Stretching Space and Splicing Time: From Cartographic Animation to Interactive Visualization

Daniel Dorling

ABSTRACT. *Animation and cartography present very different traditions to combine. This paper offers some ideas about the directions such a combination might take and presents a series of cartographic animation and visualization case studies involving several unusual representations. These examples range from the interactive exploration of high-resolution, two-dimensional images, to the use of animation in understanding temporal change and three-dimensional structure. Some of the conventional wisdom about the appropriate software applications and visual representations to use is questioned. Exploratory analysis, presenting facts to an interested audience and creating a dramatic image, are seen as distinct tasks, requiring distinctly different animation methods.*

Introduction

"Perhaps one day high-resolution computer visualizations, which combine slightly abstracted representations along with dynamic and animated flatland, will lighten the laborious complexity of encodings—and yet still capture some worthwhile part of the subtlety of the human itinerary" (Tufte 1990, 119).

Cartographic animation is a strange concept. To animate means to create the illusion of movement. Throughout history, cartographers have sought to freeze time on paper and developed very effective static representations of flow and change. The strength of the tradition of cartographic technique has meant that many early animations appeared as if someone were flicking through successive map sheets (Tobler 1970). More recent animations have moved beyond this mold. There is no reason why the map should remain fixed while the action is played out upon it. Indeed, there need not always be a traditional map in every frame of an essentially cartographic animation. The barriers that separate us from the other visual arts may disappear as we begin to use the same machines. We need to learn from the experiences of film and documentary makers and from the computer games market, and to use their tools (which often are easily accessible).

Animation is not new to cartography and there have been many past claims for its potential to solve all our problems: "Certainly, the development of computer-generated animated cartography will be welcomed by the cartographer, the teacher, the student and the researcher, whenever they are concerned with visualizing and communicating those geographical complexes which include time as a significant parameter. For many, thinking or visualizing in three space dimensions is difficult, if not impossible; to visualize four adds more in difficulty than the simple proportion would suggest. This need not be a problem much longer with the advent of the computer generated film in animated cartography" (Cornwell and Robinson 1966, 82). We have had time to reflect on such ambitious claims to see what actually can be achieved and what has turned out to be most useful. Now is the time to question how appropriate animation is, to see how many dimensions we can cope with.

During recent decades, experiments with animation in cartography have moved from film (Boggs 1947) to video and then to personal computer graphics (Gersmehl 1990). This has not been a simple progression; each change in media has offered different technical possibilities and a new audience. Several years have passed since visualization in scientific computing was declared a new subject and the first few flurries of optimistic articles appeared, offering insight through the use of graphics (Winkler et al. 1987). The problems have matured from technical difficulties with scan rates and graphics standards (Blinn 1990) to the imaginative hurdles of using transformed spaces and interpreting translucent representations of evolving multidimensional structures (Hart et al. 1990).

This paper seeks to clarify some ideas in all this complexity and discuss which avenues have been most fruitful to follow in the maze of opportunities that the versatility of the computer has opened. The issues addressed are ones that face many current users of computer graphics. How should we visualize the patterns that interest us and for which is animation an appropriate tool? To address these questions, a series of animation experiments are introduced, ranging from visualizing detailed social structure to evolving political alliances and to the medical geography of rare diseases. These diverse examples all tackle the same basic problem—that of representing a complex process through the dynamic geometry and color of the computer screen. I have divided the examples in this paper into three groups, each of which dispenses with past solutions (which used many static maps) but in very different ways—animating space, animating time, and three-dimensional animation.

The practice of research through visualization received recent publicity as supercomputing centers in the United States vied for more resources through the creation of this new subdiscipline (Rosenblum 1990). Visualization is not

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new. The more established history of visualization dates from around 1800 rather than 1987, when almost all the basic graphs and charts we use today (other than maps) were either invented or popularized (Beniger and Robyn 1978). The purpose of visualization has been "to make visible" the patterns trapped in tables of facts and figures or in mathematical equations. Computers are being used increasingly to do this (Neal 1988). Now, as in cartography, a tradition based on static representation has been confronted with new possibilities by computer animation (Baecker 1973). However, the two traditions of cartography and visualization have served very different purposes and we find them offering frequently opposing guidelines on what makes good animation.

A classic example of these conflicting prescriptions is that researchers in scientific visualization may discuss how to represent up to nine variables by combining signals in the color, size, shape, orientation, and position of thousands of symbols (Anderson 1989), whereas cartographers might argue that using more than five types of shading on a map could be confusing. This conflict comes to a head with animation, as often the same machines and software are used by both groups, and neither group is sure how to use motion effectively. Influential writers in both camps (Tufte 1983; Bertin 1983) have refused to discuss the subject of animation as it veers into uncharted territory for both their disciplines. The apparent conflict in available advice reflects a need to address different audiences with different goals and different problems. Do we want simple or complex messages? How much does the audience already know about the subject? How difficult is the subject and how long can the audience's attention be held? Are we investigating through graphics (Root-Bernstein 1987) or teaching with them? And, technically, what is animation?

"To animate is, literally, to bring to life. Although people often think of animation as synonymous with motion, it covers all changes that have a visual effect. It thus includes the time-varying position (motion dynamics), shape, color, transparency, structure, and texture of an object (update dynamics), and changes in lighting, camera position, orientation, and focus, and even changes of rendering technique" (Foley et al. 1990, 1057). If experts in the field describe computer animation as loosely as this, a narrower definition may be inappropriate.

For the action to appear lifelike, the pictures must alter smoothly enough for the motion to be seamless. This speed of change initially required preprocessing onto film or video; now computers can create animation in "real time." Movement can be used to represent change of viewpoint, passage of time, or any variable in principle (DiBiase et al. 1992). The value of animation is that it presents information in a natural way. This is a prosaic point, but we are used to seeing things move. The problem with animation is that if we cannot control its progress ourselves, the picture may change before we have had time to understand it. A single map to show something can be extremely effective; hundreds to look at can be bewildering. Animation often can solve this dilemma—but it also can compound it. Thus, we must decide how and when its use is appropriate. Such decisions can only be made with experience.

Animating Space

Animating space is the process of panning and zooming around and into a large two-dimensional static image. Here we are using the computer screen to show only a portion of a detailed picture, preferably at variable levels of magnification. Such a process is not normally considered cartographic animation, as we are not looking at a dynamic map (Moellering 1980a). What justifies this as "animation" is the speed and smoothness with which the image can alter. What makes it useful is the degree of control we can exert over the process. Some examples are helpful to illustrate these techniques at increasing levels of sophistication.

The first comes from a classic geographic information system application that allows a portion of an encyclopedic database (including many maps) to be viewed at any one time and for this view to be changed at will. The BBC Domesday System (Armstrong and Tibbetts 1986) was one of the earliest products to allow many people the opportunity to inspect, in detail, maps on a computer screen. A major problem of the Domesday and similar systems is an unnecessary adherence to what could be achieved in the past with a book or an atlas. The Domesday system did not allow neighboring map sheets to be joined on screen and only published scales could be shown (because the database only held photographic images of the original printed maps).

As with the Domesday system, geographic information systems often adhere unnecessarily to a paper-based past (Goodchild 1988). One consequence is that many such systems require the screen to be completely redrawn between updating, as if a pen plotter were being used. In many modern systems, the speed and flexibility with which one image is transformed into another still rarely approaches acceptable animation rates, despite the use of very expensive hardware. It could be argued that these application packages are essentially based on archaic "automated cartography" programs; Peuker (1972, 28) provides a good starting point for investigation. Aside from technical problems, the market place of many such applications may well be too conservative to encourage interesting cartographic animation innovation.

A more promising future is offered by recent developments in computer graphics systems that allow a portion of a high-resolution picture to be shown in a window and instantaneously enlarged, reduced, and scanned as the user's hand moves a mouse or presses a button. "(W)e find ourselves manipulating plots which change so fast that they appear in motion for all practical purposes" (Buja et al. 1988). The interaction can be good enough to make you think you are moving your head over the image, or using a magnifying glass on a map—with more than perfect eyesight. In my experience, this kind of map has to be at least 1,500 × 2,000 pixels in size to be more informative than a printed page and to make interactive enlargement worthwhile. Practically instant image compression and decompression allows much higher resolution images to be seen on inexpensive, low-resolution monitors.

An example given here (and explained in more detail in Dorling [1991]) is a population cartogram based on trivar-

iate color mapping of three occupational variables in more than 100,000 British census enumeration districts (Figure 1 [see page 267]). On paper, particularly at publication size, the image appears confusing and overdetailed. After a little interactive exploration on screen, some unusual conclusions can be reached about the relationships between place and occupational class at that detailed scale, which are lost in simplified maps (with fewer colors and larger geographical areas). Interactive animation allowed the fractal-like patterns in human geography to be both seen and appreciated. What emerged was a picture of the way in which areas of affluence simultaneously surrounded, looped around, and appeared inside the places where the less prosperous lived. Every city needed its managers, teachers, and doctors, but, in general, they aimed to live as far apart as they could from the people for and with whom they worked. One of the most interesting patterns occurs in inner London, where a thin, snakelike belt of "professionals" winds from north to south, between areas sharply differentiated as being dominated by the housing of those working in the lowest status occupations.

Social scientists can guess that this kind of pattern exists, but cannot quite see it. The animation of this detailed picture provides a more concrete starting point for them to ask: Why is it that we see such patterns? These patterns rapidly blur away as the spatial scale of analysis is reduced. To see them we need to map very small areas and to see those clearly we need to animate space.

More advanced applications use an object-based graphics file that can contain not only pixel maps, but also vector-type symbols (curves and text), groups of objects, and even currently undefined graphics (i.e., an animation within a static image). Figure 2 shows a portion of this type of graphics file containing an annotated map of the boundaries of more than 10,000 named local government wards in Britain, shaded by unemployment rate for illustration. This is used here as a practical example of a researcher's everyday use of cartographic animation.

