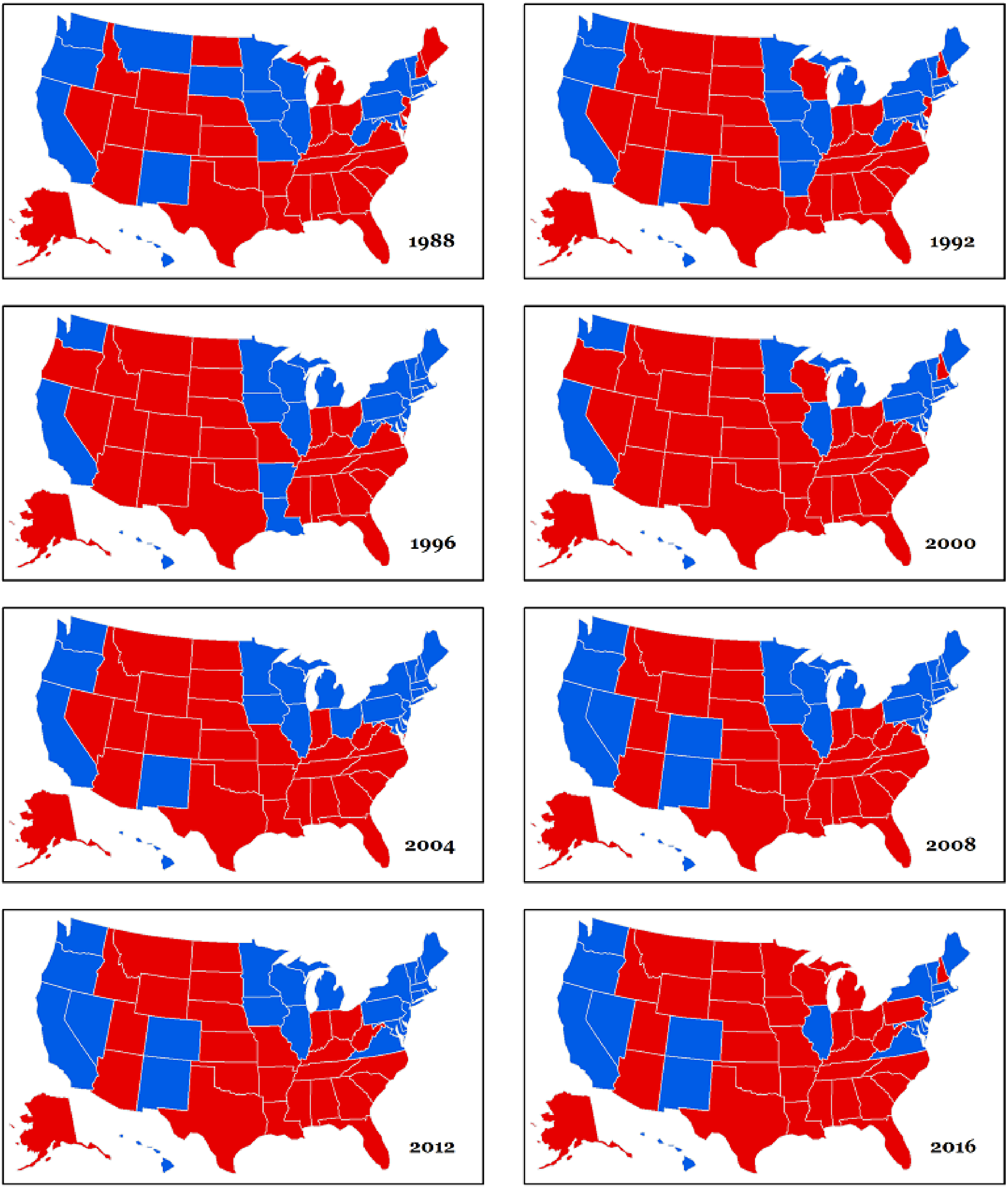

Figure 9. Small multiples of electoral college results from 1988 to 2016. Source: author.

4.3 Single Dynamic Maps

Single dynamic maps use animation to depict existential, locational, or attribute changes in thematic content while keeping the underlying basemap unchanged. These maps are the simplest version of animated maps and are the easiest animated maps to create.

Animated maps provide advantages over other types of spatiotemporal visualization because they offer the cartographer with a method for congruent representation of time by using time to represent time through use of the **congruency principle** (Tversky et al. 2002). Harrower called these types of maps "scale models of space and time" (2014) to describe this congruency principle as it relates to the representation of spatiotemporal data.

