

Area Cartograms: Their Use and Creation



Daniel Dorling

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Sources

The illustrations in this booklet are provided to give readers an idea of the variety of cartograms which have been produced, the methods which can be used and the wide range of applications for which they are useful. Because of the detail inherent in some of the illustrations the quality of their reproduction may suffer. Readers should refer to the original source if they are interested in a particular illustration. The source page of every such illustration is given in the reference section. All of these originals can be obtained via the British Library.

Some computer programs are also included as appendices. These have been deposited at the ESRC Data Archive at the University of Essex. Readers who are interested in these programs can obtain copies by contacting the Data Archive (University of Essex, Colchester C04 3SQ, England).

Glossary

• anamorphose	a French term for a cartogram.
• basemap	a map which defines areas.
• bivariate	a distribution of two variables
• cartogram	a combination map and graph
• centroid	the geographical centre of an area
• chorographic	large scale equal area (basemap)
• choropleth	thematically shaded (map)
• contiguous	adjacent (area)
• digitizing	converting boundaries to vertices
• edge-wise	areas having a common boundary
• gravity-model	a model of the movement of planets
• grid-square	a square area on a lattice like map
• isodemographic	an equal population cartogram
• mappa-mundi	an ancient map of the world
• mercator-projection	the first "modern" map of the world
• national-grid	a standard grid used in British mapping
• noncontinuous	not preserving contiguity (cartogram)
• part-postcode-sector	areas used in the census of Scotland
• pictograms	illustrations which use small pictures
• point-wise	areas meeting at a point
• pseudo-cartogram	an approximately correct cartogram
• pseudo-code	a stylised computer program
• pycnomirastic	cartogram (American term)
• quadrivariate	a distribution of four variables
• tessellation	a simple pattern repeated
• topology	the way in which areas connect
• travel-time	the time it takes to travel
• trivariate	a distribution of three variables
• varivalent	cartogram (Russian term)

I. Introduction

"The fundamental tool for the geographical analysis is undoubtedly the map or, perhaps more correctly, the cartogram."

Sir Dudley Stamp (President of the Royal Geographical Society, 1962: 135)

Mapping is a way of visualizing parts of the world and maps are largely diagrammatic and two dimensional. There is usually a one-to-one correspondence between places in the world and places on the map, but while there are limitless aspects to the world, the cartographer can select only a few to map. Usually cartographers attempt to create precise miniature replicas of a few land features. Inevitably some distortion occurs, but traditionally this has been seen as a relatively unimportant side effect of mapping. For instance, conventional maps of Britain based on the National Grid magnify the area of the Western Isles of Scotland. Maps are called cartograms when distortions of size, and occasionally of shape or distance, are made explicit and are seen as desirable. Typically places on a cartogram are drawn so that their size is in proportion to their human populations. However, their size could be made proportional to any measurable feature. Conventional maps can be seen as land area cartograms — as places on them are usually drawn in proportion to their land areas — although this is often not the case for features on these maps. For instance, road widths are not drawn to scale on most Ordnance Survey maps as the roads would not be visible if they were. Similarly, river size, mountain heights (through dramatic shading) and the width of beaches are often exaggerated on maps as these are seen as particularly important aspects of the physical geography of an area.

Cartograms are produced for a variety of purposes. They can be used, like the London Underground map, to help people find their way. In atlases they are often used for their ability to shock; cartograms where area is drawn in proportion to the wealth of people living in each place show a dramatic picture. A major argument for the use of equal population cartograms in human geography is that they produce a more socially just form of mapping by giving people more equitable representation in an image of the world. In research, cartograms are increasingly used to provide alternative basemaps upon which other distributions can be drawn to see, for example, whether the incidence of a particular disease is spread evenly over the population. Cartograms can also be used like conventional maps where different areas are shaded with different colours to show variation over space. For instance, to be able to map both the absolute and relative concentration of elderly people across the population a cartogram is required.

The reader may have noticed that the nouns "map" and "cartogram" have been used interchangeably here. Once you are familiar with cartograms they no longer appear strange enough to warrant an alternative term, although you do often wonder why so many maps drawn in human geography books are based on land area rather than population. Many cartograms are shown in this monograph. This reflects only a tiny part of the huge effort which cartographers have put into creating alternative bases for mapping. A little imagination should reveal how these basemaps could be used to investigate further the multitude of ways in which the human geography of life is organised.

It may be helpful to begin with a simple example. Figure 1a gives population statistics and a map for a fictional island. Its area is 20 square kilometers and 100 people live on the island which is divided into three districts: the Farm, Town and City. The figure shows that the mean population density of the island is 5 people per square kilometer, although most of its population live in the City at a density of 15 people per km². The equal area map of the island has been simplified to fit on a grid. The cartogram of the island was drawn by hand, starting with the City and trying to alter the shape of the island as little as possible while making the area of each district proportional to its population. Note that the Town still separates the Farm and City. The impact of this transformation is illustrated by using two pictograms in which icons are placed on both the map and cartogram to show the distribution of the population. The icons differentiate people depending on whether they are in work, but even on the cartogram it is difficult to tell where workers are more numerous from these icons. The final pair of equal area map and population cartogram in the figure have each district shaded by the proportion of the population who are working (the dependency rate). Clearly the map and cartogram give very different impressions. One shows that on most land many people are working while the other shows that many people live in areas where most people do not work.

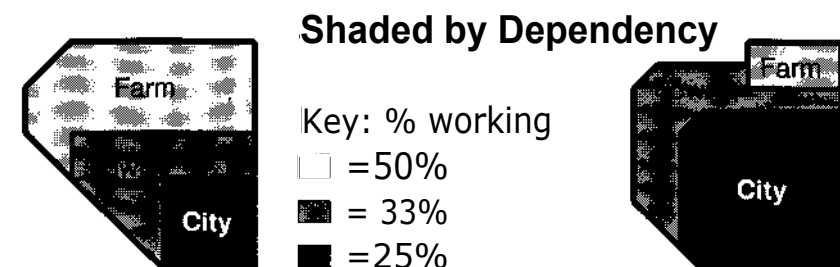
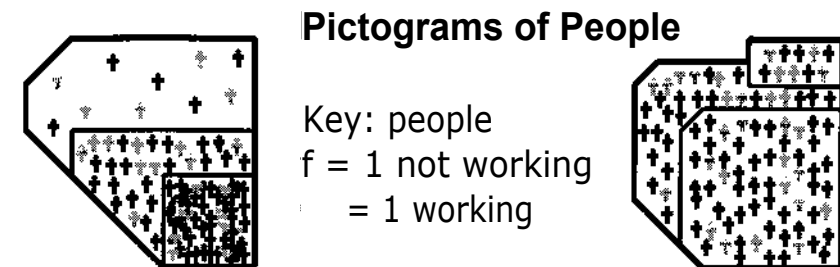
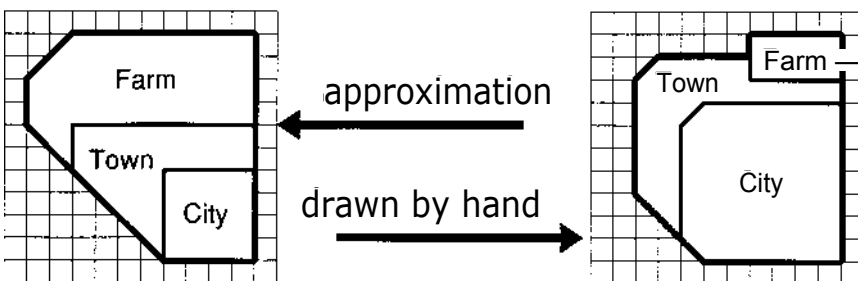
The monograph is divided into 14 Sections and each Section is illustrated by a set of maps or cartograms. Each of these figures is described in the text and they are used to illustrate particular points and to introduce various concepts. The reader should work through the monograph to gain a broad understanding of cartograms. There is no "best" cartogram or method of creating cartograms just as there is no "best" map (Monmonier and Schnell, 1988). However, many things can be achieved with cartograms which cannot be shown successfully on ordinary maps. After reading this monograph, the next time you draw an ordinary map you will at least have thought of how the distribution might look on a cartogram and hopefully you may even experiment with using these "distorted maps". Most cartograms in the past

Vital Statistics	Farm	Town	City	Total
Area	10	6	4	20
People	10	30	60	100
Density	1	5	15	5
Working	5	10	15	30
Dependency	50%	33%	25%	30%

Equal Area Map

Population Cartogram

Scale f1 = 1 km² **Scale** = 5 people



were drawn by people who had never seen a cartogram before so you should have an advantage over them. Here a wide selection of cartograms and construction techniques are shown to illustrate the variety of solutions which have been developed to overcome the problems of this form of mapping. These solutions were often developed in isolation to one another. It is remarkable how many people have independently thought that there must be a better way of mapping people than can be achieved with the ubiquitous equal land area choropleth (shaded) map.

1. Population Distributions

People are unevenly distributed over the surface of the earth. This has always been so and is true no matter how closely these geographical patterns are studied. It appears that the ways in which people organize their lives require them to be spread unevenly over space. This presents a problem for looking at how their lives are organized spatially as, if conventional maps are used at any level of detail, the maps will always highlight the uneven distribution of people over the land rather than the differences between groups of people, which are of more interest.

Figure 1b shows a tiny inset of a map of the distribution of population in Britain in 1991. At the top of the Figure is a map of the wards of London (wards are the smallest areas for which politicians are elected in Britain). These are also the areas for which many social statistics are produced. In London each ward contains, on average, 9000 people. A national cartogram based on these units is described in Section 14. At the bottom of figure 1b is an inset from this map showing the distribution of population in central London where it can still be seen to be extremely uneven. Each dot drawn represents a postcode area with its size in proportion to the number of people whose address has that postcode. There are over 1 600 000 postcodes in Britain, each locating roughly 35 people. Only just over 7000 are shown on this map. To print a map of the whole of Britain at this scale would require an enormous amount of paper. From the coordinates shown in the figure, the amount of paper needed can be calculated to be approximately 250 square metres in size. A map of this size would be difficult to visualize and would not be easy to use. On such a map the black dots would cover only a minuscule fraction of the paper (less than 0.01%). Most cartograms are designed to make visualizing the detailed human geography of people possible and sometimes even to make it easy.

Figure 1a: Example of a cartogram created and shaded by hand for a fictional island (Author).

2. Mapping Projections

Ever since the first maps were drawn, cartographers have had to decide how they will distort the shape of the earth to best show what they wish others to study. The six global projections shown in Figure 2a are included here to illustrate how people's views of the world have altered over time and how this has altered the way they draw maps (Snyder, 1991). First is shown the structure of an ancient *mappa mundi* in which Jerusalem is at the heart of the world. Below that is drawn a modern orthographic projection now centred on the United States (the modern "world centre"). The United States are magnified in the remaining four pictures which illustrate how different projections can emphasise different parts of the map. The focus of these maps is deliberate and it is a legitimate form of mapping if it is from these particular angles that the cartographer wishes the situation to be viewed.

The views of the earth from space shown in Figure 2a are relatively recent perspectives. Below them, in Figure 2b, are shown six very different projections of the world which illustrate the lengths to which cartographers have gone to try to represent the earth in different ways (Dahlberg, 1991). A frequent criticism of cartograms is that even cartograms based upon the same variable for the same areas of a country can look very different. There is nothing new about that in cartography, as these world projections illustrate. Mapping involves making compromises between conflicting goals which result in the variety of views that we have of the world. Inevitably they alter how we see different parts of this world. In Figure 2c, the visual impact of choosing different projections is illustrated by drawing two copies of an identical face on different parts of twelve well known map projections (ACA, 1988). The projection which is chosen determines how the faces look just as it alters our impressions of the sizes and shapes of different countries. Each of these projections has a particular advantage, but they all result in often unintended distortion of one if not both of the faces. In contrast, with cartograms, distortion is not seen as unfortunate, but is deliberately used to convey information.

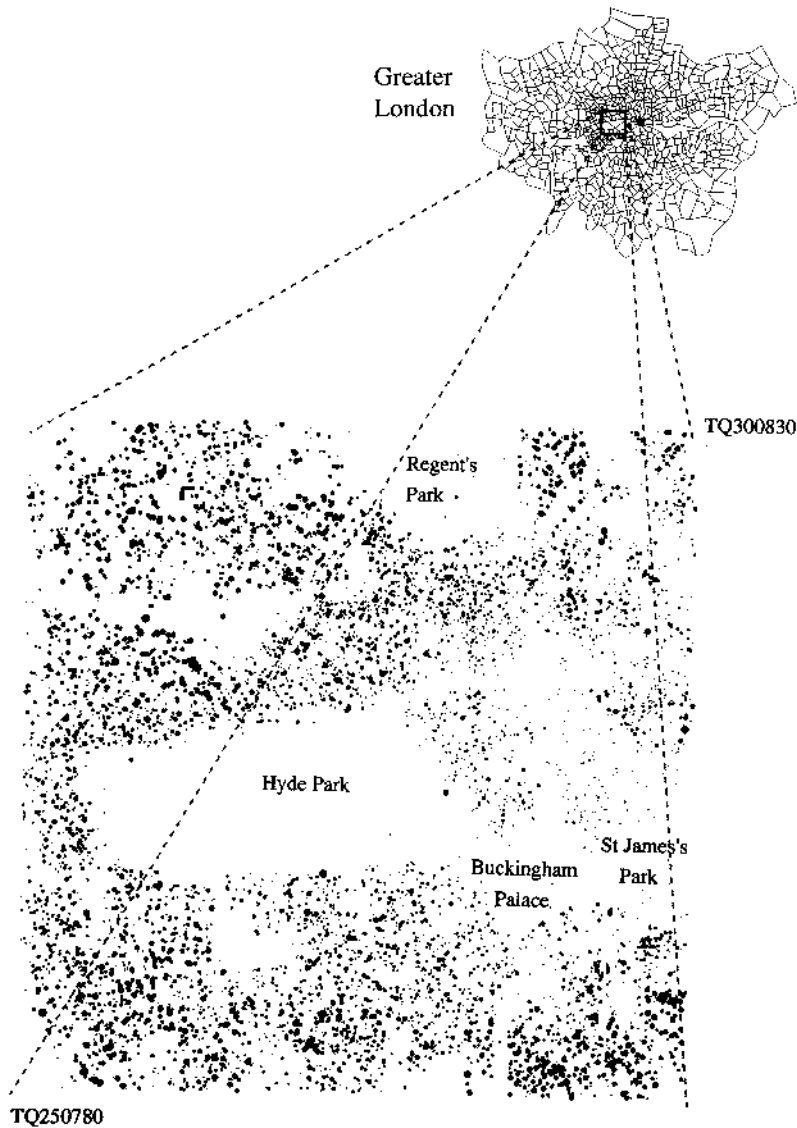


Figure 1b The 1991 distribution of population in central London by unit postcode areas (Author).