Scalable and automatically placed text can be reproduced instantaneously on a well-configured system, again allowing interactive animation. A single graphics window replaces the need for several hundred map sheets, which would require numerous insets. Objects within the graphics file also could be tagged with information about suitable representation for various levels of generalization if desired. The map, which contains the name of every ward, can be magnified at will or zoomed out of to see large areas at a glance. The facilities to do this were all contained in the built-in software of the Archimedes computer used.

Having chosen your subject matter, you need only write the program to create the appropriate type of file (Acorn Computers 1989, 1790). The basic entities of operating systems today have expanded from characters, numbers, and "strings" to include such things as sound "voices" and graphical objects that can be manipulated with the same ease as strings were handled 20 or so years ago. The file your program creates is simply a list of the graphical objects that constitute your map. The difficulty of doing such things has dramatically decreased from the time when researchers were considered foolish to write their own software. In the two years between when I started this research and wrote

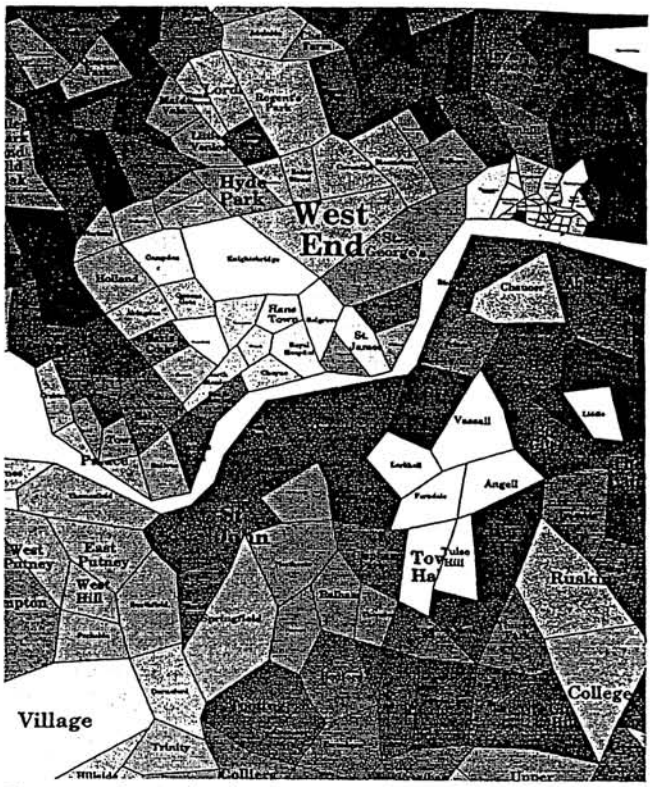


Figure 2. *Inset of a simple annotated map of 10,444 wards in Britain. The wards are shaded in relation to the unemployment rate. Interactive animation is possible with such highly generalized images and useful for identifying possible errors in large spatial data sets such as this (acquired from the National On-line Manpower Information System). The picture is investigated using a standard "Draw" application—now part of the computer's extended operating system.*

this paper, home computer speed increased fivefold; what was just possible in 1989 became commonplace by the end of 1991. On revising the draft of this paper in 1992, I find the goal posts have moved again and wonder for how many months the technical points made here will be relevant.

The examples of animating space described earlier constitute a common group, because a shared set of useful functions can be defined for them. The functions are those of a film camera—to pan, zoom, and focus at will. The first two specify the position and magnification of the image, the third action sets the level of generalization desired (the resolution). The high-resolution pixel map image described previously could be "smoothed" by applying a filter, altering the geographical units or coloring scheme, or using magnification. The commercial software used did not have this last feature implemented, but did refer to the process with filming terms, providing a window showing the camera's view, another window for manipulating the graphical objects, and another for editing the "script" of the film. One technical point that might not lose its relevance too quickly is that the application cost only 25 pounds or the equivalent of $45. Such things are not expensive to implement anymore and should not be too costly to buy.

It is worth briefly raising the issue of generalization and animation in the context of these two kinds of graphics

files. Conventional cartographic generalization, where features have very different representations at different map scales, is simple to implement with object graphics. A "city" object would merely consist of a structure that pointed to, say, three alternative graphic objects, depending on the scale at which it was being rendered in the window on the screen; for example, a dot at low resolution, a gray outline if intermediate, and a street plan if detailed. As you zoomed in on the city, its appearance would jump from one representation to the other. This is not very original, but neither is it unexpected. It actually increases the efficiency of the animation, as detailed structures are only rendered as they are being focused upon. A more ambitious aim would be to implement some form of interpolated generalization (Monmonier 1990b). One simple starting point would be to dispense with arcs and segments altogether and use Bezier curves and such to describe lines (straight or not).

The simpler graphics file, a pixel map, invites a slightly more complex, interactive generalization procedure. Here the intensity of each pixel is spread to its immediate neighbors and itself by the ratios 1:2:1. The two-dimensional version of this is given by Tobler (1989) and used here (Figure 3 [see page 268]). What makes this filter attractive is that it is simply based on applying additions of variables to various powers of 2. Such an operation translates to single instructions in the machine code of some RISC microprocessors, which can execute many millions of these per second. The potential for instantly taking detailed pictures in and out of "focus" should be clear and perfectly possible on inexpensive, state-of-the-art home microcomputers. The theoretical merits of such generalization are not immediately obvious, but its practical feasibility is unquestionable. The extension of these filters to three-dimensional "space-time" smoothing is discussed later.

Geographic information systems and other "professional" pieces of software currently widely used by cartographers may develop the potential for this degree of interaction (Gimblett and Itami 1988), but perhaps a more likely scenario is that cartographers will export their map databases from these systems to more open computer environments. These environments enjoy the higher standards of implementation that come from addressing much larger, and perhaps more computer literate, markets (rather than adding limited animation capacity to already overly complicated geographic information systems). If your children can "fly" their spaceships over exotic terrain on the home computer in the bedroom, why is your workstation at the office having trouble drawing acceptable contours? It has more to do with the size, expectations, and turnover of the respective customer bases than with any technical problems involved.

Animating Time

In this section, we consider examples where the map is held still and the action played out upon it. Here we are showing differences using time rather than space to change the image. Traditionally, cartographic animation has consisted of researchers producing a fixed loop of film or videotape, which is shown to many audiences and can be repeated several times (Cebrian de Miguel 1983; Beruchashvili 1987). Most productions to date have been experimental in nature, attempting to determine how useful the media may be in the future (Moellering 1980b; Mounsey 1982a). Past justification has been that as the costs of production fall, access to animation facilities will become available for large numbers of students. This is now happening. Some very novel approaches have been attempted; for instance the use of holographic imagery in place of film (Dutton 1978). Almost always in this form of animation, however, movement is used to represent a function of time (Charlton et al. 1989).

Moellering's animation (1973) of the incidence of traffic accidents in a U.S. county is one well known early example of this work. The film consists of a series of small "stars" appearing and disappearing at the locations of traffic accidents on a road map in a "compound" day, made up from many hundreds of incidents occurring over several years. Such a basic presentation of the information allows the simple clustering of "black spots" (appearing as "bright spots" on the projection) in time and space ~~to~~ be imagined. Unfortunately, however, the eye-brain system requires time to scan such a picture—collating the rapidly changing spots of light. Conversely, our visual memory is very poor, comprehending only a brief rendition (Marr 1982), so any patterns reoccurring over time—other than the simplest clusters—may not be recognized. Much of the cartographic animation produced to date has followed the practice of such early examples. This writer has created similar animations, in this case with choropleth maps changing color. The results are very confusing. Most objects in the real world do not change their colors like this or instantaneously appear and disappear. We do not easily appreciate such animations; they are not what we have learned to encounter.

I suspect that animation needs to resemble natural visual experiences—in general, objects should not change color (even though that is easy to program), but should move, because we are good at registering movement. It is through altering reality in our interpretation that we see new sides and gain understanding. To appreciate the impact of what we study, be it voting on election day or a traffic accident taking 30 seconds (in reality), we have to extend the amount of time and space we use to represent each incident beyond the simple scaling down from real world to animation time. After all, the effects of the incidents can last from years to a lifetime, and it is because of the consequences of those effects that we are studying these incidents at all. Just as in the cartography of space, where features of interest are not drawn to scale, the cartographers of space-time must learn how to distort to their advantage. A simple animation of traffic accidents may merely serve to outline the layout of an area's road system. We know where the roads are. We want to know where unusual numbers of accidents happen within that network; not just see a flickering image of that network.

The eye-brain system is particularly adept at monitoring continuous movement. The most successful cartographic animations the author has made have been those that exploited this fact. A study by the author of the changing voting patterns of 10 British general elections (from 1955 to 1987) used a triangular representation of the proportion of

the vote given to each of the three major parties in more than 600 constituencies (following Upton 1976). Inside the triangle, a dot was placed for each constituency, its position determined according to the proportion of the vote that each party won. In the animation, the dots floated toward their respective destinations from election to election (Figure 4 shows the 11 "key frames" to the animation). A striking overall impression of the votes shifting was achieved. Sometimes one section of the "flock" of dots would break away; two sets could even pass between each other and the components of movement would still be recognizable. The animation was successful because most constituencies followed common trends. It is these common trends that we follow across time. They are essentially quite simple features, but nevertheless take time to recognize.

The animation was not straightforward to create. Two reorganizations of seats occurred in the period, so some dots had to fade out and some new ones be made to appear—representing abolished and newly created seats. The Liberals did not have candidates in many seats during the early years of the series. The dots representing those constituencies lay on the base line of the triangle, "bouncing up" when a third candidate stood in an election. Nationalist parties in Britain won a few seats and these were shown by coloring their respective dots distinctively. The Northern Irish constituencies abandoned the main political parties after 1970—the dots representing Ulster can be seen to fly out of the triangle halfway through the animation (they form a line to the right in the static illustration). To have made it more successful, a detailed sound commentary would have been useful. The main element missing from the original animation was any measure of the turnout for each seat. Later, this was included by altering the intensity of the dots according to the level of abstentions, as is shown in the illustrations here; you could see the turnout tended to be greater the smaller the margin of majority (i.e., the closer the result). The pattern forming becomes increasingly clear in later years. The 1992 results were added as this paper was revised (Figure 5) and the feeling that some basic political transformation of Britain is quite literally taking shape before our eyes is remarkable.