Map animations are now easily created with a variety of different available software on personal computers and even on mobile devices. These types of graphics can be interactive by allowing map users to stop, rewind, or fast-forward the animation, but they do not need this interactivity to be useful (e.g. Figure 10). For instance, popular animated GIFs auto-play and do not afford users any interaction, however these are useful for general tasks such as identifying patterns. Temporal legends allow users to accomplish elementary tasks related to identifying what happened when. These legends change as the map changes and can be designed in several different ways (Kraak et al. 1997) (Figure 11).

How the cartographer chooses to design an animation relies on adjusting the dynamic variables. The **dynamic variables established by DiBiase et al. (1990) are** similar to the visual variables in the static domain (Bertin 1967|83). These are: **rate of change, order,** and **duration** and describe the aspects of an animated map that can be adjusted for different effects and different representations of dynamic spatial data. Rate of change and duration, in particular, allow the cartographer to adjust how long a particular snapshot in time is shown and how fast the next snapshot appears for the map reader.

One of the primary critiques of animation are the cognitive limits of the map reader in viewing these types of maps. While Harrower (2007) noted that animated maps are no longer difficult for the cartographer to make, they are often difficult for the map reader to process cognitively. Several researchers have identified that cognitive load capacity (Harrower 2007) and change blindness can impair map readers abilities to understand map animations (Fish et al. 2011, Goldsberry and Battersby 2009, Battersby and Goldsberry 2010).

The space-time cube is another example of this type of map. These maps represent geographic locations on the x and y axes and the z-dimension is devoted to representation of the temporal component of the data (Figure 12). This map is a single view, ideally it allows the user to interact by rotating the cube to better understand spatiotemporal patterns when represented with this map design. While creating 3D visualizations of data is more complex than 2D, there are many tools while allow users to represent spatiotemporal data in three dimensions.