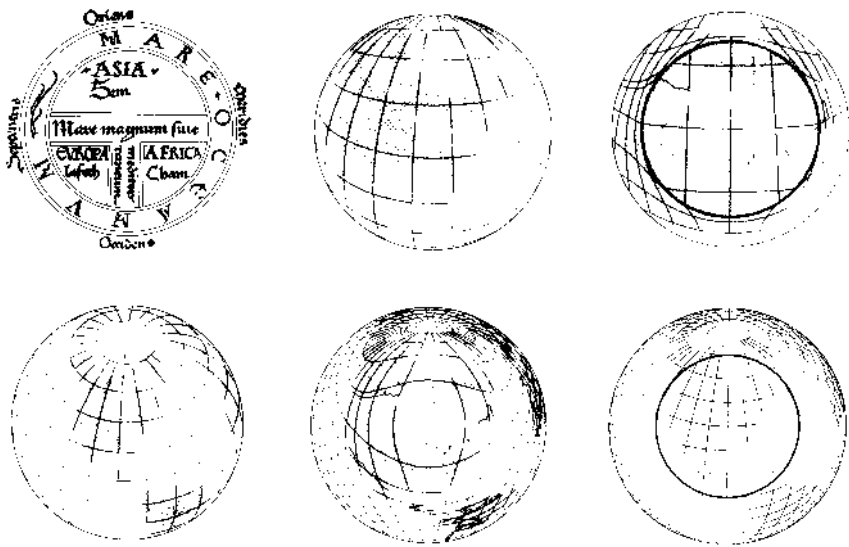


Figure 2a: From Mappa Mundi to satellite-eyes-view : six alternative global maps (Snyder, 1991: 13).

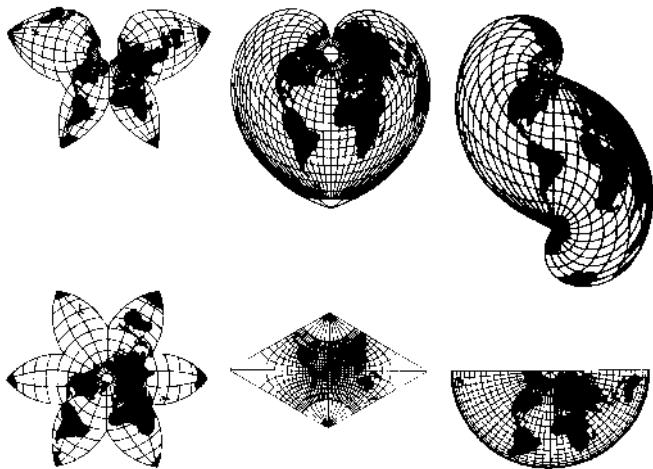


Figure 2b: Unconventional world projections: butterfly projection to projector maps (Dahlberg, 1991: 7).

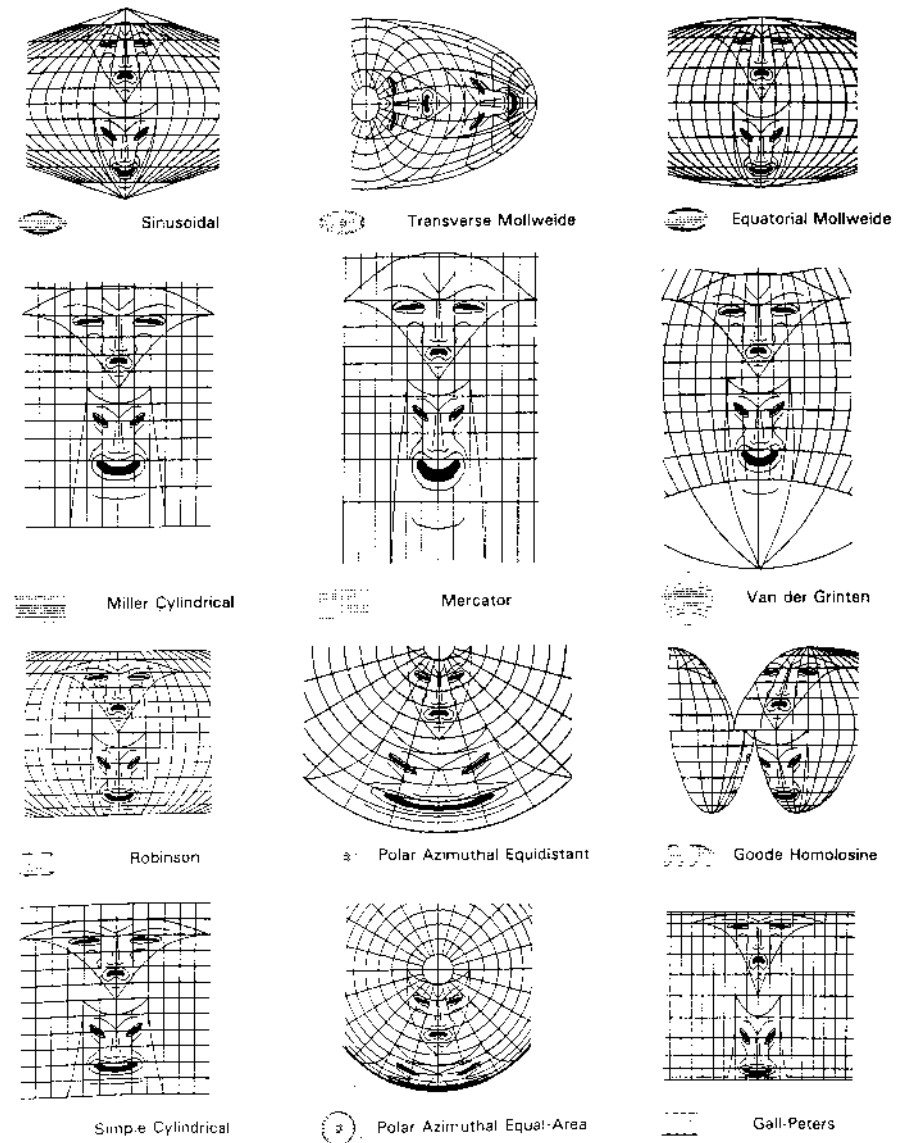


Figure 2c: Two identical copies of one face on twelve conventional world projections (ACA, 1988: 15).

3. Popular Maps

Popular maps rarely employ equal area projections. Figure 3a shows a detailed *mappa mundi* (Angel & Hyman, 1972) which dates from the eleventh century. Jerusalem lies at the centre, and at the edge of the map is an eternal sea (see also Figure 2a). For hundreds of years maps like this defined the way people thought of the world, as the maps were designed to do. Maps are used as much to alter the way people think about places, as to help people to get to places. Very different world projections have been used at different times. For the last four hundred years the Mercator projection has been dominant in world mapping (see Figure 2c). Initially designed to aid navigation, it can now be seen behind newscasters' heads on television and on the computer screens of promotions to sell "modern" geographical information systems.

Traditionally mapping has never long respected "traditional" cartographic conventions. Below the *mappa mundi* is a satirical map of the United States, Figure 3b, which is supposed to represent the archetypal New Yorker's view of America (Gould & White, 1974) in which Brooklyn is larger than California! This is obviously a cartogram as it is the deliberate distortion of space which is important. The presentation of this map as a cartoon illustrates how the idea of stretching space is intrinsically acceptable to a large audience. In contrast to the "New Yorker's Idea of the United States" is many a train traveller's view of Britain, reflected by the British Inter-City Railway cartogram (Figure 3d) which is used by millions of people every year. For many of them the city of Newcastle is as much a station they pass through between Edinburgh and London as it is an area of 112 km². This is often described as a topological map as the clarity of the network is maintained at the expense of other features, although direction and distance are still roughly preserved.

Figure 3c is part of a tourist map of the United States (Unique Media, 1992) which shows the main roads, cities and landmarks of the country. The cities are deliberately drawn huge and their attractions are highlighted, while the distances between them are minimised so that the next attraction appears to be "only down the road". Considering the amount of time a tourist spends in different parts of America this is a fair representation. Often only a few hours are spent driving or flying between cities, while much more time is spent sightseeing within them. Popular maps are often very different from the maps which are usually drawn by academic geographers.

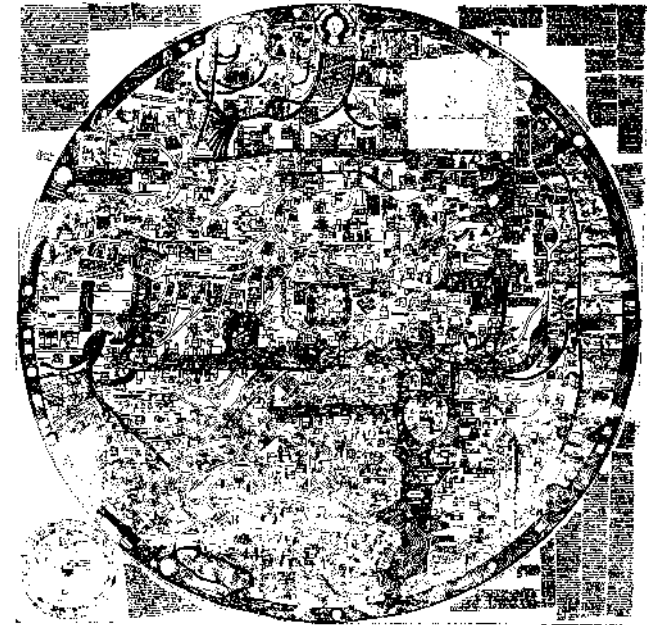


Figure 3a: A detailed Mappa Mundi: the Ebsdorf map of the world (Angel & Hyman, 1972: 351).

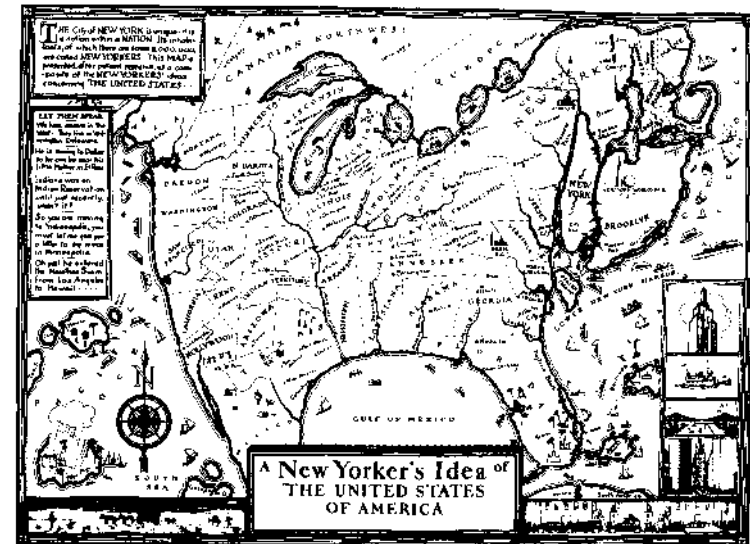


Figure 3b: Daniel Wallingford's map of a New Yorker's idea of the USA (Gould & White, 1974: 20).

II. Methods

4. Introduction

There are numerous methods of creating cartograms. We begin this section by looking at three examples which were created by using very different techniques. The first was drawn by hand, the second was created by using a computer program and the third was made by using a mechanical model. Each method produces useful maps which could not have been created by the alternative techniques. In general manual methods are useful when only a few areas are being represented, while computer algorithms have to be used to produce area cartograms of many places. Mechanical methods provided a compromise between these two options in the past.

Although most cartograms in the rest of this monograph are based on population, we start with one based on another denominator. More cartograms have been drawn of the countries of the world than of any particular place in it. A world map in which every country is given equal prominence is shown in Figure 4a (Reeves, 1994). At first glance this cartogram appears rather pointless, containing less information than a conventional map of the land areas of the countries of the world. However, the greatest value of a cartogram is often not to illustrate a single statistic, but for use as a base map upon which many other statistics can be drawn. This cartogram would be ideal for showing voting at the United Nations, depicting regional alignments with much more clarity than an ordinary map in which countries with small land areas are hidden. This cartogram was created by hand by Catherine Reeves.

A cartogram constructed using a computer algorithm is shown in Figure 4b which contains an equal population cartogram of America based on the 1990 populations of each of the mainland counties. This is the first attempt by the author to map the detailed human geography of America. The uppermost circle is Wayne county (Michigan), furthest right is Nassau county (New York), lowest is Dade county (Florida) and furthest left is San Francisco county (California). Although this cartogram could be refined, it does show that it is possible to draw area cartograms at this level of detail. A total of 3111 circles are drawn in this figure with populations ranging from almost nine million for Los Angeles county (California), to only just over one hundred people for Loving county (Texas). The cartogram was created by using the circular algorithm described in Section 9.

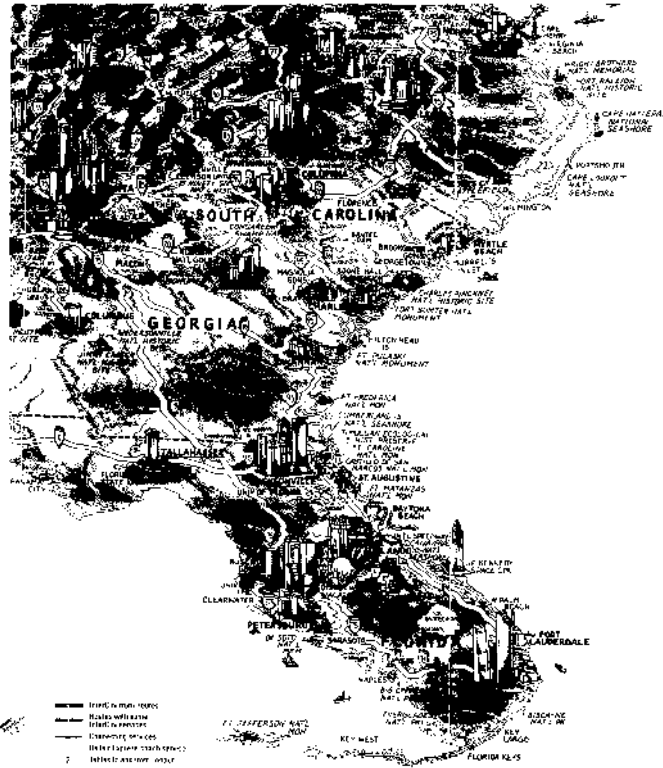


Figure 3c: Unique Media tourist map of the United States of America (Unique Media: 1992).

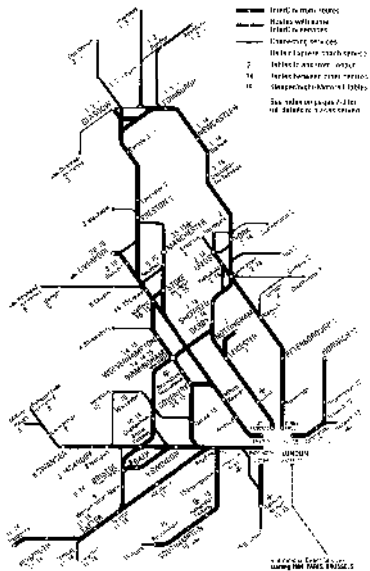


Figure 3d: Bernard Slatter's map of the British rail inter-city network (British Railways Board: 1993).

IASBS EQUINATIONAL PROJECTION

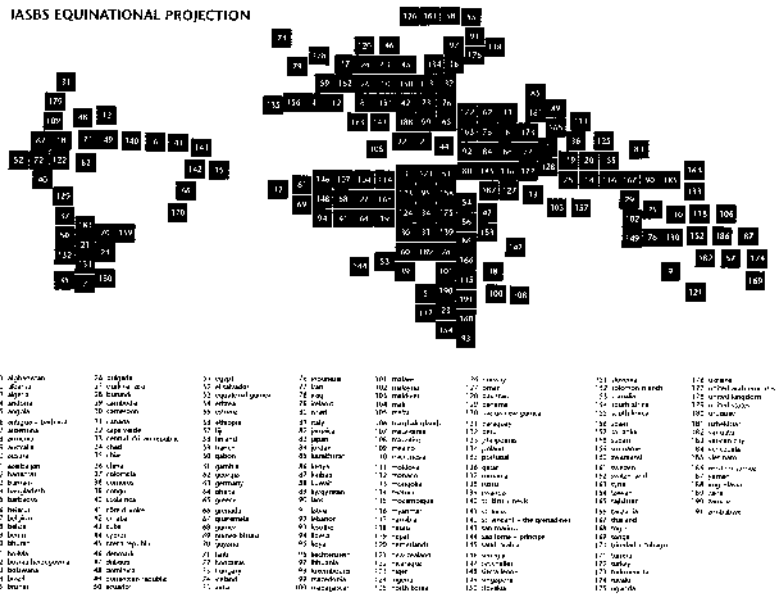


Figure 4a r. Institute for Advanced Studies in Big Science equinational projection (Reeves, 1994: 18-19).