Interestingly, almost everyone who was shown this video wished to control it personally, rewinding, pausing, and fast-forwarding to enable them to grasp what was being shown. As "film" it would not have worked. As "video"—shown to well-informed individuals—it revealed facts they had not previously appreciated (see Devaney [1989] for similar results in mathematics). The standard national television representation of the same facts (as appears regularly on news coverage) can be found wanting. It consists more and more of simple bar charts showing three percentages changing; ray traced and animated to look nice, but still only presenting us with three numbers summarizing up to 30 million votes. The more widespread use of animation allows a video to be made that can address the particular interests and abilities of small audiences. Video control allows a complex, three-party, multiconstituency situation to be vividly portrayed and better understood by a selective audience.

To try to represent the changing spatial structure of party politics in Britain, a more elaborate animation was devised. The last example of animating time showed no spatial information, space being used to represent political position. To see geographical patterns in the changes, an equal electorate cartogram of the constituencies was constructed and in each seat an arrow placed (following Upton [1991]). The arrow was colored by a mix of blue, red, and yellow (also adopted usefully by the three parties—Conservative, Labour, and Liberal). An orange arrow would thus represent a marginal Liberal/Labour seat. The direction of the arrow was set according to the direction in which the dot representing the seat would have moved between elections on the triangle in the previous example (upward indicating a swing to the Liberal party, left to Labour, and right to the Conservatives). The length of the arrow at any given time indicated the magnitude of the swing (Figure 6 [see page 269]). Color and orientation combine to create a new visual political variable.

The animation was at first extremely confusing and had to be repeated several times before patterns in the movement could be discerned easily. The arrows tended to move together—like a group of synchronized swimmers or flock of birds (Kerlick 1990)— most notably those representing seats spatially or politically close. Interesting anomalies could also be noticed. The effect of political scandal in a single constituency at a particular election would cause an arrow to swing around suddenly and grow greatly in length as a very large swing in the vote was recorded. At times the arrows would be well aligned; at others their movement appeared more confused. The Northern Irish seats swung dramatically around and around before they left the three-party political arena. The insight gained was greater the longer the animation was viewed. Such a reaction is not uncommon in this work: "When I first saw the animation, I watched it over and over again. I thought something like this was going on—but never exactly this" (La Breque 1989, 527).

An interesting technical aside: The underlying cartogram was also slowly evolving as the animation played and the electorate changed over the 30 or so years. Inner-city seats shrank in size and some were squeezed out altogether when two redistributions occurred. Elsewhere, new seats would squeeze in between old ones, their representative arrows growing in size as their electorates expanded and the overall shape of Britain's "electoral space" changed over time. Between 1970 and 1974, roughly 28 old seats disappeared and 33 new ones were created; between 1979 and 1983, the figures where 27 and 42, respectively. Since then, from 1987 to 1992, only one new seat has been created, but the geography of British parliamentary constituencies is set to change dramatically before the next general election. Those studying the geography of political change have to find a better way to cope with moving boundaries than amalgamation. Animation is one alternative, accepting and showing that the boundaries change, rather than trying to conceal the fact.

A difficulty with this animation came when it was recorded on videotape both in the PAL and NTSC standards. Six hundred fifty tiny spinning arrows tended to blur and it became difficult to see in which direction they were pointing—let alone how they were subtly colored. The problem is more serious than television resolution (al-

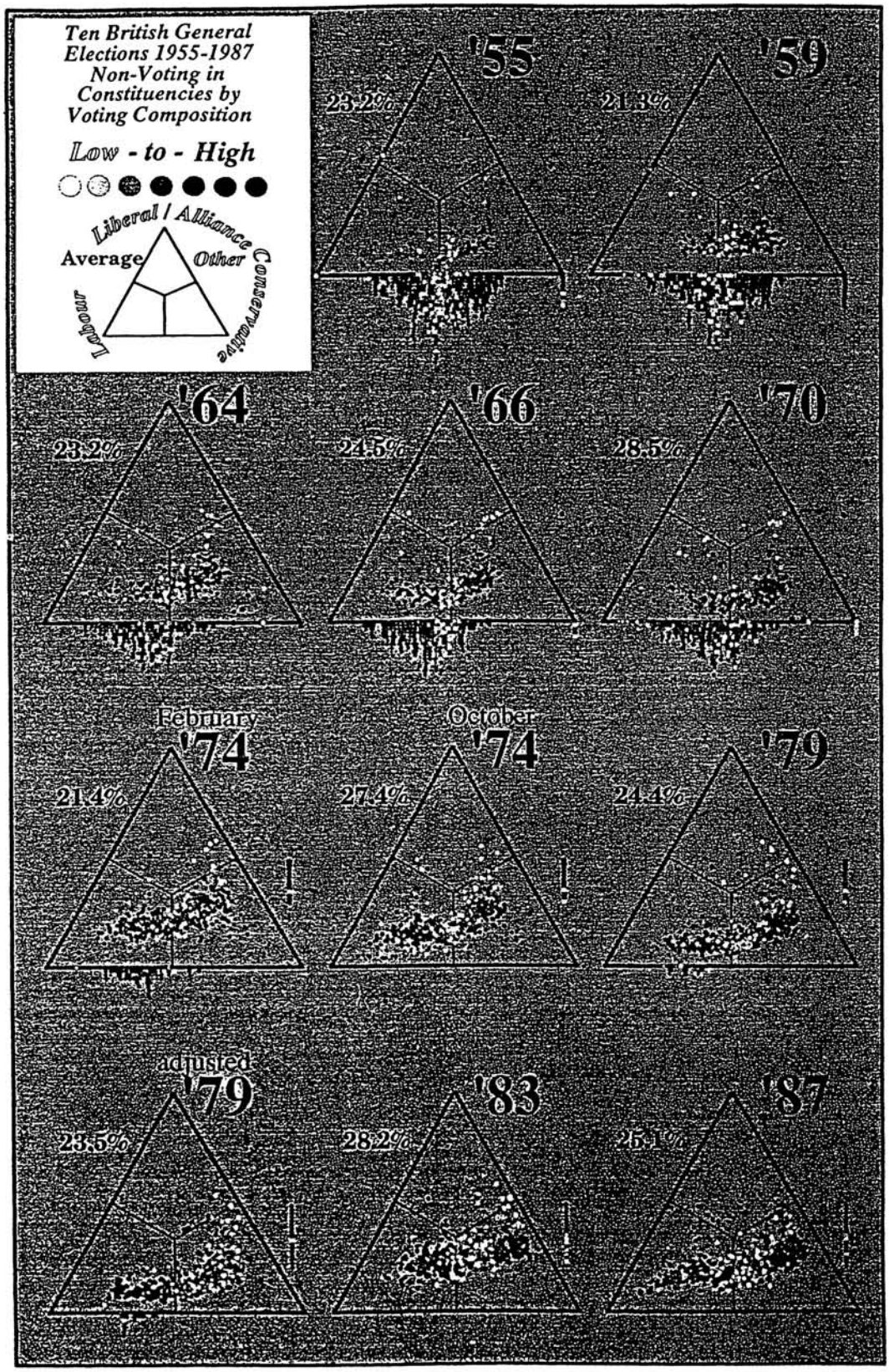


Figure 4. *Key frames from an animation of the distribution of votes among the three major parties in British general elections from 1955 to 1987. Each dot shows the political position of a constituency, shaded according to the turnout in that seat. Animation helps show the evolution of the distribution over 30 years, and many millions of votes. The constituencies are lightly shaded when there was a high turnout and are dark when there was a high rate of abstention or "nonvoting."*

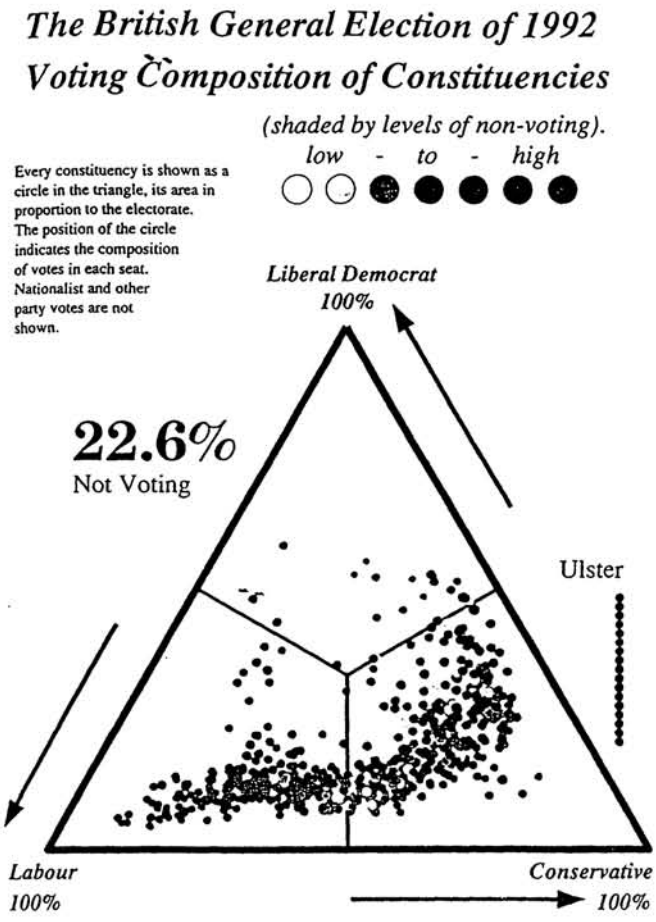


Figure 5. *The political composition of constituencies in the British general election of 1992. Although this figure clearly shows what political situation has evolved from the period shown in Figure 4, it cannot show how the political change happened—which constituencies moved in what way for the new order to form. Linking points through time with arrows quickly creates a tangled mess in the triangle. Animation is needed to see the detail of this political evolution.*

though wall-sized high-density television will be nice). In general, with detailed images (as described in the first group of examples), we need to pan and zoom around the picture to understand it. Doing this, however, adds problems; we are unable simultaneously to see detail and the "big picture." The viewers are unsure where they are, needing an inset to orient themselves globally (spatially and temporally), and always have the uncomfortable feeling that they are missing something off the screen. They would focus on a particular area of interest and then pan around to other collections of arrows; but could not easily see whether or not two distant sets were behaving synchronously or not.