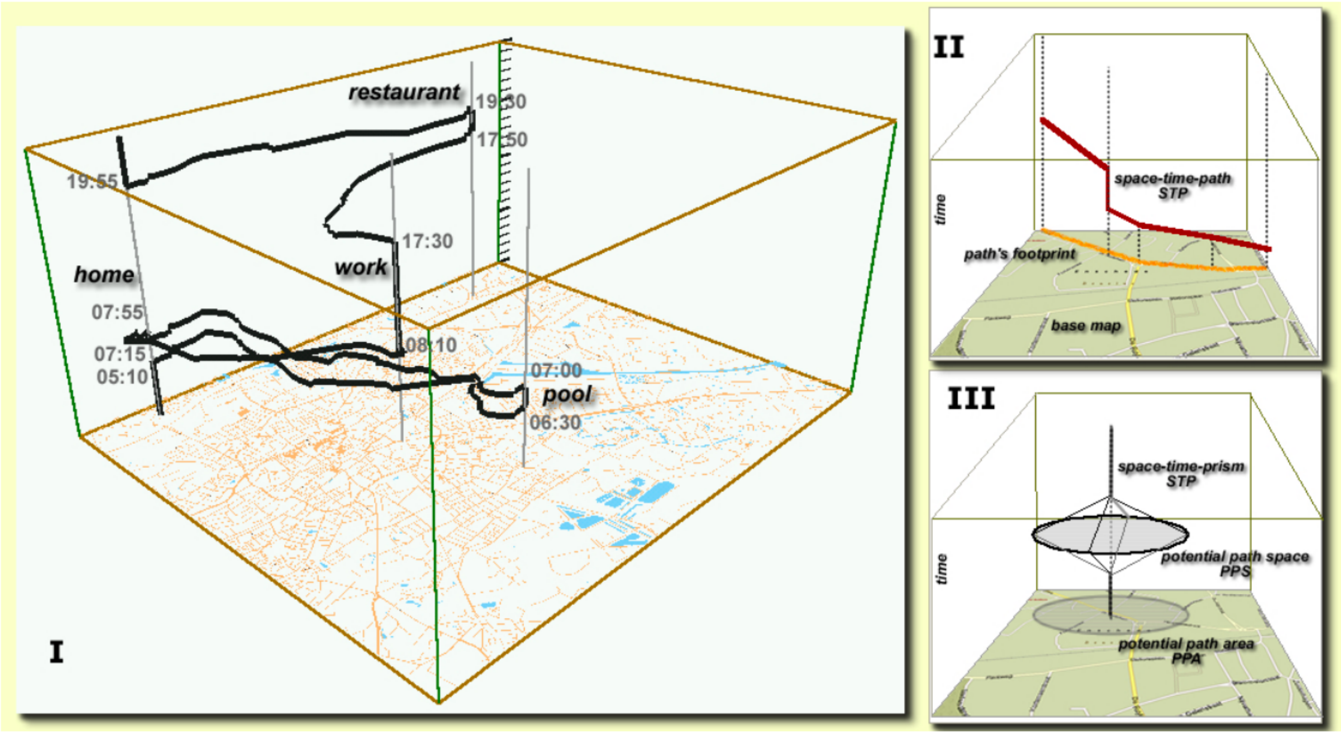

Figure 10. Space-time cube representing the path of daily life of a professor in Enschede, The Netherlands from Kraak 2003. Source: reproduced with permission from its author.

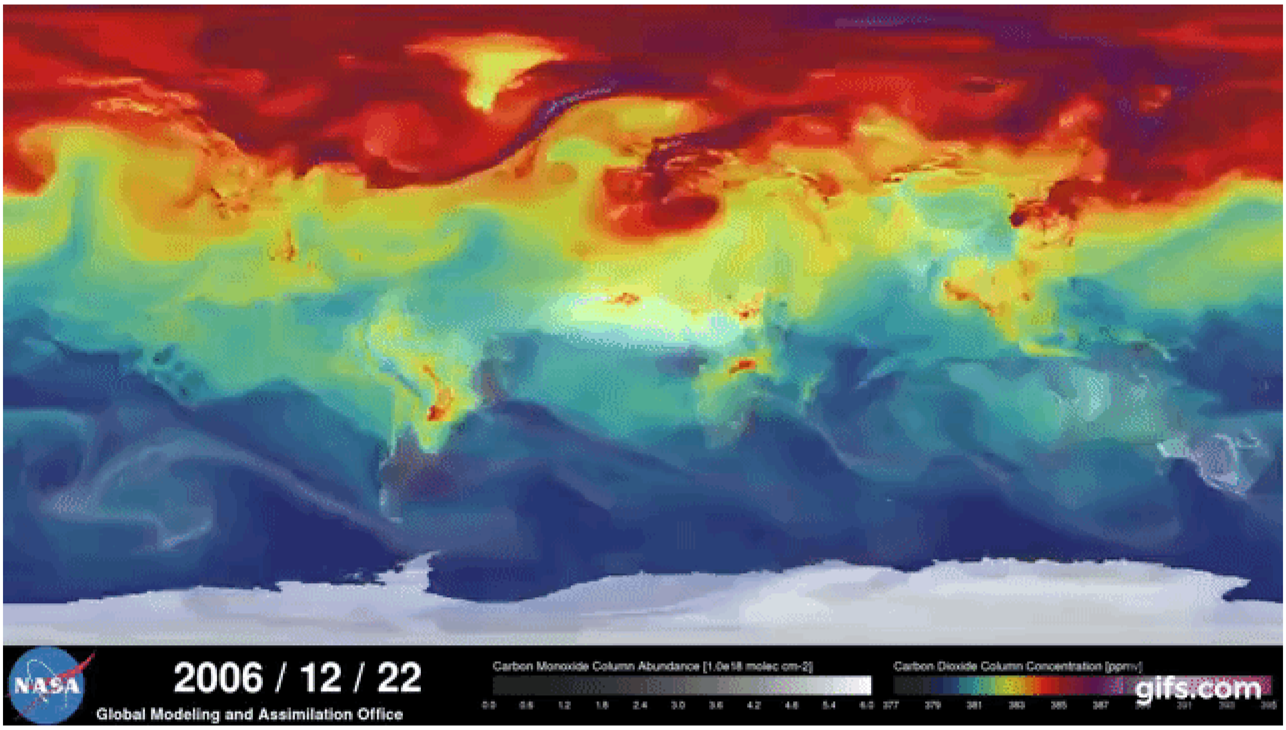

Figure 11. Animated .gif of the movement of atmospheric carbon dioxide created by the NASA Scientific Visualization Studio. Source: NASA.