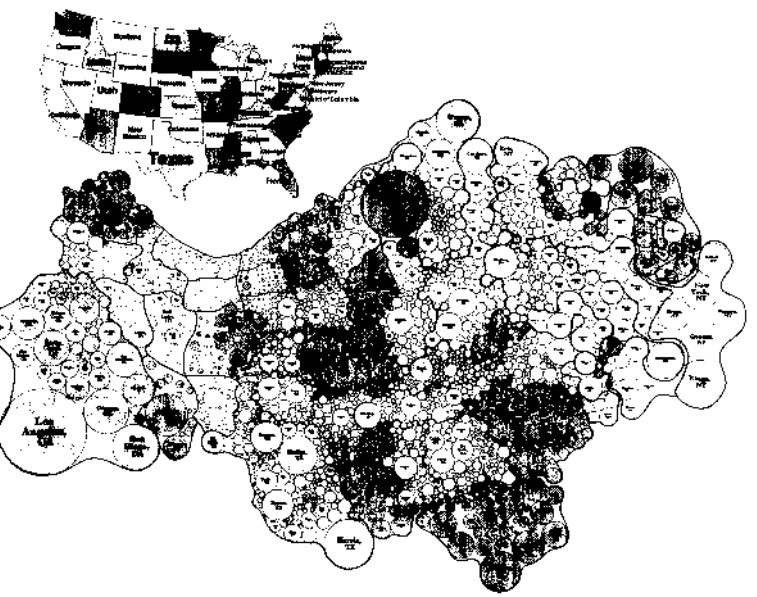


Figure 4b : 1990 population cartogram of the coterminous United States of America by county (Author).

Our last example in this section is a cartogram of Britain, created manually like Figure 4a but using a less ad hoc method - the manipulation of small blocks. The result is shown in Figures 4c and 4d (Hunter & Young, 1968). The visual effect is very different to the last two examples because more detail can be incorporated when smaller blocks are used to create a larger shape, rather than by using simple symbols such as squares or circles to represent each area. Figure 4c was created by a process called physical accretion modelling described in Section 5. Figure 4d shows this cartogram being used to represent the distribution of overcrowding in 1961. Partly because of the wartime damage to property, and the population growth since then, there was an acute housing shortage at this time. On the normal map the problem did not look too severe, but on the cartogram it becomes evident just how many people in large cities were living in overcrowded housing in Britain in the 1960s. It is because details such as this become explicit on cartograms that they are so useful to create but, as the following sections illustrate, there is no single best method for creating them.

5. Physical Accretion Models

The term "physical accretion models" was first introduced by John Hunter and Johnathan Young based in Michigan (America) and Durham (England), respectively. They attempted to formalize the approach taken to produce the cartograms of British general election results drawn in the Times Newspaper in both 1964 and 1966 (see Figure 10a here, and Hunter & Young, 1968). The term physical accretion model describes the technique of constructing cartograms by using wooden tiles and rearranging them by hand. In the case of the old counties of England and Wales, 9214 wooden tiles were painted 62 different colours and were then manipulating to create a cartogram which was 2.4 square metres in size before being copied onto paper. The manipulation alone took 16 hours and involved attempting to maintain the shape of prominent features such as estuaries and preserving contiguity as well as making area almost exactly proportional to population. The result is shown in Figures 4c and 4d. In constructing that cartogram Hunter and Young began with London and proceeded northwards.

All the cartograms in this section were first created as wooden models. Figure 5a shows the distribution of income measured by the 1960 American census of Detroit Standard Metropolitan Statistical Area (SMSA) drawn upon a land area map (labelled as a "chorographic" base on the illustration) and a population cartogram (labelled as a "demographic" base). The concentration of poverty in the downtown area of this city is clear only on the cartogram. A land area map and a population cartogram of an entire country is presented in Figure 5b which shows geographically how the Chinese-born were not an

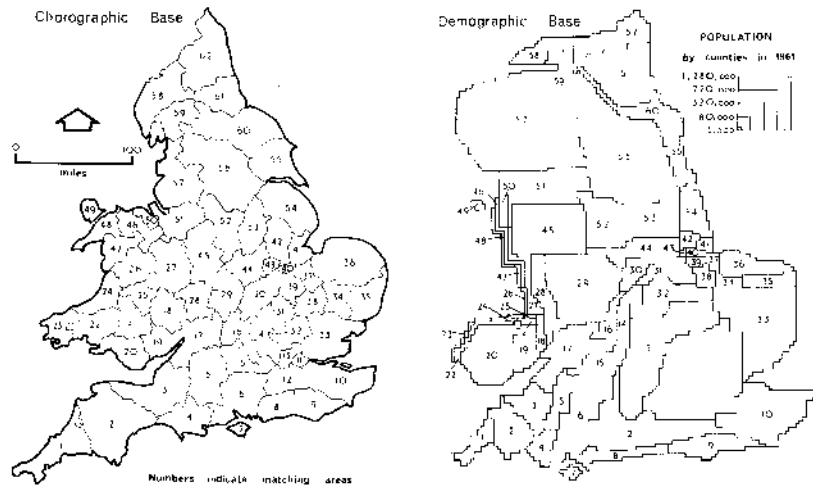


Figure 4c : Map and 1961 population cartogram of England and Wales (Hunter & Young, 1968: 403).

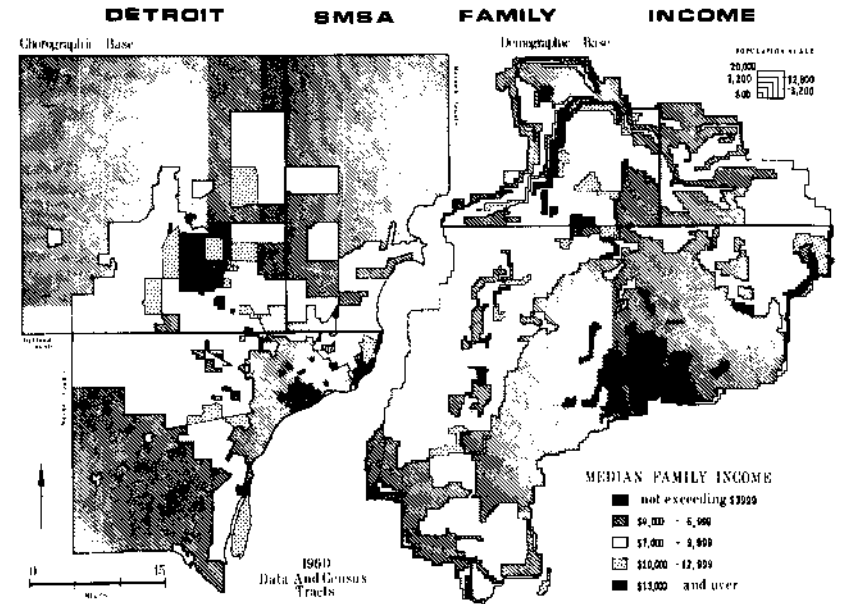


Figure 5a: Median family income in the Detroit SMSA by census tract (Hunter & Meade, 1971: 101).

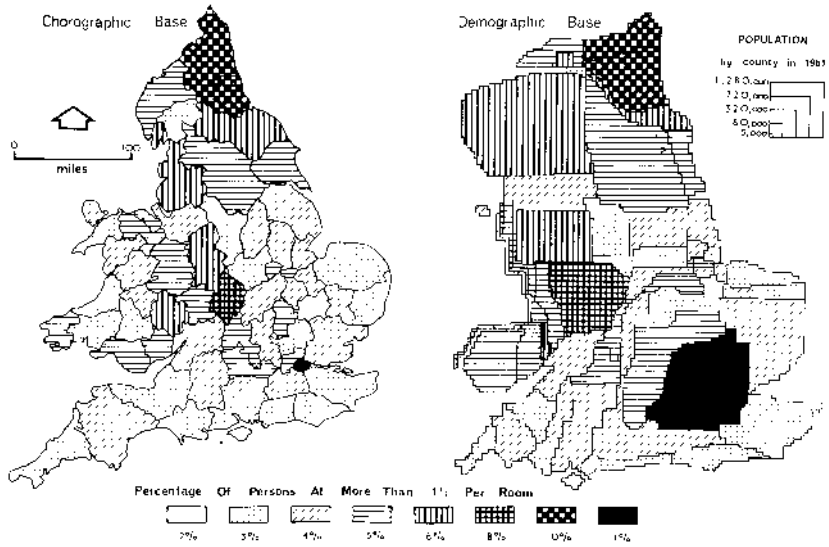


Figure 4d : An indication of overcrowding in England and Wales in 1961 (Hunter & Young, 1968: 404).

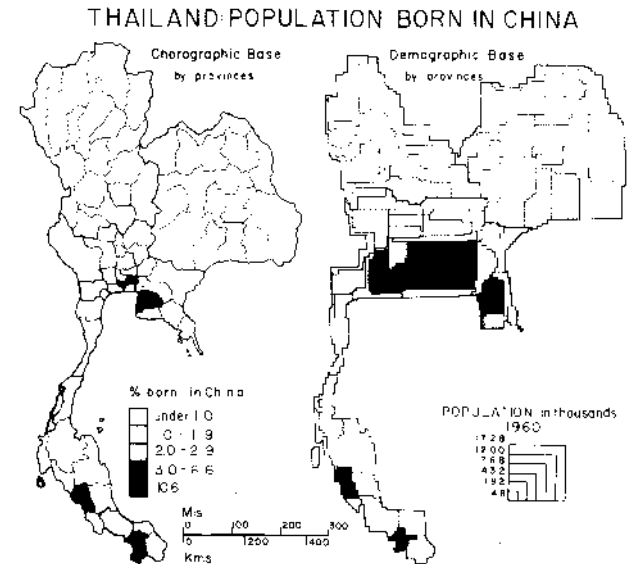


Figure 5b : Residents in Thailand who are China born, by Thai province (Hunter & Meade, 1971: 100).

insignificant proportion of the population in Thailand in 1960. Figure 5c is a photograph of how these cartograms were created in practice using the example of the entire African continent which took 20 hours to complete and was 6 feet wide when finished. This cartogram is used in Figure 5d to show how the population of different African countries was changing at the time the figure was constructed. The article from which these figures were taken goes on to discuss three-dimensional population models and how these cartograms can be constructed in the classroom (Hunter & Meade, 1971). Many thousands of school children may have used this method and hundreds of undocumented cartograms could thus have been produced!

6. Mechanical Methods

Only a year after John Hunter and Melinda Meade produced their series of cartograms created by combining wooden blocks, a paper was published by the Canadian government which illustrated a mechanical method of making population cartograms. The "isodemographic map of Canada" was commissioned from the University of British Columbia by the Economic Geography Section of the Department of Fisheries and Forestry. Their remit was to create a map of Canada in which the divisions of the 1966 Census were drawn with their areas in proportion to their populations (Skoda & Robertson, 1972). Furthermore, this map had to attempt to approximate the actual shape of places, maintain contiguity, include lines of longitude and latitude and the census tract boundaries of the twelve urban areas with populations in excess of 200 000 people. There were 266 census divisions to be included for the map of all of Canada and a further 1408 census tracts for the large cities. The original map is shown in Figure 6a and the final result in Figure 6b, which includes the locations of the major cities and of meridians and parallels on the new projection.

To create the isodemographic map of Canada, Skoda and Robertson developed a mechanical model in which 265 000 steel ball bearings, each with a diameter of one eighth of an inch, and each representing 140 people on the main map (and 70 people on the separate city maps) were poured into an equal land area map of Canada constructed from brass hinged aluminium strips. The ball bearings were weighed rather than counted and the whole model was assembled on several 5m² plywood boards surfaced with formica which allowed the balls to move easily within the hinged metal district boundaries. Different types of hinge were used for different types of geographical vertices, so that as the ball bearings were pressed down to form a continuous layer, correct contiguity was maintained — while a population cartogram was created (see Figure 6c). Transparent perspex sheets were used to apply an even pressure to all the ball bearings across the map and to

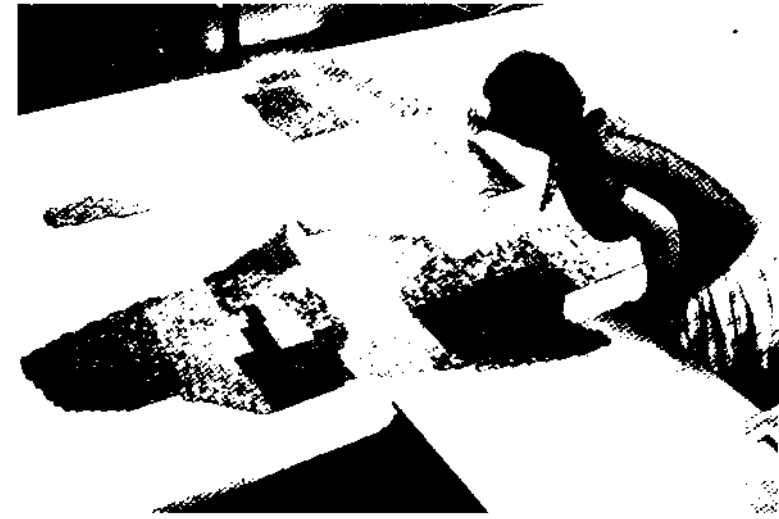


Figure 5c: Constructing a population cartogram of Africa by hand (Hunter & Meade, 1971: 97).

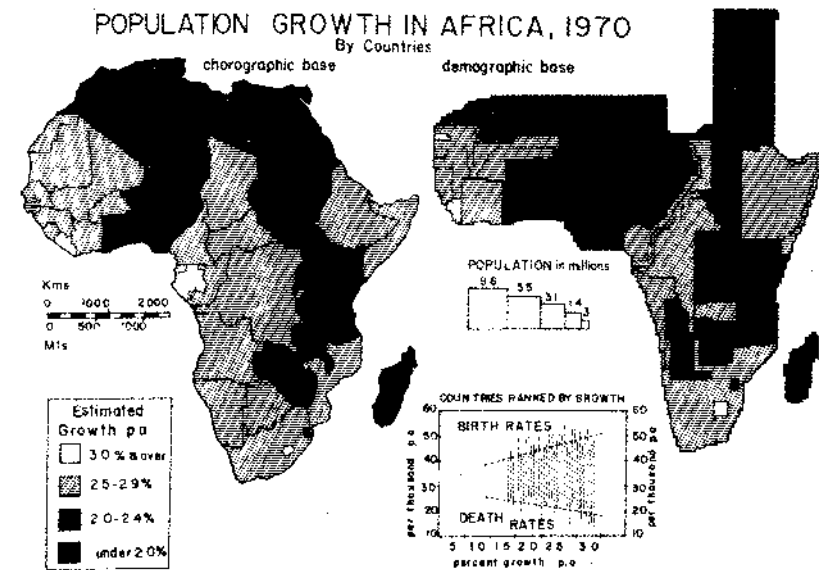


Figure 5d: Maps of population growth in Africa by country in 1970 (Hunter & Meade, 1971: 98).