It is possible to have several windows showing different portions of the same high-resolution animation placed alongside on the computer screen, but what if you were also interested in whether history was repeating itself? One window could be played a few years behind another, but comparing two moving images simultaneously is in general very difficult (although easy to implement on current graphical interfaces). Instead, a third window could be invoked to show explicitly the change while the others remain in the background to remind us from and to what the image is changing.

It is through simplifying our pictures of society that we gain an understanding of it. To animate space, we needed to freeze time; to animate time, it helps to freeze space. In other words, if the symbols on the map move, it is better if the map stays still. This causes problems, because in human geography we are increasingly interested in seeing the detailed picture that such recommendations would deny us from viewing. These animations cannot help us when investigating such complexity, as there are too many sequences to be viewed. The alternative to using dynamic animation for investigation is to trust a producer to select an interesting sequence, creating an illustration of the process that promises to show the most interesting incidences and pertinent connections in a sensible way—an animated film. A hybrid approach may also be possible; as multimedia takes off, the first truly interactive animated atlases could soon appear.

To produce good animated films requires knowledge of how to entertain. On television, producers cut quickly from camera to camera. A series of experiments in computer graphics pasted one after another on videotape does not hold the viewer's imagination for long (as this author discovered). A successful animation of this type should be interlaced with conventional "talking heads," photographic images, and continuous commentary—real "multimedia." Today's audiences will not tolerate poor-quality cartographic "television."

Three-Dimensional Animation

This last group of examples uses animation to investigate three-dimensional structure. This has become a major preoccupation in scientific visualization (Hibbard and Santek 1990) and involves making use of movement, perspective, shading, and shadows to compensate for the lack of an actual third spatial dimension on the flat screen. Movement has been found to be far more important than any other depth cue in bringing three-dimensional objects to life in our visual imagination.

Examples of animation described as three-dimensional are becoming increasingly common in cartographic work, but are often limited to a surface representation of simple terrain or cityscape that is "flown over" (called 2 ½ D in MacEachren and DiBiase [1992]; see also Moellering [1980a]; Klasky [1990]). As early as 1959, Tobler suggested such work would be useful. One of the more interesting recent developments has been to show models of proposed new buildings from pavement level rather than from above, as they are more often seen when physically constructed on a table (Herbert 1987). As is increasingly being realized in scientific visualization, however, imitating reality is not the most ambitious option computer graphics has made possible (Moellering 1990; Haggerty 1991).

We have already seen how an artificial two-dimensional space can be created in which to represent party political position, given three major parties. When there are four serious contenders, extending the previous example results in a three-dimensional form in which political constituen-

cies can be positioned. The author came across this problem when looking for structure in the four-party politics of Scotland, where the Nationalist contingent often fares better than some of the three major parties mentioned above (Bochel and Denver 1988). Several hundred wards are contested during local elections in Scotland. If the Nationalist party is represented by an apex above the center of the equilateral triangle used in the three-party situation, a tetrahedronal space is created in which a cluster of points lie. Viewed from one angle and lit from another, the entire tetrahedron can be rotated and an animation produced (Figure 7 shows the wire frame basis of this). The form of a complex shape, made up of hundreds of seats and millions of votes, can then be understood. The relationship between the Nationalist and Labour parties is close, with the Nationalist vote generally rising as the wards move toward Labour. Local tactical voting is also well understood in Scotland, with far fewer truly three- and four-way contests than even political support would produce.

The frames from the animation are confusing seen in static isolation. A two-dimensional net of the tetrahedron has been "unfolded" (Figure 8) to allow something of the patterns found to be seen here. Tactical voting in Scotland tends to leave the center of the political tetrahedron sparsely populated by wards. A hollow structure is formed, with the wards toward the Labour party pole being much denser and creating the overall impression of a "tear drop." There are, of course, many other details that could be added to this description; the planes of wards scattered across the sides of the tetrahedron when one candidate does not stand, or the lines formed when two fail to do so. The position from which we light the space easily can change our appreciation of the picture, as can the direction in which we choose to rotate it (for general references see Magnenat-Thalmann and Thalmann [1989]). With enough time spent

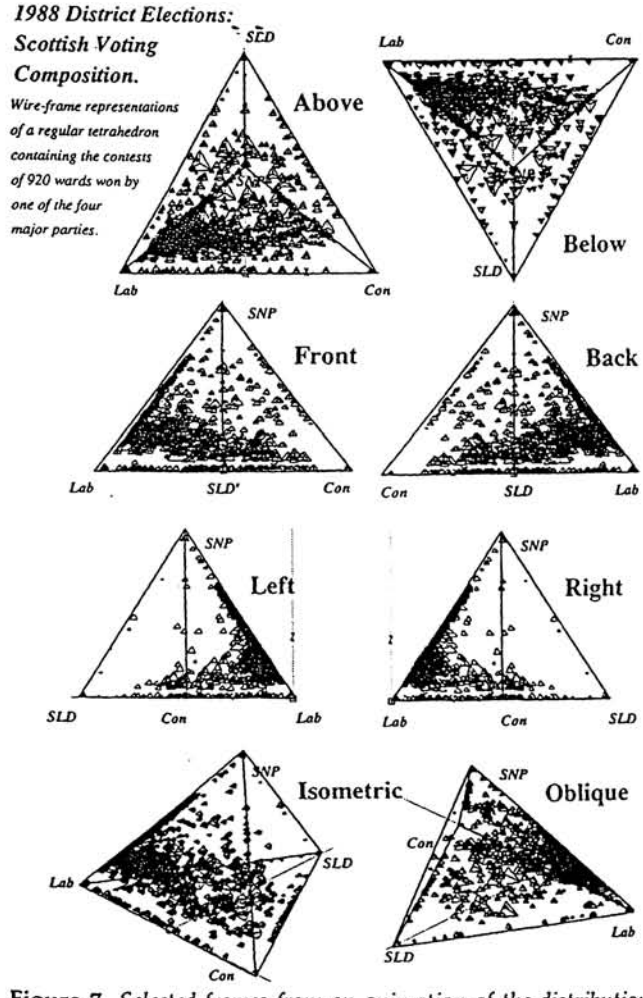


Figure 7. *Selected frames from an animation of the distribution of votes among four major parties in the Scottish local elections in 1988. Each small tetrahedron shows the political position of a ward, its volume in proportion to the respective electorate. Animation is required to comprehend the three-dimensional structure of the four-party voting pattern; these still images are far too misleading. Here, only the black-and-white "wire frame" versions are shown for printing clarity.*

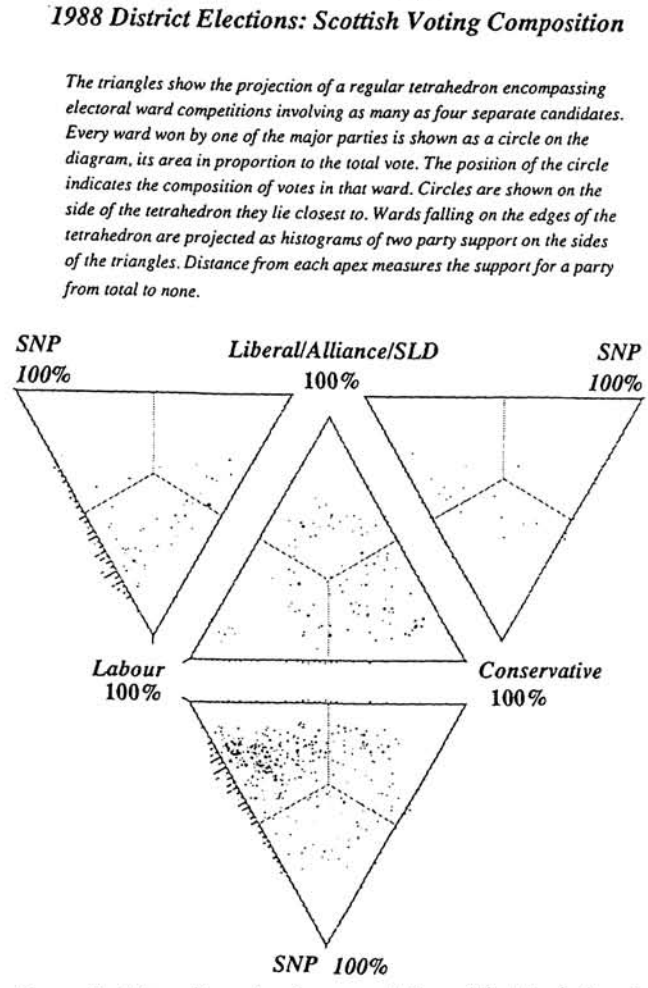


Figure 8. *A two-dimensional representation of the tetrahedron in Figure 7, "unfolded." Each dot is analogous to a dot in the small tetrahedrons in the previous figure. Figure 10 helps explain this image. If a three-dimensional representation can be avoided, then animation can be reserved to show changes over time. When three dimensions are collapsed to two like this, the distribution appears sparser than it is. Circular cross sections of the "tear drop" can be seen in the central and bottom triangles.*

studying the pattern, however, it is possible to get a good idea of its shape. Interactive animation of so many points is still taxing to a home microcomputer, however. A ray-traced version of such an animation may take many hours to record a few seconds of motion (Glassner 1988).

However, what if we were interested in the changes between successive local elections? We are already using time for our rotation of the structure. We could also employ it as before, to allow the dots representing wards to move between successive elections, to see the "tear drop" evolve. To see the tear drop when static requires time, thus to comprehend its evolution would be even more time-consuming. What if we wished to view the geography of this four-party voting across the Scottish nation? We almost certainly could not gauge the direction of hundreds of tiny arrows pointing out of the plane, let alone tiny arrows spinning in three dimensions (Helman and Hesselink 1990). In moving to three dimensions, we lose much of the versatility that flat representations afford. We have to use animation to understand it and color (and shadow) to light its form—providing depth cues—before we can use either of these aspects for other purposes.