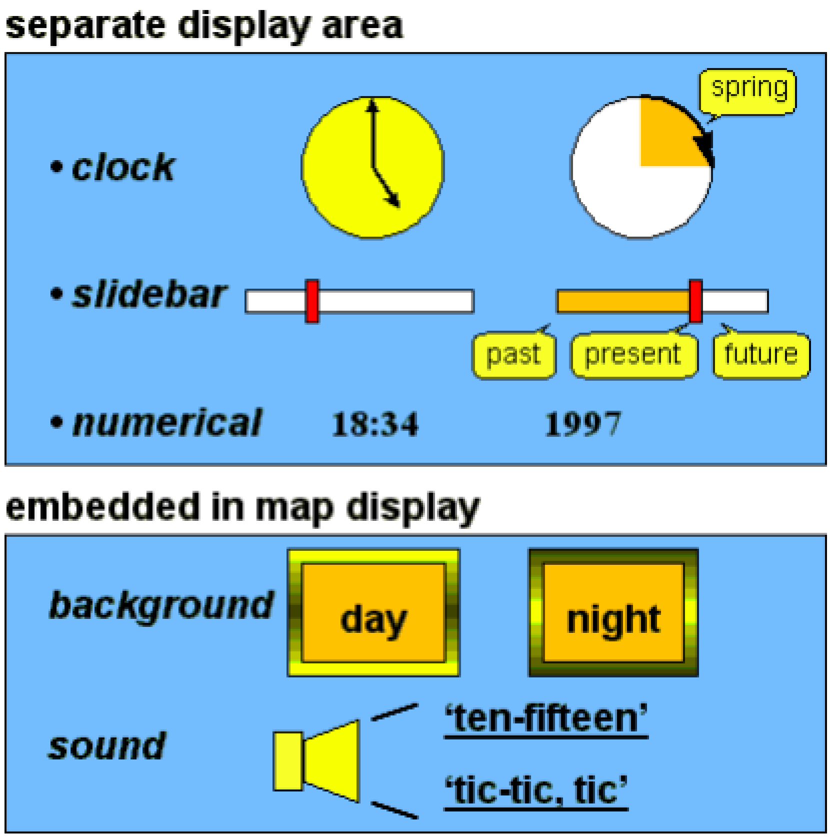

Figure 12. Illustration of different types of temporal legends in an animated map which support identifying when an event or object happened or changed. Source: Kraak et al. (1997), reproduced with permission from the author).

4.4 Multiple Dynamic Maps

Multiple dynamic maps are visually more complex and offer both advantages and disadvantages to the map user (different from "reader" in the static domain). Monmonier (1990) divides multiple dynamic maps into two groups: 1) programmed sequences of meaningful or interesting views, such as combinations of animations or flythrough changing the basemap context, and 2) high-interaction graphic analysis. The first group is primarily concerned with map animation, and the latter is primarily focused on multi-coordinated views where maps a component.

High-interaction graphics allow map users to discover unknown patterns or investigate complex comparisons across space and time through the use of an interactive interface. These interfaces rely on several representations of spatiotemporal data displayed in a singular dashboard-type view with both statistical graphics and maps where the component graphics are linked. Many of these **linked views** include multidimensional statistical visualizations such as parallel coordinate plots and scatterplot arrays in conjunction with interactive maps (e.g. Figure 13). Map users brush over elements within the display with their mouse to see corresponding connections between the data illustrated in each view. These types of interfaces use highlighting when a user mouses-over a data point in one of the views the corresponding data point is highlighted in one of the other views (Robinson 2011).

These highly interactive interfaces specifically support the visualization end of the Cartography3 model, in particular, the exploration task of revealing unknowns (see **Geovisualization**). While the goal of these displays is exploration, their power is in supporting complex comparisons tasks across space and time. The map user has control in how they interact with the data which in turn allows the user to see and make comparisons that were not necessarily readily apparent to the developer.

Figure 13. View of the GeoViz toolkit, linked view high interaction interface for identifying unknowns in spatiotemporal data. Source: Robinson 2011, reproduced with permission from the author.

5. Cartographic Decisions for Representing Spatiotemporal Data

Research in geography and experimental psychology has investigated whether dynamic or static displays of change over time are more effective for readers. The research on the differences and best choice have been mixed. Tversky et al. (2002), attributes this to the lack of informational equivalence between the two different types of displays. In other words, the static and animated versions of the same data do not, in fact, illustrate the exact same information. Instead, one representation provides more information to the reader and thus is more useful. Sara Fabrikant and her colleagues (2008) reiterate this and add that static displays allow users to visually interact in ways that an animated display does not. Cartographers are faced with making decisions as to which type of method is most suitable for their audience and purpose and need to evaluate the pros and cons of each of the different representations for the best use for the type of data and how it will be used.

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