Figure 6a: A Lambert conformal conic projection of Canada (Skoda & Robertson, 1972: frontispiece).

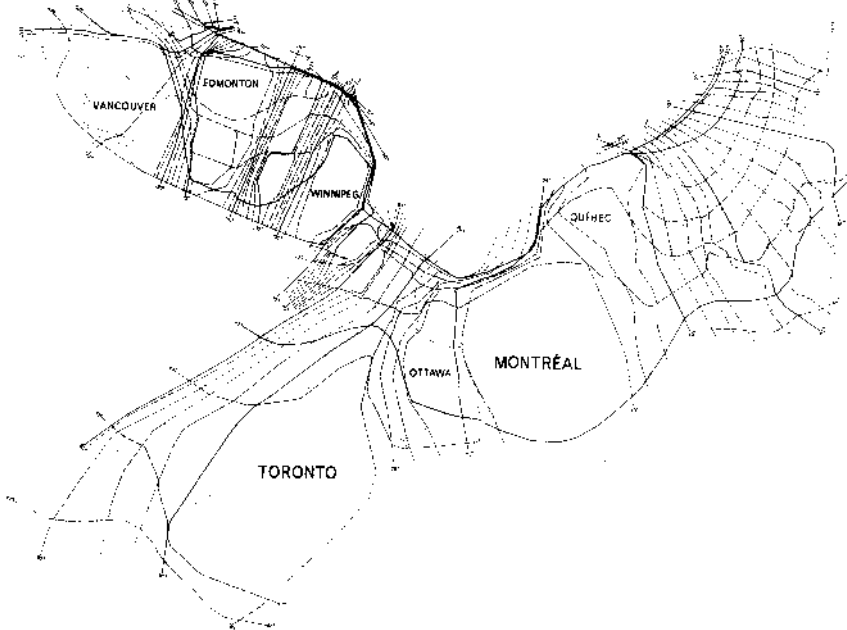


Figure 6b: Graticule on the isodemographic map projection of Canada (Skoda & Robertson, 1972: 13A).

prevent spillage. The authors had some licence in the design process and used this to attempt to keep the final result as conformal (shape preserving) as possible, by attempting to ensure that graticule lines intersected at roughly right angles. Some lakes were also included to help preserve the shapes of rural areas. Apart from a few problems with the ball bearings tessellating between more compact hexagonal arrangements in some census divisions and less compact square arrangements in others, the model resulted in a very accurate isodemographic map of Canada and particularly detailed population cartograms being produced of the major cities. The cartogram of Montreal, with almost four hundred census tracts, is too detailed to be shown here; instead the one hundred census tracts of Winnipeg are shown in Figure 6d.

The main purpose of the isodemographic map of Canada was for it to be used to provide a framework for the "analysis and communication of social and economic variables". The rising interest in urban geography in the 1960s and early 1970s was cited as one reason why this cartogram might be used by other researchers (Skoda and Robertson, 1972: 25). Its authors also argued that it could be used to construct a different way of measuring distance. For instance, on the cartogram, Broadway main street in Vancouver is "longer" than the British Columbia section of the Alaska Highway, once distance was measured by the number of people who lived along the lengths of these respective roads. The way in which cartograms can radically change people's views of the world was being explored in some detail. In practice, however, there is little evidence that this cartogram was ever used to map social or economic variables. Just five years after the isodemographic map was printed Canadian cartographers were publishing maps of general elections by using conventional equal land area projections (Coulson, 1977). The one factor which advocates of cartograms have consistently underestimated has been the hostility to changing from conventional projections, and the more a cartogram is needed, such as in mapping aspects of the unevenly distributed human geography of Canada, the more unconventional that cartogram will look.

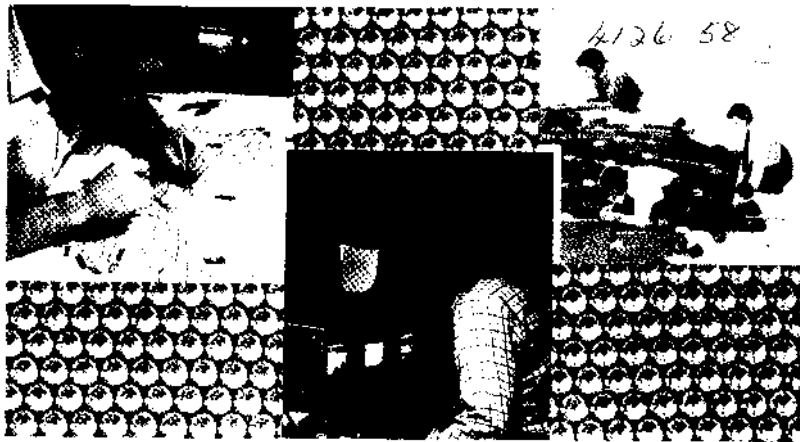


Figure 6c: Constructing the isodemographic map of Canada (Skoda & Robertson, 1972: front cover).

7. Competing Cartogram Algorithms

A year after Skoda and Robertson released the details of their mechanical model for constructing cartograms, a method which used a computer program was published (Tobler, 1973). The method was described by Waldo Tobler, then based in Michigan, and consisted of a mathematical and textual description of the means which were used to produce the transformed maps shown in Figure 7a. The maps were produced to solve a particular locational problem - how to define areas of equal population on a map of the United States. Tobler had constructed the method with the aim of producing a cartogram which was as conformal as possible as well as correct (area being proportional to population). Conformal mapping means to preserve angles locally so that the shapes of very small areas on a traditional map and a cartogram would be similar. To summarise Tobler's method, an estimate was made of the population living in each cell of a grid which had been laid over the United States of America (the grid is shown in the top left hand corner of Figure 7a). The position of each vertex in the grid was then repeatedly altered according to the populations in, and the areas of, the four cells which surrounded it, until there was little improvement in the accuracy of the cartogram to be achieved by further iterations. Figure 7a illustrates this process. The top row shows the equal land area grid squares on the original map and on the cartogram. The middle row shows the original map and the equal population cartogram after 99 iterations when it had converged to 68% of its desired accuracy. The bottom row of the figure shows an equal population area hexagonal grid on the original map and on the cartogram. The hexagons on the original map define zones of equal population size and hence solve the original problem. On these grids, areas in the sea are given a nominal population to help preservation of the coastline.

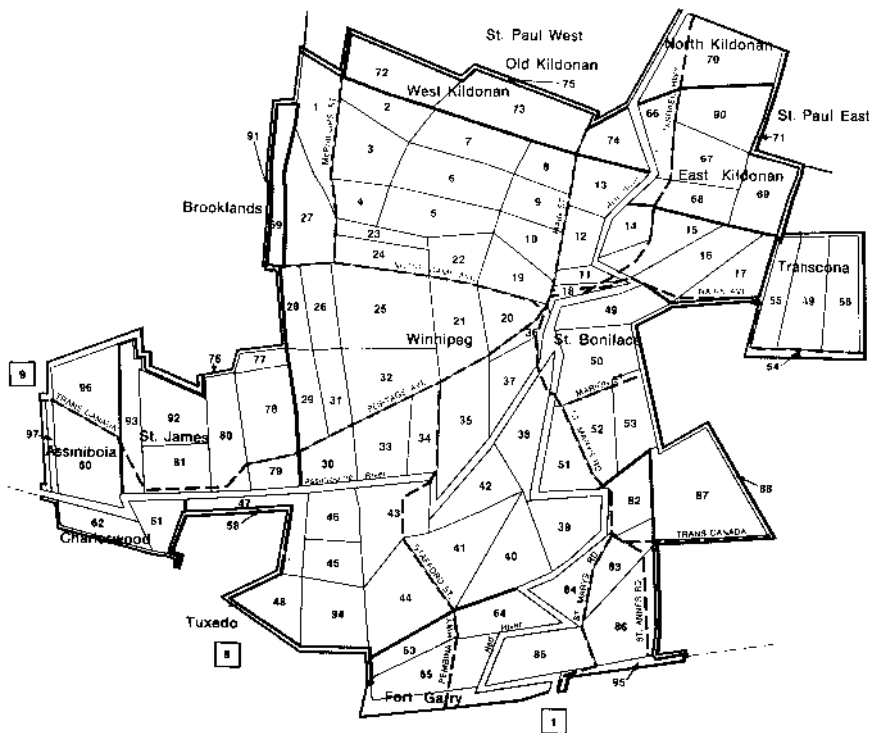


Figure 6d : Census tracts on the isodemographic map of Winnipeg (Skoda & Robertson, 1972: inset).

Although the cartogram shown in Figure 7a was one of the first to be published which had been created by computer, Tobler had been working on algorithms to produce cartograms for several years before publishing his results (Tobler, 1961) and has produced numerous examples since 1973. Figures 7b, 7c and 7d show cartograms of the United States produced in each of the last three decades (Tobler, 1976, 1986, 1994). These are all shown here to illustrate how slight alterations to one algorithm can result in very different cartograms being drawn of the same places, even when the same statistics are used. All other computer algorithms for producing cartograms suffer from the same problem. For example, Figure 7e was drawn by a "density equalized map projection" algorithm designed by a group of computer scientists and epidemiologists based at Berkeley who were apparently initially unaware of Tobler's work (see Section 14). Because this algorithm operated on state boundaries and populations rather than on grid-squares, the mountain states

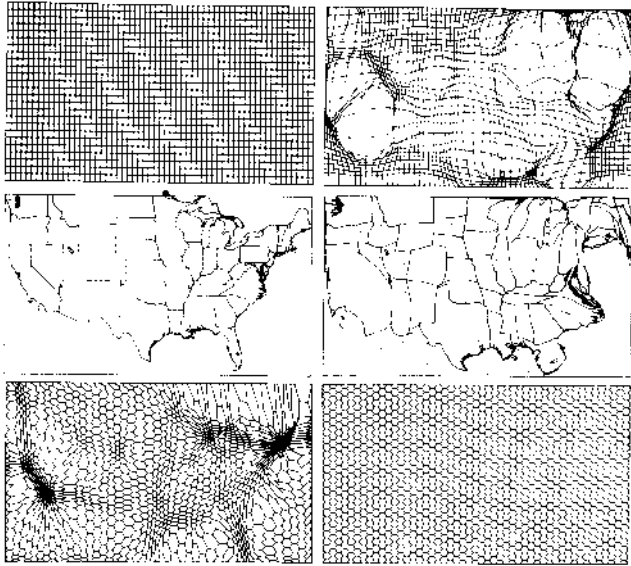


Figure 7a Continuous transformation population cartogram of the USA states (Tobler, 1973: 217).



Figure 7b Population cartogram of the USA states by computer, drawn August 1967 (Tobler, 1994).



Figure 7c : Population cartogram of the USA states by elaborated transformation (Tobler, 1976: 56).

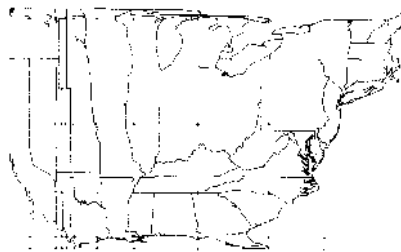


Figure 7d : Pseudo-cartogram of the USA using one degree quadrilaterals (Tobler, 1986: 49).

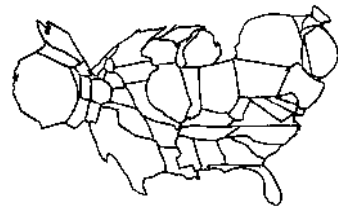


Figure 7e: Population cartogram of the USA states by the DEMP algorithm (Selvin et al, 1984: 21).

are concertinaed (Selvin *et al.* 1984). All computer algorithms appear to produce differently shaped cartograms of the same distribution, often because of differences in the type of data being input, as well as due to differences between the algorithms themselves.

The propensity of slight alterations to a basic algorithm to produce very different end maps has resulted in many researchers claiming to have produced better algorithms since Tobler's first suggestions were published. Figure 7f contains the pseudo-code of one such algorithm and the transformed map of the United States which it produces, with the result used to illustrate the results of the 1960 presidential election (Dougenik *et al.*, 1985). This cartogram, produced by Harvard University graduate students, was first presented to a wide audience during the 1983 Harvard Graphics Week when it was claimed to represent significant improvements over the "insufficient accuracy of Tobler's results" (Dougenik *et al.*, 1983: 12). However, the "new" algorithm could be viewed as simply an elaboration of Tobler's first implementation, with the most important difference being that an alternative input data set was used. Population was recorded by state rather than by grid-square subdivisions. This same process could be seen occurring ten years later with a new set of researchers, this time based at the University of Moscow. Sabir Guseyn-Zade and Vladimir Tikunov published details of a "new technique for constructing continuous cartograms". The results of this algorithm are shown in Figure 7g alongside the results which older algorithms are alleged to produce (on the right hand side). Although there is a vast improvement in the speed of convergence of this method over others and the results may be more pleasing visually, again this algorithm can be viewed as an improved version of the first implementation of a computer algorithm made by Tobler over thirty years ago. This is because all the methods described here have two common features. Firstly, they attempt to produce a numerical approximation to a pair of equations which cannot be solved by analytical means and they attempt to do this through many small adjustments to the vertices of a digitized map (Tobler, 1973: 216). Secondly, they cannot yet be used to produce cartograms as detailed as those produced by manual or mechanical methods (such as Figures 6d and 10a).

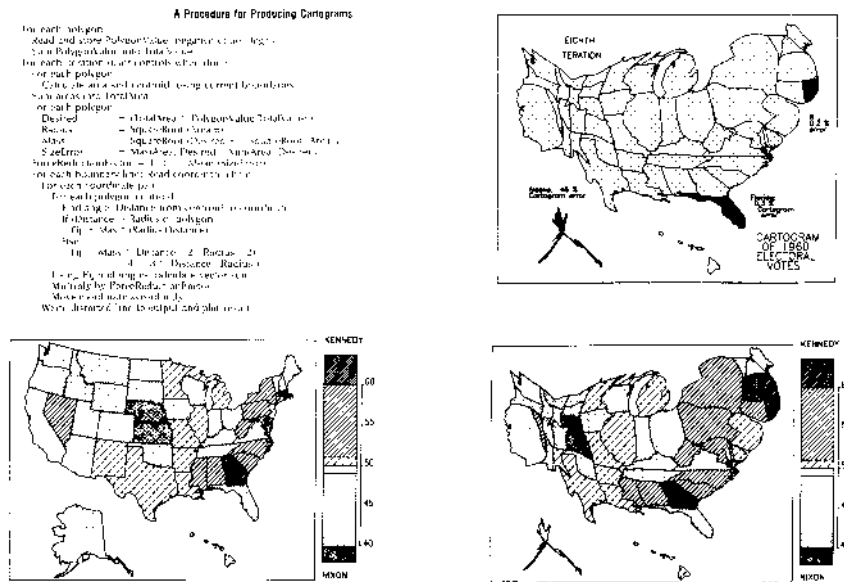


Figure 7f : Algorithm pseudo-code and resulting population cartograms (Dougenik et al., 1985: 77-81).



Figure 7g: Comparing different continuous transformations (Guseyn-Zade & Tikunov, 1993: 172).