The cartographer's graphic options are severely reduced as the dimensions increase (i.e., the lighting required in three dimensions affects the coloring of choropleth maps draped over complex surfaces). You can begin to imagine some ridiculous scenarios: "Is that an area of bad unemployment or just the shadow cast from that mountain of high house prices? I'll just position the cursor to shine the interactive search light in there to find out." Combine those problems with our limited visual ability to gauge depth (even when we think it is clearly presented) and our meager mental ability to cope with the three-dimensional geometry involved, and the difficulties may appear almost insurmountable (Parslow 1987).

There are, however, many situations when using a third dimension cannot be avoided, processes that, for instance, create complex patterns over time as well as in space. Consider the case of the incidence of one general disease, childhood leukemia, as it occurred over the last 20 years in northeast England (Knox 1964). Several hundred single incidences have been identified of several different types of the disease (some of which may be related). In space, these cases could be plotted on an equal-population cartogram to see if there were any obvious patterns. With substantial analyses—the fitting of a surface made up of circular kernels (Brunsdon 1991) around the points designed to maximize any slight change in the geographic propensity for the disease to strike—there appeared to be some structure in the evenly spread incidences. This two-dimensional pattern was achieved by "collapsing" the temporal element down upon the spatial plane. How were these incidences distributed in time?

A block of space-time was constructed, projecting time up from the two-dimensional population cartogram base. Within the block, several hundred incidences were represented by spheres centered at the time and spatial position of disease diagnosis. These spheres were color-coded by the type of leukemia identified. A "camera" was then placed at the familiar angle—looking back through time, with north upward and west to the left of the picture. The camera could then be rotated around the mass of spheres or "flown" into them to explore apparently interesting groups of cases from many angles. Figure 9 (see page 270) shows the cases at the familiar angle and metric, and hence, naturally clustering in built-up areas. The spheres could also be made slightly translucent, so as not to obscure those lying "behind" them (Papathomas and Julesz 1988). Such techniques require a great deal of computer time and could not be performed at acceptable animation rates. In practice, an interesting pattern was identified from still images and a "flight-plan" made for the camera (Muller et al. 1988) to create an animation overnight. The time taken would depend on the number of incidences in view, the final resolution, and number of frames required.

The still pictures produced could be misleading, but the animations dispelled many two-dimensional illusions. Seen from particular angles, groups of incidences that are actually well dispersed in space or time may appear to line up. The animations brought the true uniformity of the disease to light. This form of visualization does not require prior hypotheses to be set, at least when it is truly interactive. The distributions can be examined at will. Interesting groups of any pattern or concentrations of particular colors or shapes can be envisaged. No space-time clusters appeared. The earlier identification of spatial clusters must be reinterpreted in light of the lack of any apparent pattern in a space-time model (Dorling 1991). It is important to realize, however, that different things will probably cause spatial patterns that are independent of time, temporal patterns that are independent of space, and the space-time patterns. Without animation, it is difficult to consider the third category (MacEachren 1992, personal communication).

Discussion

From many personal experiments with animation, I have drawn some conclusions. I found the first group, animating space, to be most useful, which was far from what I anticipated when I began the research. The second group, animating time, was in general less useful during investigation than in illustrating change to other people, despite being the form most generally advocated by past work in cartography. The problem encountered when animating time is the brain's poor visual memory, although this may be improved by "visual training." The third group, detailed three-dimensional animation, I found to be extremely confusing—even though this is the direction in which a large amount of scientific visualization research is currently being directed. I would like to be able to understand three-dimensional models of these data sets, but I suspect that I would do better to concentrate on complex two-dimensional work. With more effective techniques for "animating time," more powerful machines, and extensive experience to explore three-dimensional animation, both doubtless could be improved and made more valuable. The first group—animating space—is, however, currently receiving inadequate attention, given its value and adaptability.

Animating space appears to be the most promising of the

three groups because it naturally extends our ability to focus and zoom in and around two-dimensional detail. When implemented well, it is as if we are moving a great paper map about effortlessly and can see it clearly from any distance. We can analyze very complicated two-dimensional pictures. Techniques such as these greatly aid understanding and we should concentrate our work with computers to extend that ability (MacEachren 1987). One of the ironies of animation is that often the most effective way of seeing change over time is to not use time to show it. To compare this year's and last year's figures, we place them together on the same sheet of paper. Comparison requires at least one simultaneous view. The distribution of successive years' unemployment rates is often best shown on a single map, where symbols can become very small when a large number of areas are involved. Animating space can allow detailed spatial investigation of such a complex picture, which incorporates a temporal variable statically.

Three-dimensional animation presents a set of techniques that are difficult to adopt because they try to force us to comprehend the form of structures in a space, which greatly taxes our powers of visual analysis. If the movement is allowed to cease so that we can concentrate on the picture, we lose the three-dimensional feel of the image: "One of the most effective depth cues is achieved by providing the observer with an animation sequence of parallel projections. However, the usefulness of this method is limited since the biologist can extract significant information by carefully examining a well-shaded still image rather than watching a spinning object" (Kaufman et al. 1990, 162). In cases where three-dimensional visualization tools are found to be invaluable, it is because they address the right problem, not because they are easy to understand.

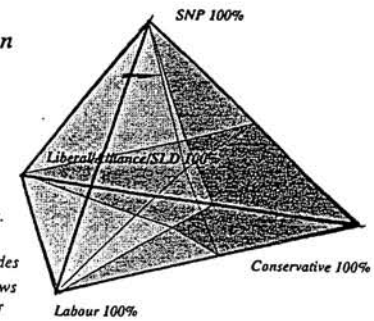
The mind holds images two dimensionally. A relatively simple three-dimensional object (a Moebius strip, for instance) can confuse it. Worse still, we often fail to realize our limitations. It is even more discouraging to contemplate the problems of including a fourth dimension. Very few people can grasp anything more complicated than the idea of a hypersphere or a tesseract (Rucker 1984), let alone gauge the relationships between objects placed in those four-dimensional forms. The computer can be used to generate projections of four-dimensional space, as easily as perspective views of three. However, these are extremely confusing to us. Our ability to handle geometry falters beyond the plane. That is why cartography is seen to work so well— because it takes visual imagery to the limit, within the two-dimensional space in which we think best (Arnheim 1976).

Animating time, the classic use of animation in cartography, works best when movement is used. We are not good at recognizing objects that change color. This does not include changes of color to indicate movement using cycling, or the spread of foreground over background—but rather change of an object's color used alone. We must remember what color an object used to be to know how it has changed. Noting many changes of direction also relies on our visual memory, which is not good (as there is so much to remember), but at least we are used to doing this. Airplane display teams use "smoke trails" to help overcome just such a problem, a technique that might be adopted profitably in this field. Motion needs to be smooth and reasonably coordinated to be memorable. Fast-frame rates and slow action are advisable. This form of animation works best when illustrating rather than investigating: "Several trial films revealed one very necessary characteristic of animated mapping: simplicity and extreme clarity are essential. In a static map, the reader has time to interpret complex or unclear information. However this is not the case in animated mapping where the image must be interpreted immediately" (Mounsey 1982b, 130).

If possible, it is advantageous to reduce a problem's dimensionality. A good example of this is to open up the political tetrahedron envisaged above to show the net of four equilateral triangles that surround it (Figure 10). Wards are then drawn on the face to which they were closest in three dimensions (Figure 8). This network can be divided into 24 areas representing every possible order of result, which amalgamate into groups showing where particular

Schematic Representation of Four Party Voting Compositions.

The diagram below is a projection of the tetrahedron which contains all possible four party arrangements. The standing of the Conservative party is shown as an example in shades of grey. Position on the diagram shows party order as well as proportions of the vote.



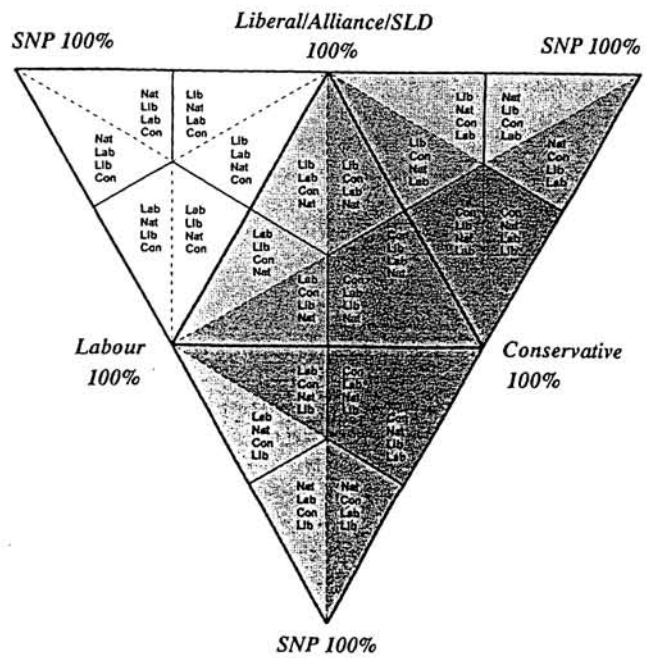


Figure 10. *This diagram shows the meaning of position in the "unfolded" political tetrahedron. If more methods can be found to reduce problems' graphical dimensionality, animation could be used to greater effect, rather than for merely "flying" around a (perhaps unnecessarily) complex three-dimensional form. However, it was only because a three-dimensional aspect of the model (position of the fourth party) was seen as relatively unimportant that it could be reduced to this form.*

parties were victorious, for example. The arrangement can be useful, but does create discontinuities, rather like a map of the globe divided at the oceans. A higher degree of two-dimensional detail is also required to compensate for this, but appears well worth the bother. Some degree of trickery is often needed to produce effective visualization (Tufte 1990). If space can be reduced to a single dimension (for example, along a road or river), evolution through time can be shown on the plane (Buckley 1987). Unfortunately, there is no general formula for successfully unfolding space-time onto a plane, but solutions can often be found for particular scenarios.

The distinctions being made here need to be clarified. Visualization versus cartographic animation is not a useful dichotomy, but illustration as opposed to investigative research is (MacEachren 1992). We rarely can genuinely achieve both at once. Illustration presents the results of our research. This research is usually a lonely affair conducted by one or two interested and often knowledgeable people. Illustrations are presented to large audiences who may be less interested in and less informed about what they are being shown, so the images have to be made visually entertaining: "The timing of animations is often driven by computing time instead of by final appearance; no time is given to introducing actions, to spacing them adequately, or to terminating them smoothly, and the resulting action seems to fly by. The details of an animation are given too much attention at the cost of the overall feeling and the result has no aesthetic appeal. When you are planning an animation, consider these difficulties and allot as much time as possible to aesthetic considerations in the production of the animation" (Foley et al. 1990, 1078).

Good illustration should tell a story. An animation of the incidence of AIDS spreading over Pennsylvania (MacEachren and DiBiase 1992) was designed to be understood by and interesting to school children. It does not use a cartogram, which would confuse such an audience. Simulated three-dimensional animation fly-bys and the like are often more useful in illustration than investigation. So-called "three-dimensional bar charts" each show only a one-dimensional variable and often visually distort that; but they can liven up a drab commercial report (although Tufte [1983], for one, would not agree with their use). Whenever a lot of complicated information is to be understood it needs to be seen clearly and in detail. To show conclusions to a larger audience, we then often need to simplify and dramatize them (but this has been avoided here). Illustrative animation can tell a story; investigative animation allows researchers to find a story to tell.

For investigation, when a single static map can display a subject effectively, alternatives are unnecessary. But when we require anything more demanding than about a dozen static maps to show a process, assimilation becomes difficult (Martis 1989). Animation can ease this problem, but it needs to be interactive to be a successful replacement. Animation, allowing the researcher a choice of viewpoints, also facilitates investigation. For an open perspective, as much information as possible should be available for presentation in its original detail (of spatial resolution). This prescription, the opposite of that for illustration, also usually requires the model we use to represent reality to be two-dimensional, to avoid unnecessarily compounded complexity. These aims sometimes conflict.

Researchers can learn from visualization's history. There are many examples of ingenious two-dimensional solutions to multivariate situations in the archives of the last 200 years of research. Multiple plots, population cartograms, and graphical brushing show some more recent alternative ways (Becker et al. 1988; Tufte 1988; Monmonier 1990a). There is no general textbook as yet, but some useful collections of examples (Friedhoff 1989; Nielson et al. 1990). To imitate such novel images as the ones in these collections with a computer, presentation packages are unlikely to help (although this field is changing rapidly). To create new computer images, and thus animations, we currently need to use general-purpose graphics packages and some simple programming, not the limited options of a dedicated mapping system.

Novel images are needed to analyze the huge mass of unexplored data that exists and is now available about our society. Animation is needed to cope with the amount and complexity of information. Our curiosity inspires us to see what stories these huge banks of data have to tell. Writers forecasting what innovations the use of computer graphics would bring when such things were first possible would be surprised at how interdependent their suggestions have become: "Solutions might be expected to include innovative uses of both graphical and nongraphical dimensions only recently rendered technologically accessible, including color computer graphics, person-machine interaction, computer animation, three-dimensional computer graphics" (Beniger and Robyn 1978, 7).

The computers that mapmakers now use can do far more than make maps. Animation demands new skills of those who so far have just created still images. As users develop more computer versatility and demand more of the software, simpler and more flexible applications will proliferate. Inexpensive hardware is already capable of sophisticated results and increases in power will occur more quickly than the demands of the users, with some vendors more than others (Verts 1989). Animations should not be produced for their own sake; and often not being able to publish the actual animations is still a great disadvantage.

We should look at what other graphical applications are becoming available, beyond those simply targeted at us. Remember that what is of primary importance is the composition of our pictures (Szegö 1987), what they show, how they show it, and why (Harley 1990). We must not allow our technical choices to become delimited by the items on the "menu bar"—the results of others' imaginations and agendas. That there is not a button marked "cartogram" in your application, for instance, is not a good excuse for not using one if appropriate to your studies. Rather than be led by products from the major software vendors, we need to see where we are and how we got here, before deciding in which direction we want our work to go.

Conclusions

This paper has outlined the use of animation for exploring large two-dimensional maps, creating video that shows changes over time, and looking into multidimensional

models of complex spaces. The first method works, but every viewer needs an individual screen to control. The second method cannot cope with too much detail, and changes need to translate into motion to be appreciated fully. The third method falters at three dimensions and fails at more, not because of the limitations of the machine, but those of our minds. However, these are all research applications. The needs of the researcher contrast with those of the illustrator. In investigation, animation should be used when it is not possible to do research without it. On the other hand, the illustrator should, and increasingly will, use animation to enliven a presentation. Just as color can dramatize a black-and-white illustration and a two-dimensional pattern be given a three-dimensional "feel," animation can add to the immediate visual appeal without increasing the information content. It is vital to decide what we are using the media for when we choose which methods of animation to adopt.

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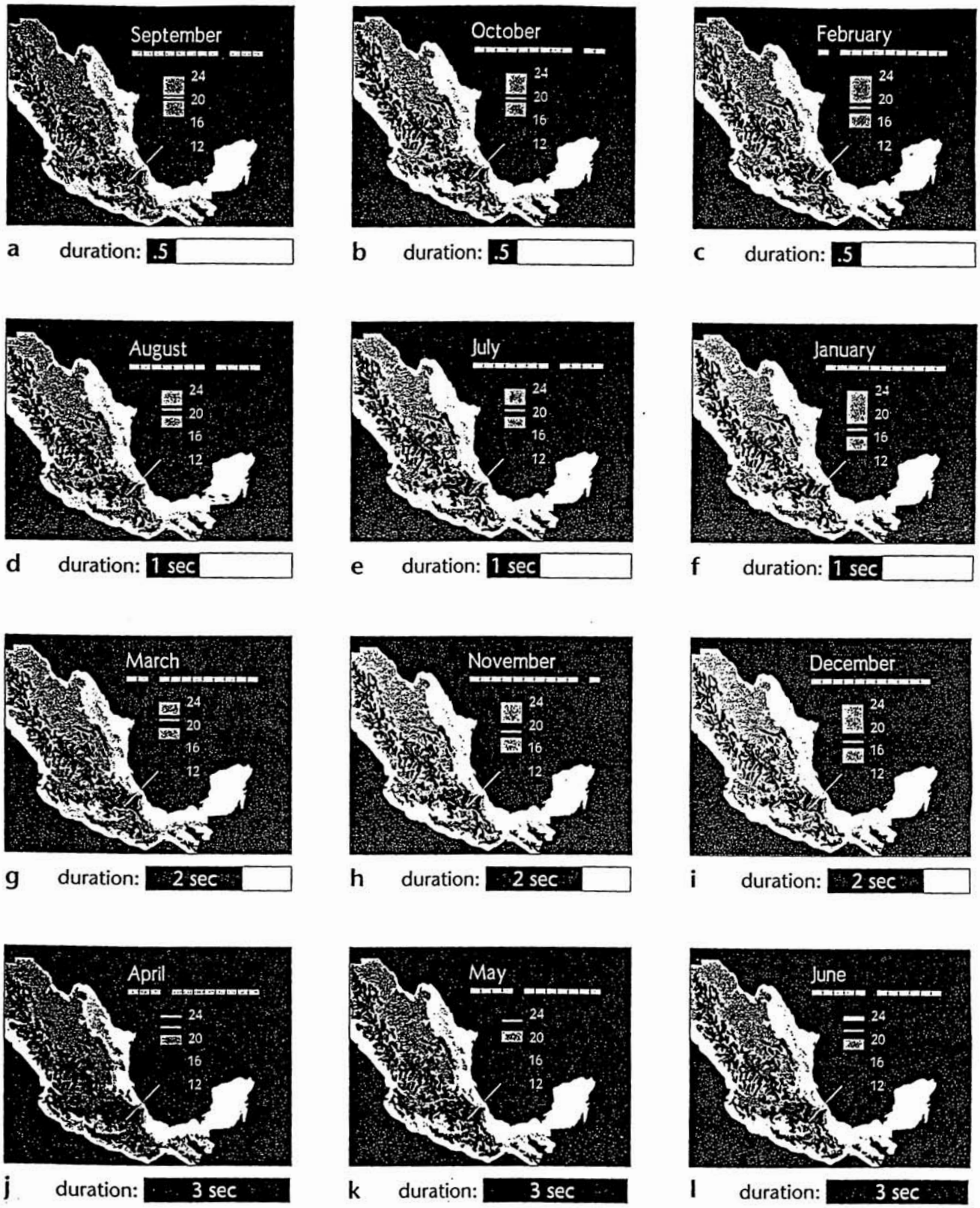

Figure 10, DiBiase et al. *Reexpressed time-series animation comparing observed temperatures and ranges of temperatures predicted by five global climate models for Puebla, Mexico, for a 2 x CO_2 scenario. Scenes are reordered from months in which model predictions vary the least to those that vary the most. The reexpression reveals maximum uncertainty of predictions during the spring planting season.*