8. Cellular Automata Cartograms

In 1968 John Conway, a mathematician at the University of Cambridge, invented the "Game of Life" which was later credited with popularizing the study of Cellular Automata (Toffoli and Margolus, 1987). The Game of Life is played on an infinite square board upon which some cells are initially deemed to be alive and all others are deemed dead (Berlekamp *et al.*, 1982: 817). A new life is created when a cell is surrounded by exactly three live neighbours; while live cells which are surrounded by more than three or less than two other live cells are deemed to die from overcrowding or exposure. Over many iterations of these simple rules incredibly complex patterns can emerge. The reason for discussing the Game of Life here concerns the similarities between the physical accretion models which were formalized by Hunter and Young (see Section 5) and the way in which the Game of Life is played. A variant of the game can be developed to grow cartograms. The method would formally be called a cellular automata machine, hence the section's title.

The pseudo-code of the cellular cartogram algorithm is given in Figure 8a. A grid of cells is set up in which each cell is assigned to one of the regions to be represented on the map, which is to have its area, eventually, in proportion to its population. To achieve this, regions represented by too few cells have to gain cells from regions represented by too many. The pseudo-code of the algorithm describes how this is achieved. The checkerboard method of updating the cell values referred to in the algorithm is a standard technique (Toffoli & Margolus, 1987: 118) and the stipulation that cells should be most prone to change state if they have few neighbours of their own kind, and less likely to change if they have many neighbours, causes the algorithm to simulate a process called "annealing". Cells on the corners of regions are most prone to be replaced by the cells of other regions and so the regions as a whole tend to form simpler shapes as the lengths of the boundaries drawn between them are minimised. However, under this implementation that advantage is partly offset by not altering cells if they are originally assigned to the sea (region "0"). Thus the shape of the coastline is maintained while contiguity is assured and a correct cartogram is produced. Figure 8b shows a basemap of 250 regions in Britain which was transformed to the shape of Figure 8c following the application of this algorithm.

A major problem with preserving the coastline is that the complexity of boundaries within the cartogram is increased as Figure 8c illustrates. To overcome this problem the algorithm could be altered to allow cells in the sea to change state, but that might result in the loss of any coastline features which are useful for identifying areas on the cartogram. A simpler solution is to transform the original base map to form a pseudo-cartogram as has been

Create a matrix representation of the traditional map to be transformed, in which each cell representing a map grid-square is given the value of the region which is contained in most of that grid-square (or "0" for the sea).

While there are still cells being altered

For each cell (visited in a checkerboard pattern)

Calculate the security factor of the cell¹

Locate the cell's neighbour with the highest density²

If ((that neighbour's density is higher than the cell's density and cell security < 12) or cell security < 8)

If changing the cell value would not break topology³

Replace the cell's region by its neighbour's region.

Else (if changing the cell value breaks topology)

Temporarily raise the population of the region⁴

1. Security is calculated as the number of point-wise neighbours in the same region as the cell plus 3 times the number of edge-wise neighbours
2. The density of a cell is the population of the region which that cell represents divided by the total number of cells representing that region
3. Topology is not broken if, clockwise, the regions of the eight surrounding cells change less than four times, and it is not the last cell of a region
4. Temporarily raising a region's population which contains cells which cannot be replaced due to topology constraints helps to break bottlenecks

Figure 8a : Pseudo-code of the cellular cartogram algorithm (see also appendix A) (Author).

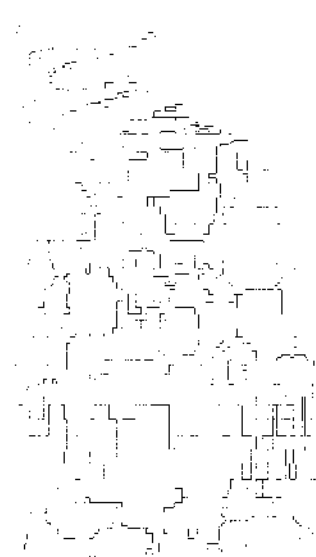


Figure 8d: Pseudo-cartogram of the population of Britain with boundaries from Figure 8 b (Author).

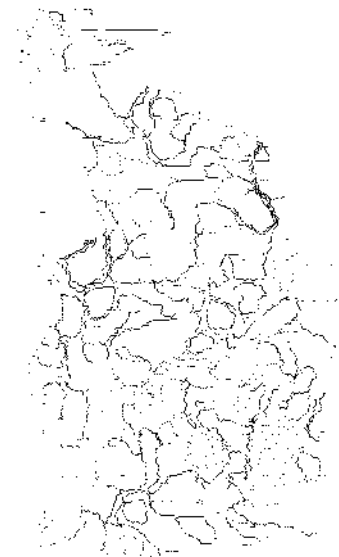


Figure 8e : Cellular population cartogram of Britain minimizing the lengths of boundaries (Author).



Figure 8b : Land map of British counties and major cities drawn on a five kilometre grid (Author).

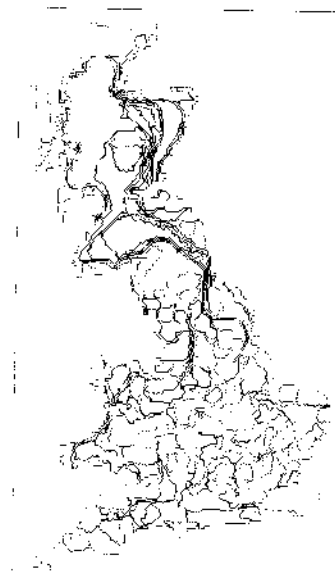


Figure 8c : Continuous population cartogram of Figure 8b preserving the coastline of Britain (Author).

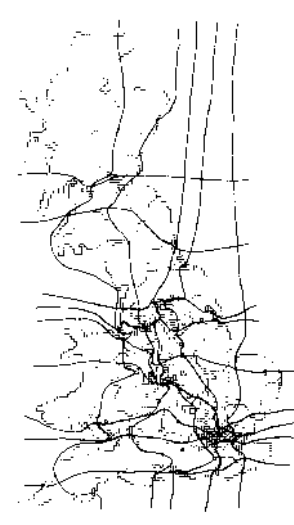


Figure 8f : An equal population size grid drawn on the cellular equal land area map (Author).

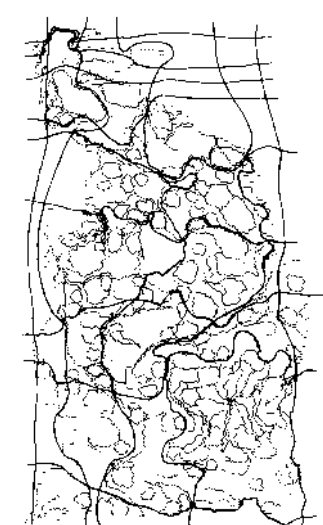


Figure 8g : An equal land area grid drawn on the cellular population cartogram of Britain (Author).

done in Figure 8d. Here lines of latitude and longitude have been squeezed together or pulled apart to approximate an equal population cartogram, while those lines remain straight and parallel (see also Figure 7d). When the algorithm is applied to this base a more visually acceptable solution is reached which is shown in Figure 8e. Because this cartogram is continuous, every region is still connected to its original neighbours and no others and so this cartogram can be used to re-project a grid of equal population sized "squares" onto the map of Britain, as in Figure 8f. In Figure 8g this process can be seen reversed to show how the national grid would appear, if it were drawn upon the cartogram. Although the results are generally satisfactory, in a few places the grid can be seen to be severely warped. This method of projection therefore does not result in a conformal map, nor does it necessarily produce a simple solution, but the final result always maintains contiguity.

9. Circular Cartograms

Cartograms which can be shown to have good mathematical properties, such as approximating a conformal projection, are not necessarily the best options for cartographic purposes. If, for instance, it is desirable that areas on a map have boundaries which are as simple as possible, why not draw the areas as simple shapes in the first place? Here an algorithm is described which does just that, using circles as the simplest of all shapes. The antecedents of this approach for making cartograms can be seen in work by Härö (1968: 456) and some results are shown in Figure 4b. Johnston et al. (1988: 340) and Howe (1970) also show examples of cartograms which define areas as simple shapes for use as a base map. There is a long tradition of mapping with circles as symbols in cartography and the advantages of using this simple shape are well known (Dent, 1972). Figure 9a gives the pseudo-code of an algorithm which creates cartograms where regions are represented by circles. The metaphor for this algorithm is not microscopic cells in a "Game of Life", but a development of the programs which simulate the orbits of stars and planets! Each region is drawn as a circle with its area in proportion to its population and is then treated as an object in a gravity model which is repelled by other circles with which it overlaps, but is attracted to circles which were neighbouring regions on the original map. Forces akin to forces of gravity are calculated, including velocity and acceleration, and the whole process is acted out as if it were occurring in treacle, to avoid any circles moving too quickly (as can occur when small objects orbit too close to large objects in the original gravity models). If this algorithm is left to run on a normal map for a few hundred iterations it eventually produces a solution in which no circles overlap and as many as possible are still in close contact with their original geographic neighbours. Some of the original coastline features are even

Create a vector from the traditional map of the centroid and population of each region which is to appear on the cartogram and the lengths of the boundaries between that region and each of its neighbouring regions.

- For each region
 - Calculate the radius of a circle so that its area is proportional to population¹
- While the forces calculated below are not negligible
 - For each region (the order of calculation has no effect)
 - For each region which overlaps with the region
 - Record a force away from the overlap in proportion to it
 - For each region which originally neighboured the region
 - Record a force towards it proportional to distance away²
 - If the forces of repulsion are greater than attraction
 - Scale the forces to less than the distance of the closest circle
 - Combine the two aggregate forces for each circle³
 - For each region
 - Apply the forces recorded to be acting on each circle to its centroid⁴

1. The radius of each region is equal to the square root of its population divided by 7, then scaled by the total distance between neighbouring regions
2. The forces of attraction are also scaled by the length of the original border between the two regions as a proportion of the total perimeter of the region
3. The ratio to combine by is 60:40 for repulsion:attraction; but given no overlaps, the total force is scaled to less than the distance to the closest circle
4. The forces acting on each circle are equal to a quarter of the sum of the focuses acting on the circle at the last iteration and the newly calculated forces

Figure 9a : Pseudo-code of the circular cartogram algorithm (see also appendix B) (Author).



Figure 9b : Land map of British counties and regions with bridges and tunnels added (Author).

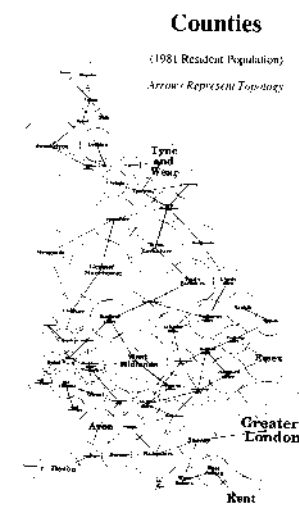


Figure 9c : Circular population cartogram of Figure 9 b showing the effect on topology (Author).

retained (because the circles of regions with sea borders experience more friction), but a true continuous cartogram is not produced as this is not possible where each place is drawn as a regular shape.

Figures 9b to 9d show a circular cartogram being created. The first figure is an equal land area county map of Britain (in which the areas in Scotland are regions). To this map the locations of bridges and tunnels have been added so that, for instance, Gwent is connected to Avon. Figure 9c shows the finished cartogram in which each county and Scottish region is drawn as a circle with its area proportional to population, and lines are drawn between those circles which should be neighbouring. In only a few cases is topology broken, for example where Greater Manchester prevents Lancashire and Merseyside from touching. Figure 9d illustrates how the process of creating this cartogram occurred, with each circle originally placed on its region's true geographic centroid. The concentration of population meant that the circles in England tend to repel each other, while those in Scotland move together. Note that the "island areas" circle is left sitting above the rest of the map (see Dorling, 1994b for more details). This cartogram has the advantage over more sophisticated forms of showing quite clearly how the populations of areas vary, without having to compare very complex shapes in more rural areas. The dominance of the major cities in the population structure of Britain is emphasised in Figure 9e, which uses a functional rather than an administrative definition of cities.

As the number of areas is increased the proportion of contacts which break topology decreases. This is one of the major advantages of this method of making cartograms — the picture becomes more accurate as more detail is added. Figure 9f shows a population cartogram of the population of the 459 local authority districts in Britain with lines connecting those which were originally geographic neighbours. The smaller geographic units mean that there are a great deal fewer discontinuities in areas such as London. When the areas also have similar populations the improvement is even greater, as Figure 9g illustrates. In this figure one circle is drawn for each of the 633 parliamentary constituencies of mainland Britain which were in use before the 1992 general election. Each of the circles is drawn with an identical area to represent voting power in the House of Commons. This cartogram shows a practically continuous transformation of the map of Britain. In Section 14 the number of areas used is increased from many hundreds to over ten thousand units and some further uses are shown for these types of cartogram.

A major problem with manual, mechanical and computer-based methods of producing continuous area cartograms is that the time this takes often escalates exponentially as the total number of individual areas to be

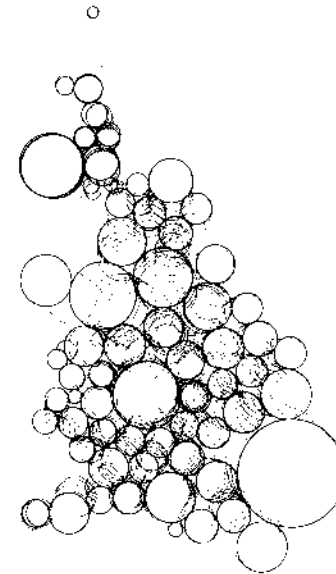


Figure 9d : Evolution of the circular population cartogram shown in Figure 9c (Author).

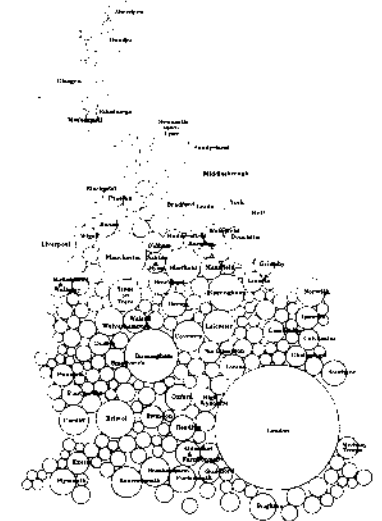


Figure 9e : Circular population cartogram: local labour market areas (Champion & Dorling, 1994: 17).



Figure 9f : Circular population cartogram: local authority districts showing topology (Author).



Figure 9g : Circular population cartogram: parliamentary constituencies showing topology (Author).

represented rises. Computer algorithms are also prone to producing bottlenecks which prevent the program progressing to an accurate solution when there are many areas to be mapped. The time taken by the circular algorithm described here to converge to a sufficiently accurate result is in almost direct proportion to the number of areas being mapped (more accurately its speed is in proportion to $a \ln a$, where a is the number of areas to be mapped). The maximum number of areas it has been used to map so far exceeds one hundred thousand (Darling 1993a).

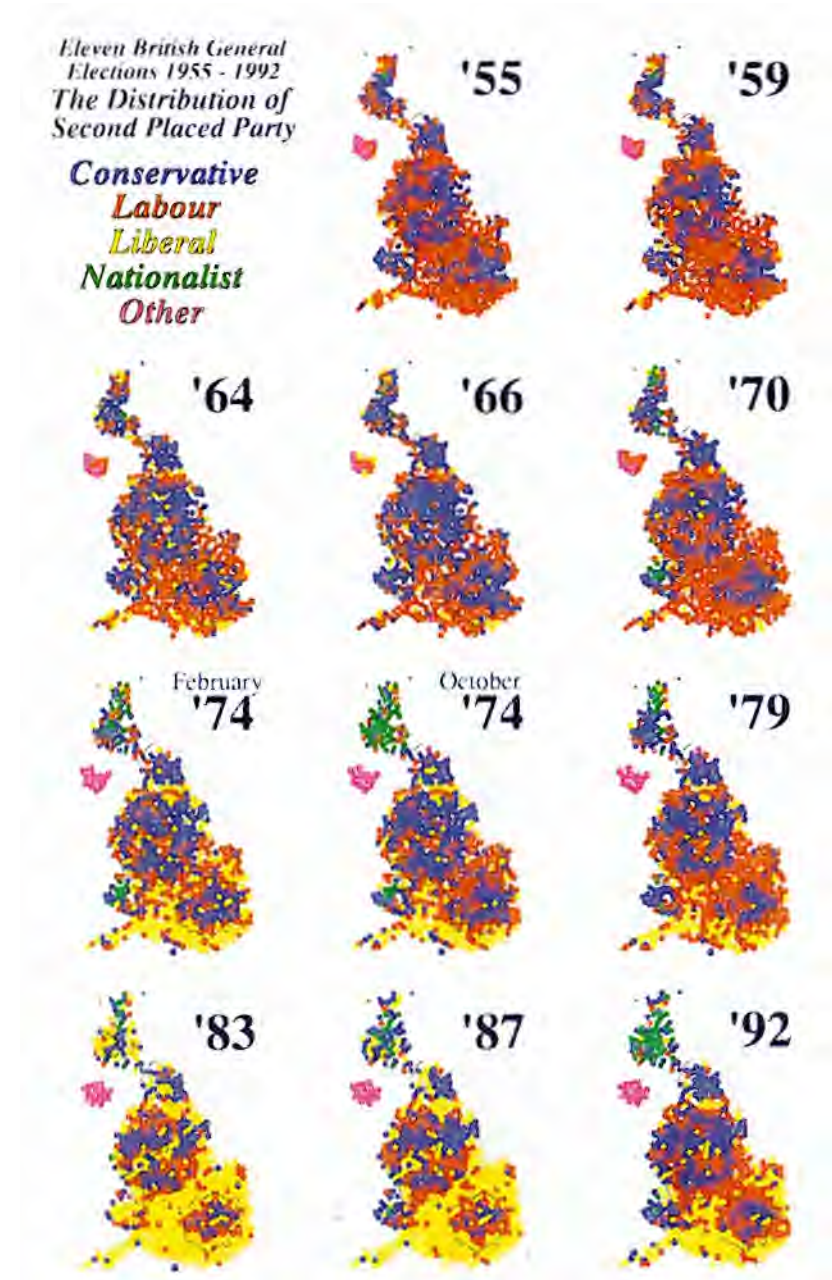


Figure 14a : Eleven British general elections 1955-92. position of the second placed party (Author).

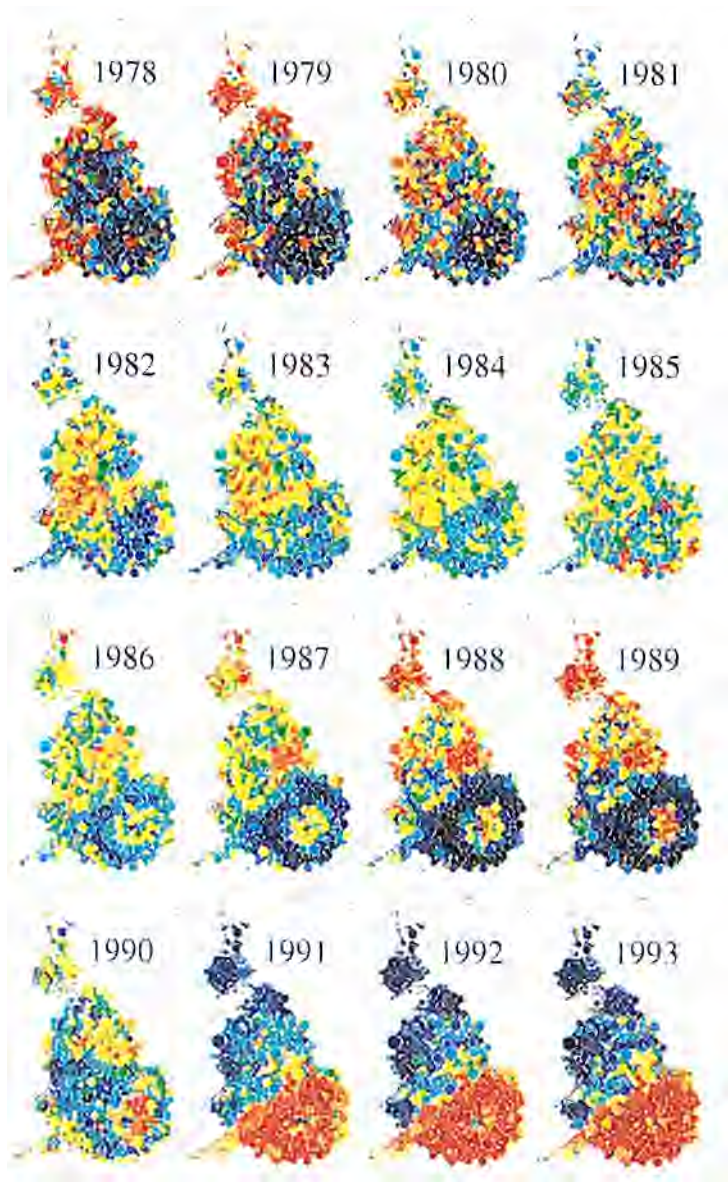


Figure 14b: Cartograms of the spacetime trend of unemployment in **Britain** 1978-93 (Author).

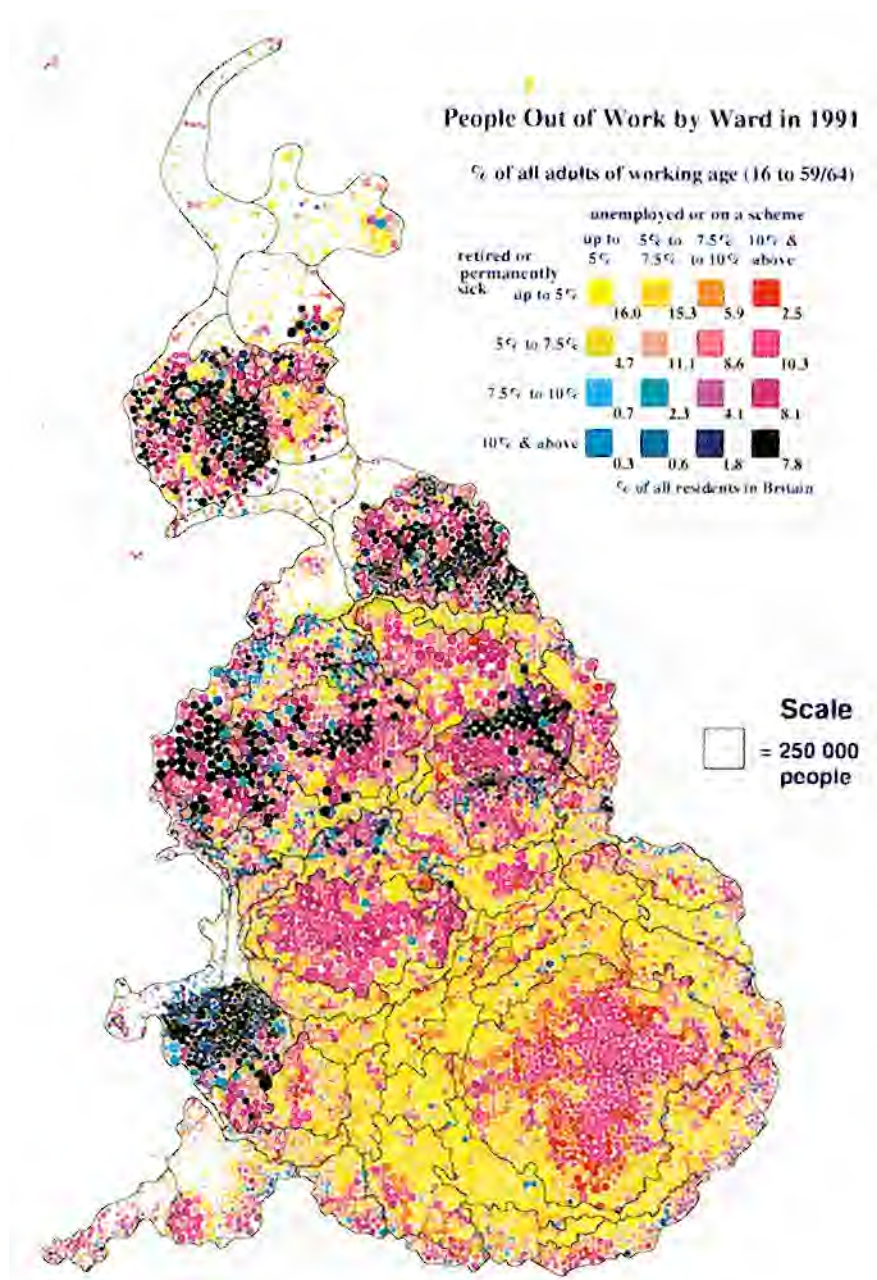


Figure 14o : The bivariate distribution of people out of work by ward in Britain in 1991 (Author).

III. Applications

10. Political Cartography

Having considered examples of cartograms drawn of the world and illustrated half a dozen methods by which cartograms can be made, we now turn to the uses to which cartograms can be put. Many of the previous examples have hinted at these and the creators of cartograms often had explicit uses in mind which have been mentioned, but there are also distinct subject areas where the use of cartograms is particularly common. The most obvious, perhaps, is in mapping the results of elections (Upton 1994). To map the outcome of political elections on a traditional map may appear foolhardy, although this has not prevented entire atlases of election results being produced using equal land area maps (see Waller, 1985, and, for a defence of the method, Kinnear, 1968: 12). A famous example appeared in Paris Match' magazine which showed the more usual method of mapping election results, illustrating the patterns of Gaullist (U.D.R. and R.I.) success in the 1967 elections in France (Lockwood, 1969: 97). Use of cartograms often, of course, dramatically alters the impression of which party has won an election as is illustrated by mapping election results in a country such as Wales. On a normal map the labour party would appear to secure only a small minority of the votes in Wales, whereas they can be seen to be by far the biggest party when the Welsh Valleys are drawn in proportion to their populations (see Madgwick & Balsom, 1980).

One aspect of political cartography which makes the use of cartograms difficult is that of frequent boundary changes. In Britain the boundaries of constituencies were altered many times before 1955 and there were large scale redistributions of seats after the 1970, 1979 and 1992 general elections. When cartograms are drawn by computer this need not present a problem, but political cartograms drawn by hand can quickly become obsolete (Dorling, 1994a). A popular method for designing cartograms to study British general election results is to have each constituency drawn as a square (as used to show countries of the world in Figure 4a). Although there are cartographic advantages to raising simple symbols (see Section 9), their use in cartograms of Britain has often meant that the constituencies of London had to be shown as an inset (Johnston et al., 1988). In Figure 10a one of the best known cartograms of Britain is shown taken from where it was first used in the pages of the Times Newspaper to report the results of the 1964 general election (Hollingsworth, 1964). The cartogram was created by Dr T. H. Hollingsworth based at the University of Glasgow. The text which accompanied the maps in the Times described how the map strictly preserves contiguity, being

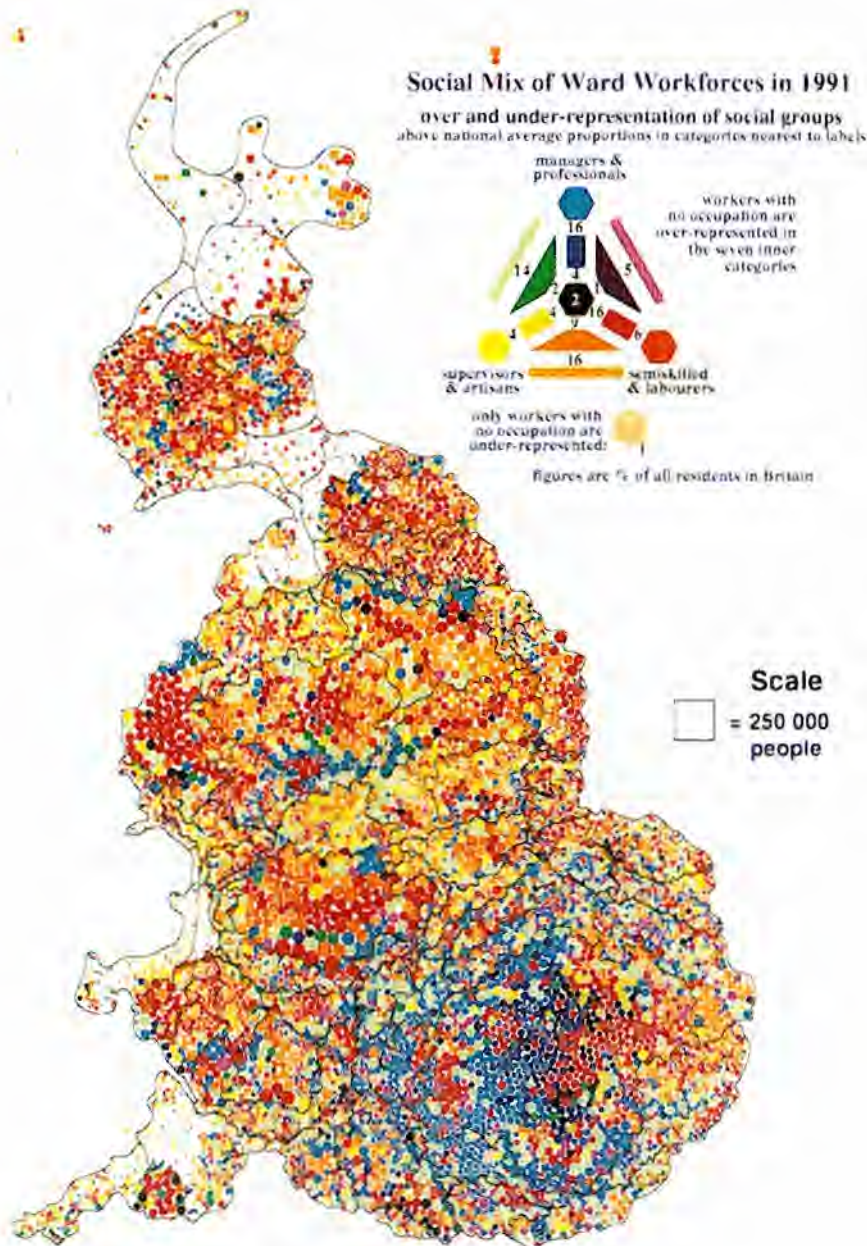


Figure 144 quadrivariate distribution of social groups by ward in Britain in 1991 (Author).