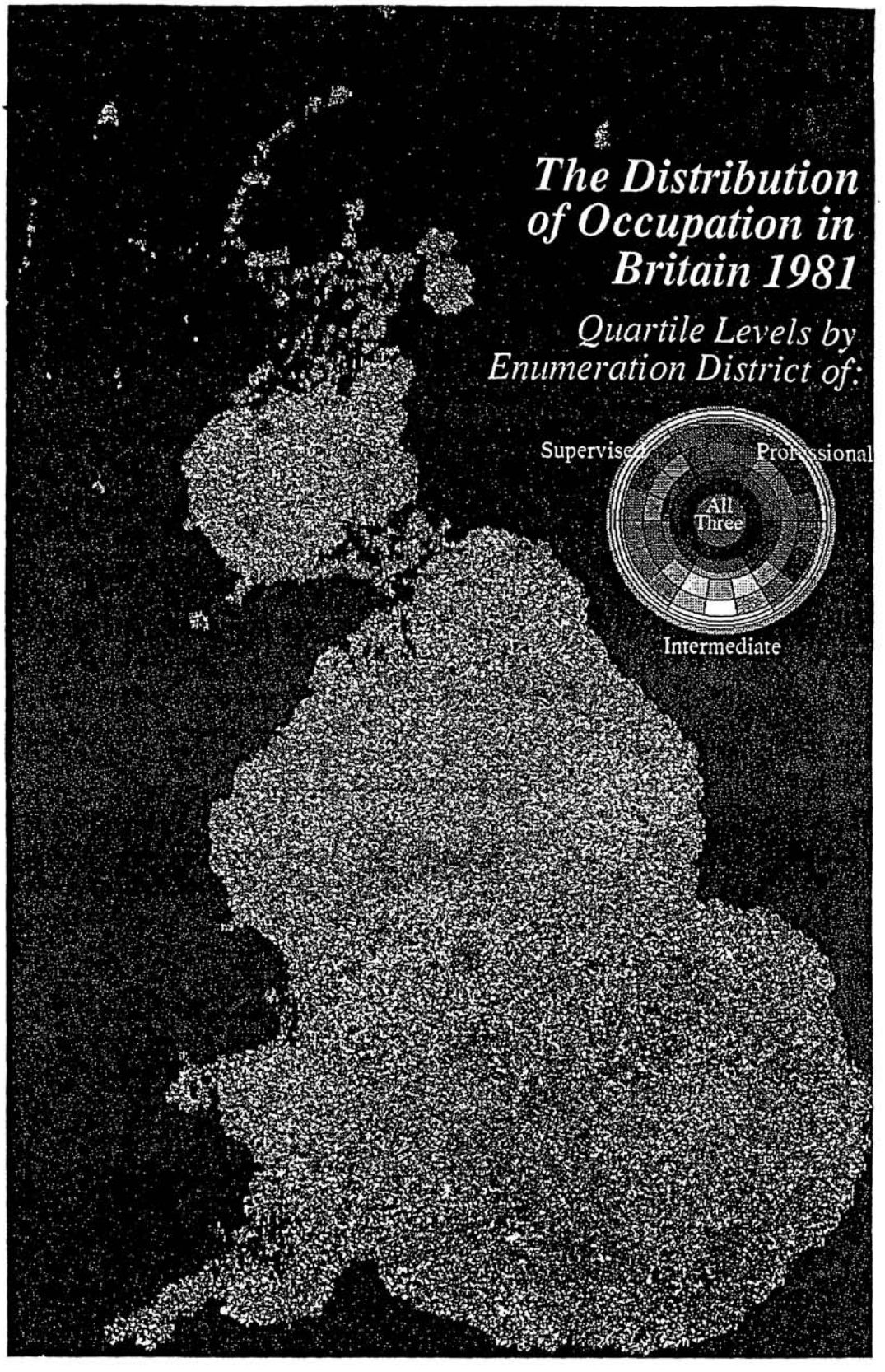

Figure 1, Dorling. *A pixel map showing trivariate color shading by socioeconomic group in 129,211 populated enumeration districts on an equal-population cartogram of Britain (data from the 1981 census). Each district is colored according to the occupations of the people in it. Animation is useful to investigate the detailed patterns formed, through panning and zooming. Complex pictures such as this can be understood, given time.*

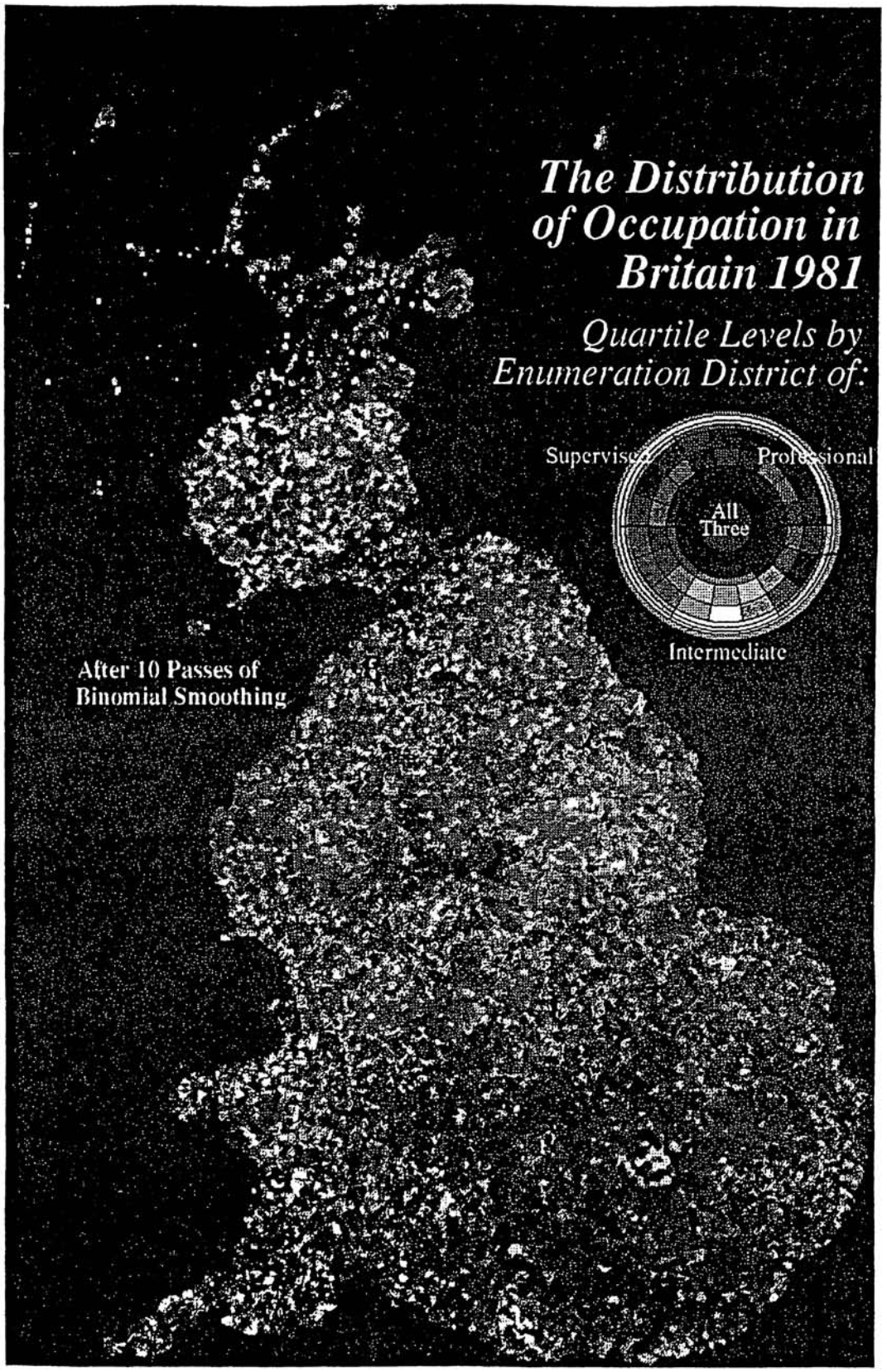

Figure 3, Dorling. *A pixel map showing the effect of two-dimensional binomial smoothing on Figure 1. It has only recently become feasible to perform this kind of operation in real time, using inexpensive micro-computers. Shifting binary registers by powers of 2 is a basic operation on RISC chip machines. After 10 iterations, the binomial distribution approximates the normal and what we see is akin to the application of circular kernels around each point in population space.*