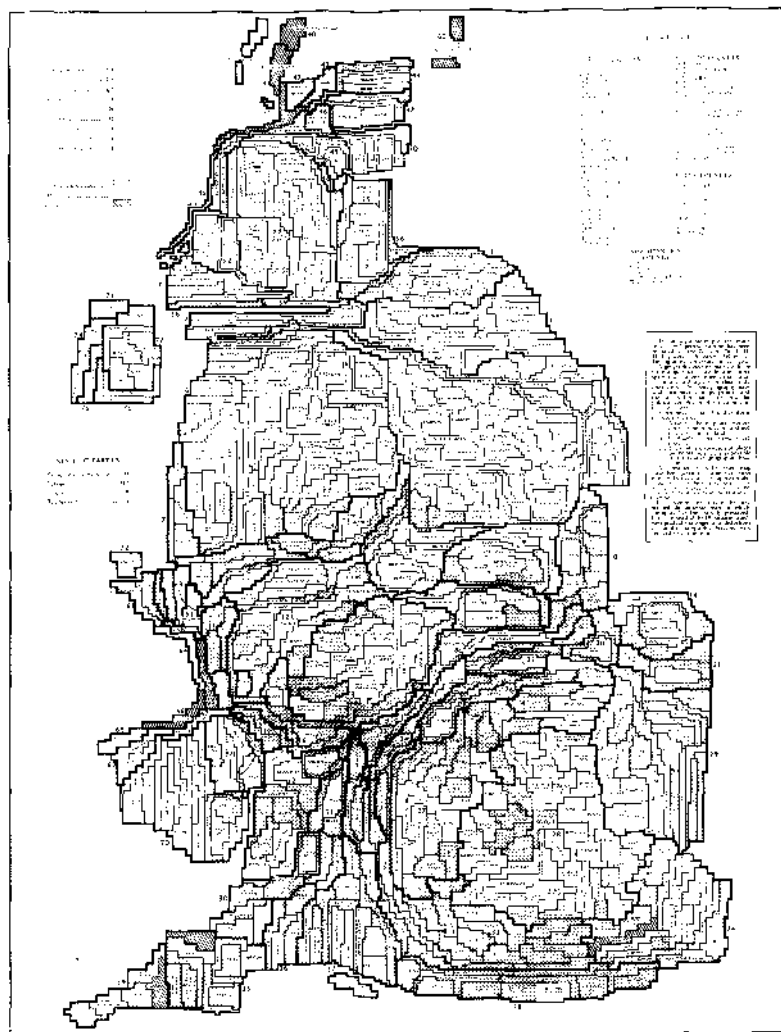


Figure 10a : Cartogram of "the political colour of Britain by number of voters" (Hollingsworth, 1964).

constructed by the gradual manual rearrangement of 40 320 square tiles, 64 for each constituency. The thicker lines on the maps are county boundaries. The cartogram was used by the Times again to show the result of the next general election (Hollingsworth 1966) but it was not used again after that, although it has been reproduced in numerous publications, most notably in an article by the Ordnance Survey where it was used to show how much progress had been made in land registration (Sweeney & Simpson, 1967). Interest in cartograms in at least both Britain and America tends to surge around the time of national elections (particularly when urban based parties win and also just after population censuses have been taken).

Population distribution is often extremely uneven in former British colonies, as the discussion surrounding the drawing of the isodemographic map of Canada has already suggested (see Section 6). These areas have also often inherited many features of the British voting system which makes mapping their election results a relatively simple procedure. In 1966 the constituency of Adelaide returned a Liberal Party member to the Australian House of Representatives, while the constituency of Port Adelaide returned a Labour Party member to the House. These facts are relatively simple to ascertain from the cartogram of the 1966 Australian general election results shown in Figure 10b, and if the original article is consulted it is apparent that this was the first election since 1955 when Adelaide did not return a Labour candidate (Hughes & Savage, 1967). In Australia the urban federal constituencies occupy only a tenth of the land, but contain nine tenths of the people. It would be almost unthinkable to show election results for that country on a conventional equal land area map. The same could be said of Australia's nearest neighbour, New Zealand, and a carefully constructed cartogram, which took four months to produce, of that country's population is shown in Figure 10c, (Kelly, 1987: 9). Unfortunately no article has been published, as far as this author is aware, showing electoral statistics on a cartogram of New Zealand.

11. Early Epidemiology

For researchers interested in the causes, prevalence and spread of disease, an equal population basemap is often seen as essential. Figure 11 shows one of the earliest examples of a cartogram designed "for epidemiological purposes" (Wallace, 1926: 1023). At the top of the Figure is the conventional map of the counties of Iowa State and at the bottom is an equal population cartogram upon which coloured pins were placed to show the locations of reportable diseases. The square in the middle of the cartogram is Des Moines city in Polk County. On an updated population cartogram of the United States this county can be seen to have grown disproportionately since the 1920s (see Figure 4b, preferably with a magnifying glass!). Given the increasingly uneven population distribution of the United States and the growing social divides between the populations of neighbourhoods living at different densities, the need for cartograms like this is greater now than ever.

The designer of the Iowa cartogram was a doctor working in the state department of health. Many doctors have been struck by the idea that they could learn more about disease through mapping. The earliest example often quoted is of a map of the incidence of cholera in London (Snow, 1854), from which map a pump in Broad Street was identified as being at the centre of the clusters of cases of cholera in the 1848-49 epidemic. The pump handle was removed. A cartogram of the area has yet to be constructed from the 1851 census of population data, so whether that pump was actually at the centre of a real cluster is still unknown. The first cartogram of London known to this writer is an "epidemiological map" which was produced by a doctor working for the then London County Council Department of Public Health (Taylor, 1955). The cartogram contained crosses, drawn in the borough rectangles, to show the incidence of polio during the 1947 epidemic. Because the rectangles were each drawn with the same height, their widths, as well as their areas, are proportional to population. The borough with the highest rate of polio and hence the tallest column of crosses in the figure was Shoreditch. Almost exactly one hundred years separates the two London epidemics which were first drawn on a map and cartogram respectively. Cartograms showing distributions within countries came later.

A claim was made to have produced the first cartograms showing national disease distributions only a decade after the crude cartogram of London was first drawn. The nation was Scotland and a separate cartogram was constructed by hand for each of eight age-sex groups (see Forster, 1966: 165). The author of these cartograms concluded that a national series of cartograms should be produced for each age-sex group for use in epidemiological studies in Britain. This was never done.

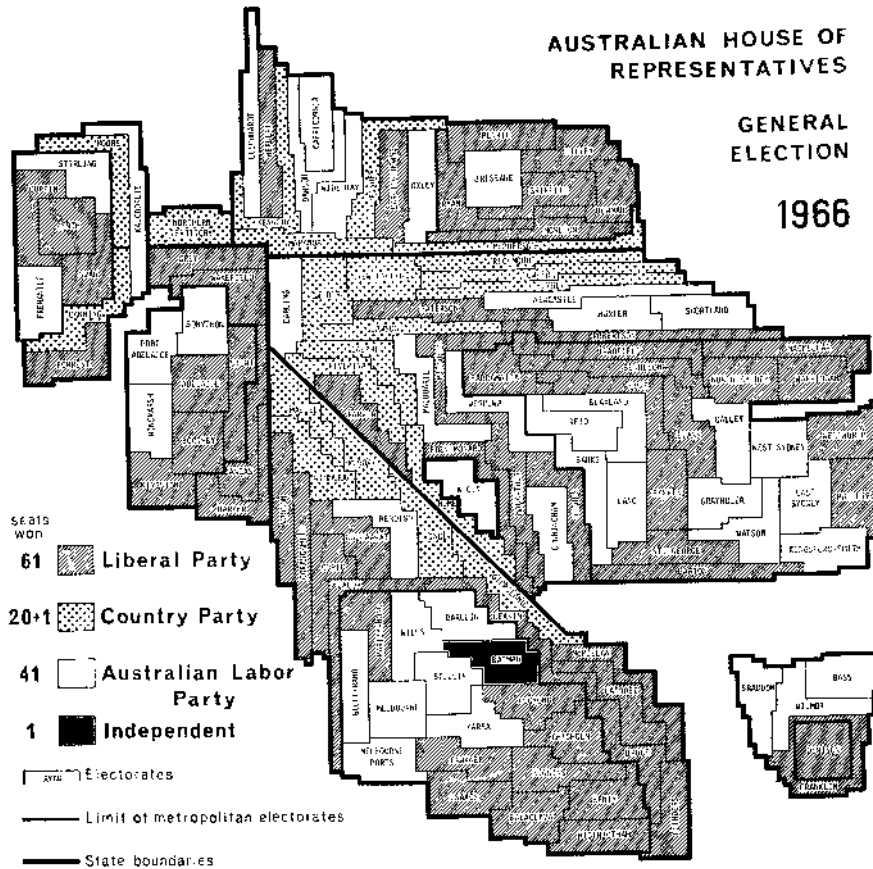


Figure 10b: Cartogram of the Australian general election result in 1966 (Hughes & Savage, 1967: 20).

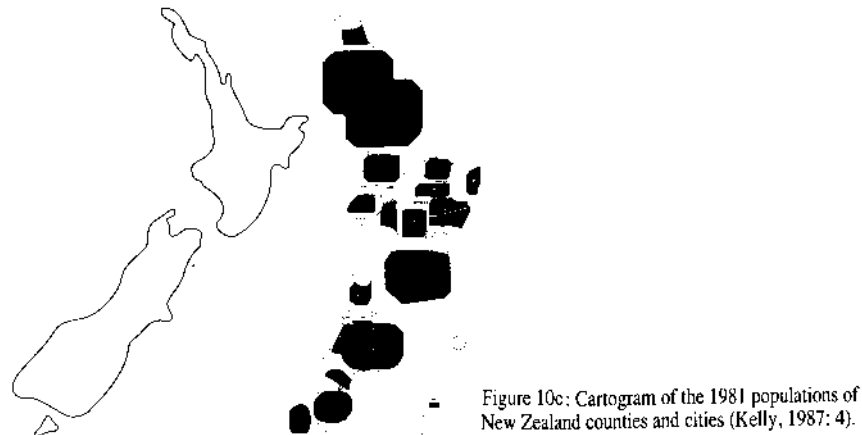


Figure 10c: Cartogram of the 1981 populations of New Zealand counties and cities (Kelly, 1987: 4).

12. Mapping Mortality

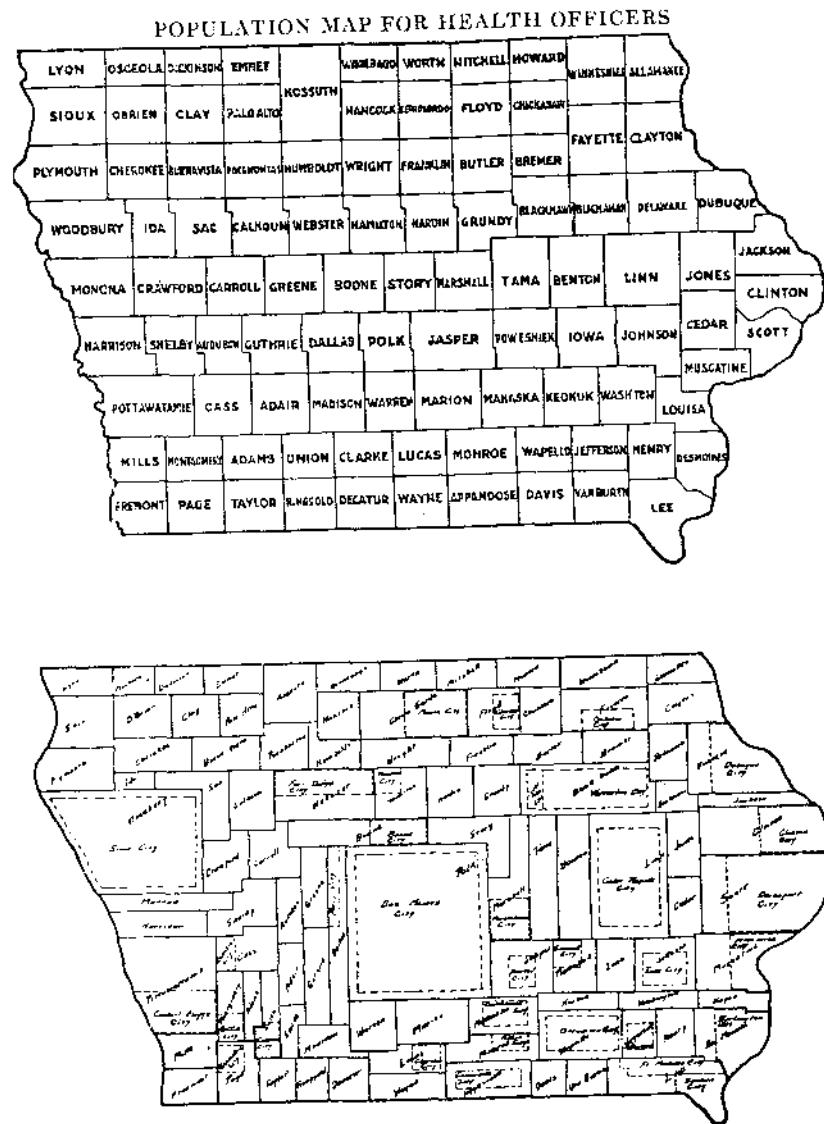


Figure 11 : Map and population cartogram of the counties of Iowa state (Wallace, 1926: 1023).

A National Atlas of Disease Mortality in the United Kingdom was published in 1963 under the auspices of the Royal Geographical Society; the atlas contained no cartograms (its original base map is shown in Figures 12a and 12b). Fortunately, a revised edition was published a few years later which made copious use of a "demographic base map" (Howe, 1970: 95). It is interesting to note that when the revised edition was being prepared, the president of the Society was Dudley Stamp who believed that "The fundamental tool for the (*sic*) geographical analysis is undoubtedly the map or, perhaps more correctly, the cartogram." (Stamp, 1962: 135). In the cartogram which was used in the revised national atlas, squares were used to represent urban areas while diamonds were used to show statistics for rural districts. No attempt was made to maintain contiguity, but a stylised coastline was placed around the symbols which were all drawn with their areas in proportion to the populations at risk from the disease being shown on each particular cartogram.

The cartogram is shown being used to display the distribution of standardized mortality from all causes of death for men in Figure 12c and for women in Figure 12d. High rates can be seen in northern districts and some inner London boroughs (including Shoreditch which is also highlighted on one of the earliest cartograms of London - see previous section). Extremely high rates in central Scotland are particularly noticeable as are the low rates in districts which surround London. At the extremes the average man living in Salford was 50% more likely to die each year than his counterpart in Bournemouth (Howe, 1970: 98). Both these areas are shrunk on a "normal" map. The pattern for women was very similar to that for men although, in general, less pronounced. However, women did have the highest mortality rate of any area on the map in rural Dunbartonshire where they were more than twice as likely to die each year as were women nationally (allowing for local age structure). The cartogram highlights this area, but also puts it in the perspective of the populations at risk from the high mortality rates for women in and around the Glasgow area.

What differentiates medical uses of cartograms most from political cartography is the mapping of clusters — individual cases of a disease or death which together might possibly be connected. One of the earliest cartograms thought to have been used for this purpose was reproduced in Figure 11. Figure 12e shows the distribution of cases of Wilm's tumour, a childhood cancer, identified in New York State between 1958 and 1962, drawn upon an equal land area map. Apparent clusters of cases have been marked on the map (Levison & Haddon, 1965: 56). In Figure 12f the same

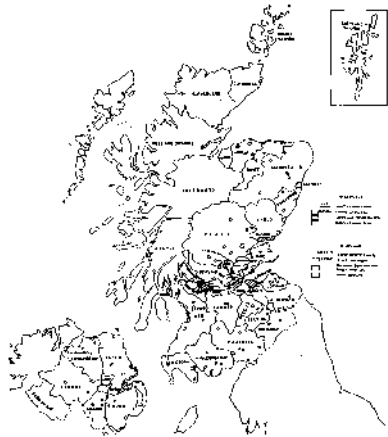


Figure 12a : Traditional map of districts in Scotland and Northern Ireland (Howe, 1970: transparency).