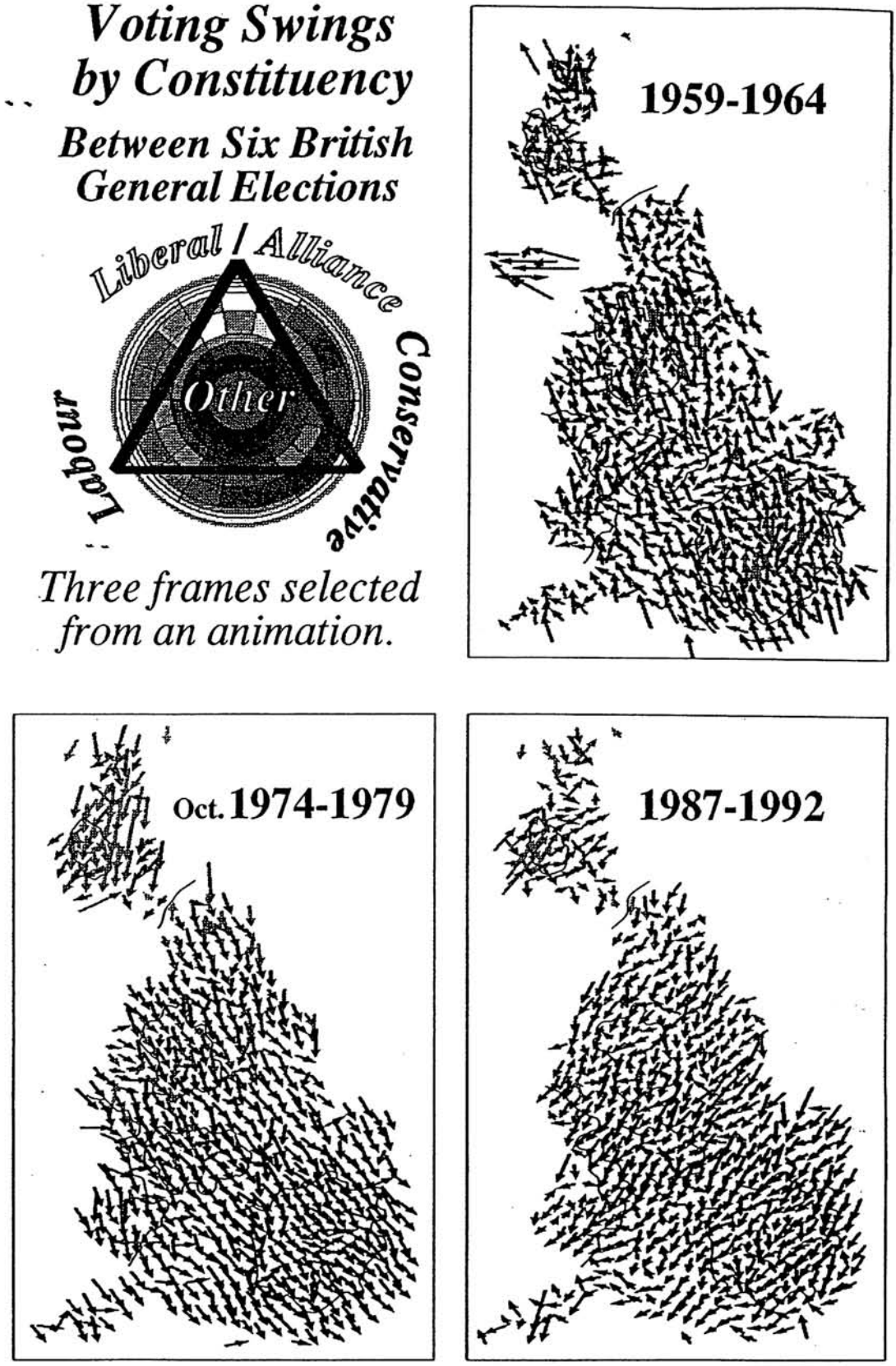

Figure 6, Dorling. *Selected key frames from an animation of the spatial distribution of voting swings in more than 600 British parliamentary constituencies from 1959 to 1992. Each constituency is represented on the cartograms by an arrow showing the magnitude and direction of the voting swing, colored by the voting composition. This pattern of change—over time and space—requires animation to try to capture the dynamics of the political process.*

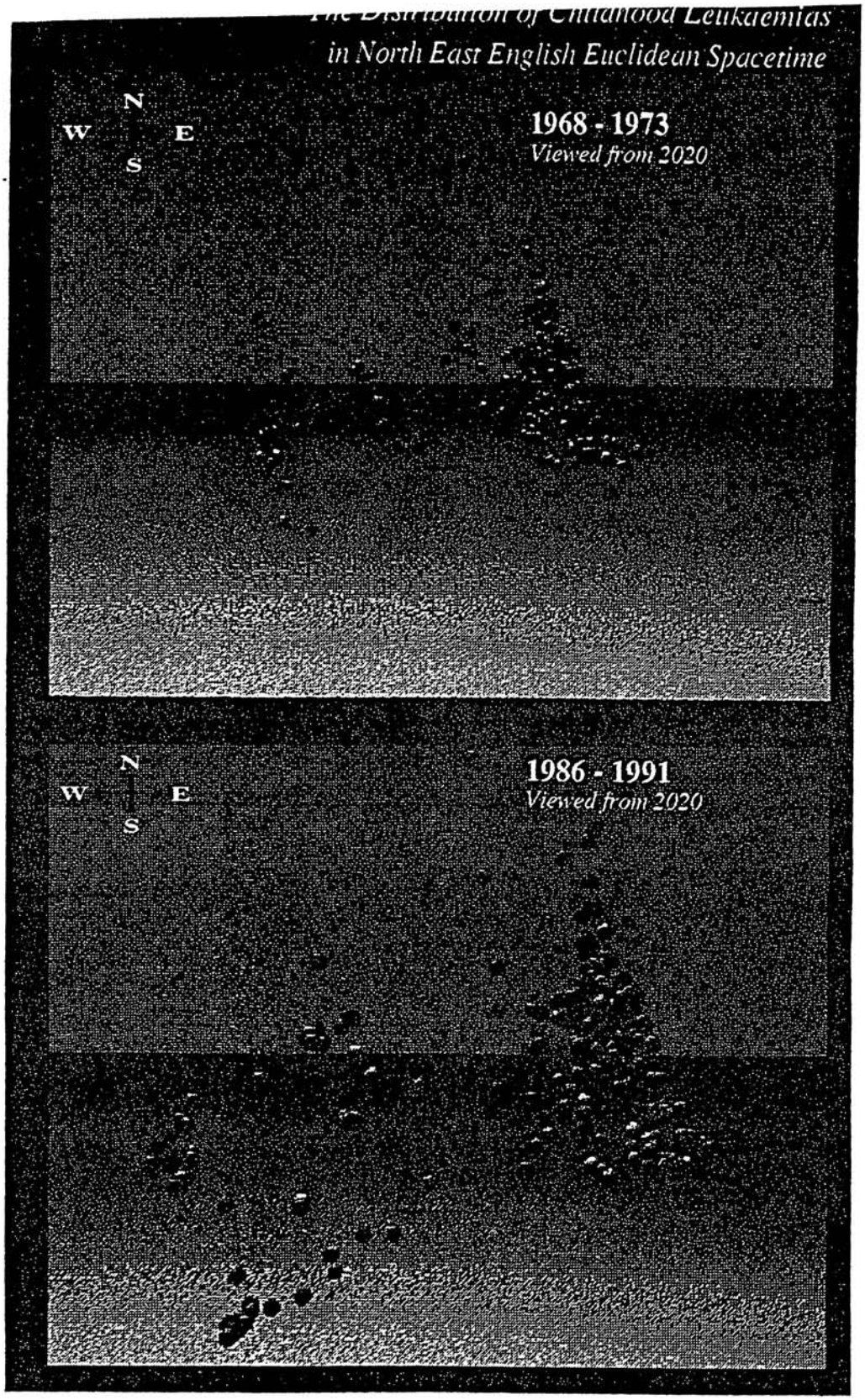

Figure 9, Dorling. *Two frames from an animation of the distribution of childhood leukemia cases in Northern England. The spheres representing the cases are color-coded by the type of disease. They are of equal size, but appear larger in the lower frame, because the group shown there is closer to the "camera" (in time). The pattern in space is that of the built-up area, when shown in this metric. Shadows and the lighting direction affect the image as the distribution is inspected from different angles.*

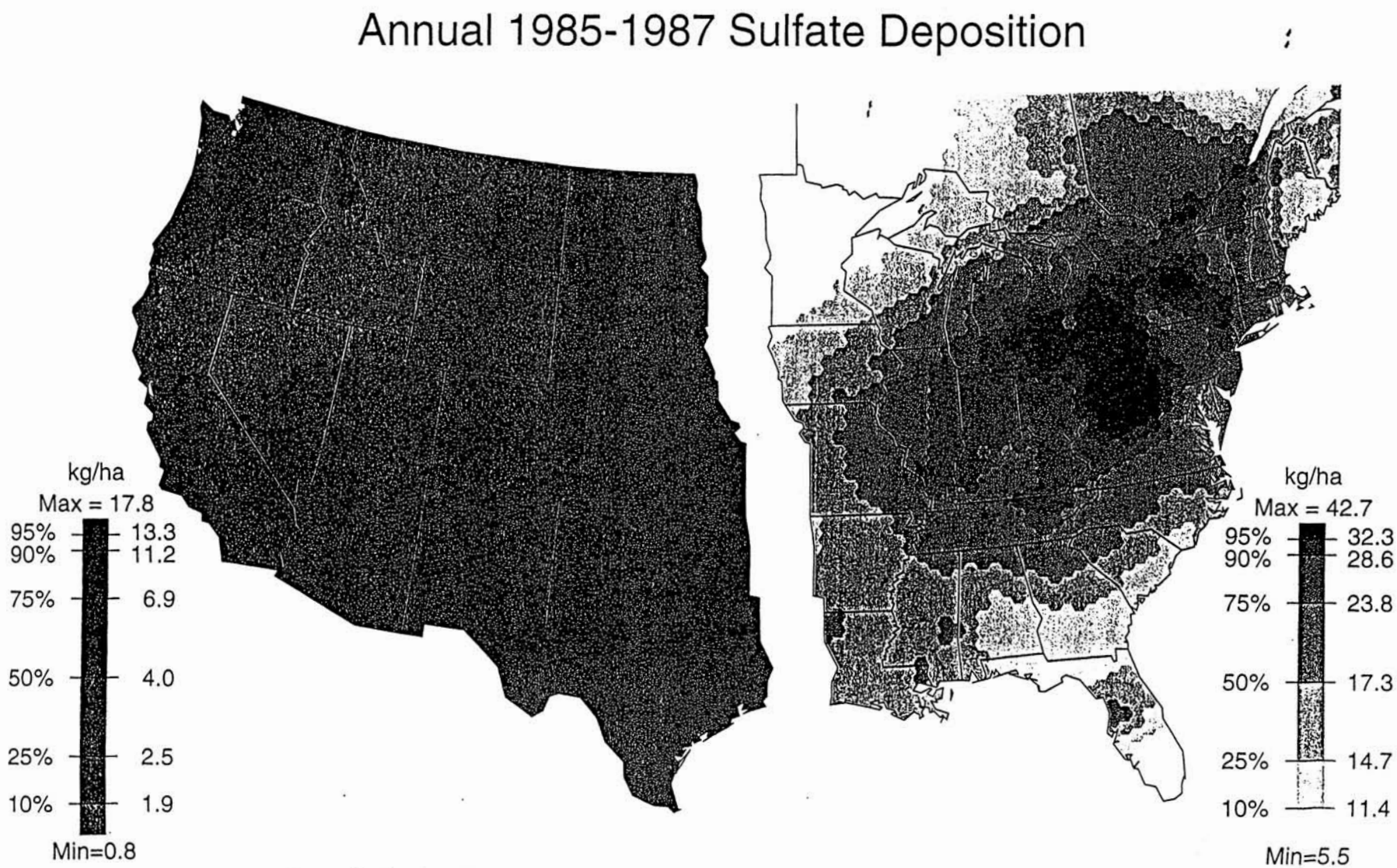

Figure 3, Carr et al. *Hexagon mosaic map of sulfate deposition (kg/ha). The map is split to provide greater resolution in both the east and west.. Percent of area, found by counting hexagons, determines the class interval boundaries. The hexagon edges at class boundaries indicate the hexagon cell size. The underlying estimation lattice consists of hexagon cell centers. The map is similar to a color-contour map, but suggests involvement of an estimation process.*