Figure 12b: Traditional map of local districts in England and Wales (Howe, 1970: transparency).

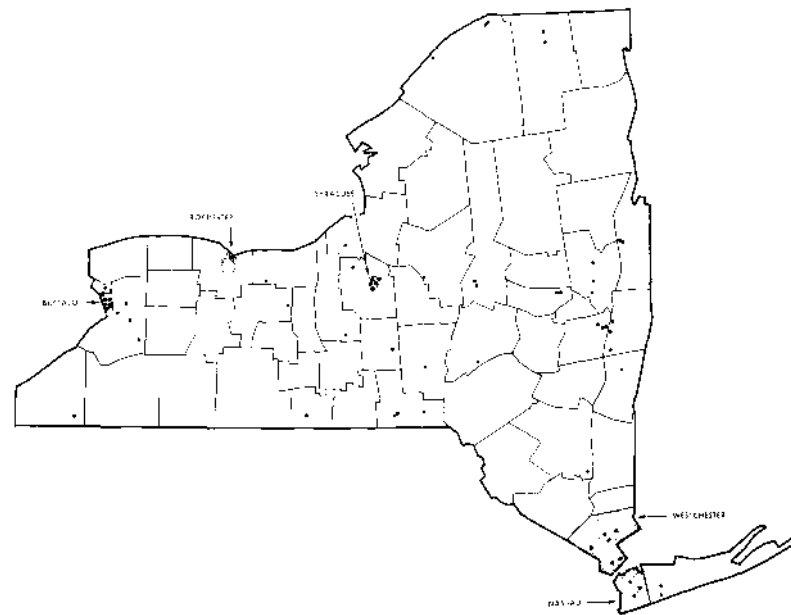


Figure 12c: New York state conventional map of Wilm's tumour cases (Levison & Haddon, 1965: 56).

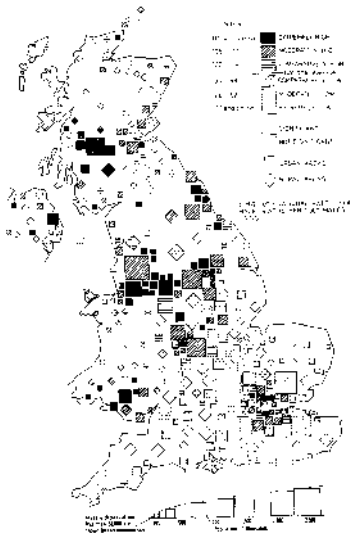


Figure 12c: Standardized mortality of men from all causes 1959-63 by district (Howe, 1970: 100).

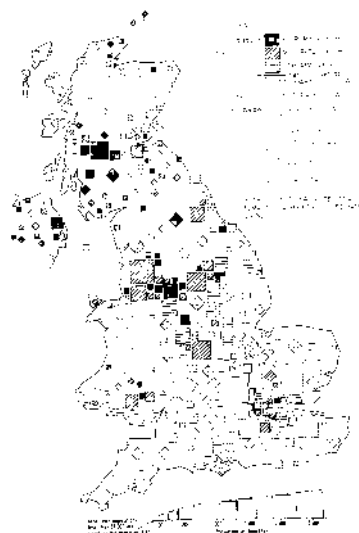


Figure 12d: Standardized mortality of women from all causes 1959-63 by district (Howe, 1970: 101).

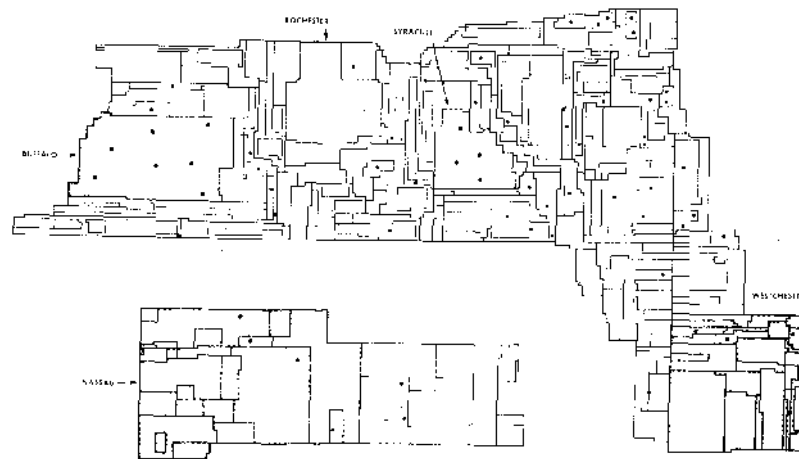


Figure 12f Wilm's tumour cases on a population cartogram of New York (Levison & Haddon, 1965: 57).

cases are drawn upon an equal population cartogram and the apparent clusters can be seen to have been quite evenly dispersed across the population. The same process has been used to illustrate how cases of Salmonella food poisoning occurring in Arkansas in 1974 were not unduly clustered in Pulaski county (Dean, 1976). Cartograms have been shown to be useful in determining that certain types of disease which appear clustered are in fact quite evenly distributed across the population. In more recent years researchers have turned their attention to trying to develop cartograms upon which actual, rather than illusory, clusters of disease can be identified.

The major problem with using population cartograms to identify clusters of disease is that the choice of which areas are closest to which on a cartogram can be quite arbitrary. For instance, if the same set of incidences of one particular disease were plotted on three different cartograms of America, then different parts of the country may appear to have dense clusters of cases depending on which cartogram was chosen. This would be true regardless of whether the clusters were to be identified by eye or by statistical procedures; the different base maps would result in different patterns emerging. The proposition that there is no single "true answer" as to whether a disease is clustered does not go down too well in some circles. Because of this problem a group of researchers at Berkeley developed a computer algorithm for identifying incidences of disease (Selvin *et al.*, 1984). The algorithm they developed was not very different from other "continuous transformation" cartogram algorithms (see Section 7) and was still slow enough to warrant testing on a Cray supercomputer! (Selvin *et al.*, 1988: 217). However, the authors of the algorithm do claim that their program would result in a unique transformation given an infinite amount of input data, and they relied upon this claim to justify its use in disease mapping. The algorithm was first used to produce the cartogram shown in Figure 7e and then to create a cartogram of San Francisco county, upon which apparent clusters of disease were shown to be false (Selvin *et al.*, 1988: 217). However, application of the method to another Californian County did provide evidence of some clustering of high cancer rates near oil refineries (Selvin *et al.*, 1987).

13. Transformed Flows

The term "flows" covers a wide range of subjects. For instance workers can be seen to "flow" between different states of employment and votes are said to "flow" between political parties. There are flows in medical mapping such as were used to plot the movement of the influenza epidemic which spread across England and Wales in 1957 using the cartogram base shown in Figure 4c (see Hunter & Young, 1971). Here, however, there is enough space to consider only two very simple geographical types of flow in which people move — commuting and migration. As both of these types of flow are influenced by distance it may appear strange to suggest drawing them on a cartogram base. However, until you produce the drawing, you cannot tell whether its results will be useful.

Commuting flows are amongst the most simple to map because people usually do not commute very far to work in a day so the flows tend to be short. In Figure 13a a line is drawn between each pair of wards where the total number of people travelling between the two wards is greater than 5% of the total number of workers living in the two wards. A picture of the city structure of England and Wales becomes apparent in which few people travel long distances. Flows involving more than 1000 workers are drawn with slightly thicker lines. In Figure 13b exactly the same lines are drawn, but now upon an equal ward population cartogram (see Section 14). The distribution of flow lines appears to be much more even as almost everywhere where people live, people travel to work. However, in London the lines are sparse as there are relatively few close ties between particular pairs of wards in the capital; the people who tend to work in one area tend to travel from many areas. Which flows are shown depends on how a flow is defined to be significant and on the nature of the areas which are used to count the flows. In the centre of London there are many very small wards and hence fewer strong patterns can emerge. The final results of flow mapping depend both on the nature of the flows being mapped and on the way in which those flows are mapped.

Flow mapping is an introduction to the complexities which result from considering drawing anything other than the most simple of geographies. For instance, time has still to be properly addressed in cartography, particularly in combination with spatial transformations. Although researchers have considered creating cartograms in which distance is proportional to time, few travel-time cartograms have been created (Angel & Hyman, 1972). Almost all travel-time cartograms which do exist show travel-time only from a single point using the fastest method of travel, such as is done in Figure 13c. Note how, in this figure, New York appears as close to London as does Stranraer. A

**Daily Commuting Flows
Between English and
Welsh Wards in 1981.**

31.7% of all movements shown

Flows of more than 1 in 20
of the two areas's participating
populations drawn as thin lines.

The line width of flows involving more
than 1000 people is drawn in proportion
to the magnitude with direction indicated.



Figure 13a Significant daily commuting flows between English and Welsh wards in 1981 (Author).

**Daily Commuting Flows
Between English and
Welsh Wards in 1981.**

21.7% of all movements shown.

Flows of more than 1 in 20
of the two areas's participating
populations drawn as thin lines.

The line width of flows involving more
than 1000 people is drawn in proportion
to the magnitude with direction indicated.

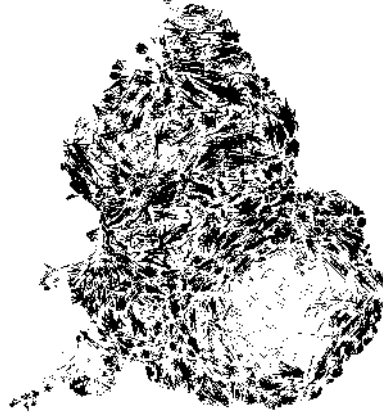


Figure 13b : The same commuting flows as in Figure 13a, drawn on a population cartogram (Author).

cartogram could be created in which travel-time distances between all points was shown; this would result in a complex surface being drawn but it should not be impossible to achieve. On this surface cities would appear as mountains, as commuters fight their way through the rush hour to enter them. The deep gorges of inter-city railway lines would cut through them, or perhaps appear as tunnels coming out of the mountains. The surface could be drawn upon the two-dimensional base of an equal population cartogram and so both time and population could be measured from its geometry. And, if a different surface were drawn for different times of the day or for different days of the year, those surfaces could be combined as a space-time volume in which distance is proportional to hours and volume is proportional to human lives. This cartogram, and a thousand other variants, are all waiting to be drawn.

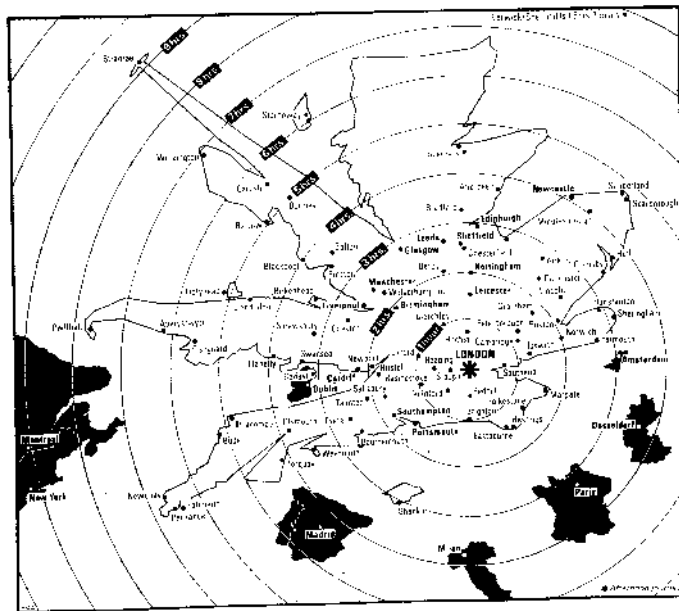


Figure 13c : London travel time distance cartogram of Britain, "New Society" (Lockwood, 1969: 100).

IV. Conclusions

14. Multivariate Mapping

In the previous 13 sections, I have attempted to illustrate how the use of cartograms is widespread in academic and popular writing and how cartograms are not as difficult to create as many readers might think. No commercial geographical information system exists which will create cartograms from scratch, but that is largely due to a perceived lack of demand and, perhaps, due to an inflated view of how difficult it is to implement computer programs to create cartograms. The two algorithms which are included as appendices here are relatively simple to implement in a variety of packages, while many versions of the algorithms described in Section 7 are available around the world (although none of their authors, to my knowledge, has published the implementations of these algorithms in an easily accessible form). In this final section some of the more complex uses to which cartograms can be put are illustrated using the examples given in the four colour plates. These examples attempt to show how the use of cartograms can shed light on complex spatial processes. The evolving structure of British social geography, looking in detail at unemployment, voting and social

Figure 14a shows an evolving equal electorate cartogram of the parliamentary constituencies of the United Kingdom, including changes in their number since 1955. Between 1955 and 1970 there were 630 constituencies in the country. They are coloured in the illustration to show which party came second at each of the five general elections held in this period. Note how the south east of the country grows in size over time (as its population grew) and how the territories of the two major parties expand and contract. At this time seats where Labour came second were almost all won by the Conservative party and *vice versa*. However, the following six general elections saw a very different pattern emerge. For the general election of February 1974 the number of parliamentary constituencies was increased to 635. It increased again to 650 in 1983 and to 651 in 1992. Compare the number of seats in Northern Ireland on the figure between 1970 and 1974 to see how these changes are accommodated on the cartograms. The rise and geographical spread of both the Liberals and the Nationalists in this period are quite striking (the Social Democrat Party are included with the Liberals here). The cartograms show that although the last four general elections were all won by the Conservative party, their share of seats in which they came second was falling over time. Most importantly, the way in which the main opposition parties had established clear geographical territories by the aftermath of the

last general election is also made evident (Dorling 1994a). The geographical evolution of political preferences over eleven general elections can be shown on a single A5 page if seats are drawn in proportion to the number of people who can vote.

Figure 14b also shows an evolving space-time pattern, but here twice as many statistics are shown as in the previous figure. The longest series of unemployment rates for small areas extends back to 1978 for places known as "amalgamated office areas" (which are groups of unemployment benefit offices). There are just over 850 of these areas and the number of people claiming unemployment benefit in each of them was recorded by the Department of Employment in almost every month over the sixteen years shown in this figure. In this illustration the changing spatial distribution of unemployment in Britain is depicted using these statistics. The shading of each place at each time reflects its unemployment rate then, compared to its average unemployment rate over the whole period (for more details see Dorling 1995e). The red and orange areas show higher than average, yellow is for average and green and blue represent lower than average rates of unemployment for that particular place in that year. All the monthly rates for each year are averaged to allow for the effects of expected seasonal employment variations. The figure shows how the worst period for Devon, Cornwall and Wales was 1978-79, for Scotland 1978-79 and 1988-89, but for the south east 1991-93. For the latter region, the maps clearly show how the blight of unemployment took hold in central London in 1987 and spread out across south east England in subsequent years. Compare this pattern to the rise in Conservative party losses in London at the last general election and the return of the Labour party as the main political contender between the capital and the midlands on Figure 14a. The use of cartograms allows possibly unexpected connections to be seen between different spatial processes where the importance of events is weighted by how many people are involved.

Figure 14c takes this discussion to another level of detail by showing how it would be misleading to think of the north of the country as economically prosperous in static terms at the start of the 1990s. Although the south did experience particularly high rates of unemployment then, unemployment is not the only way in which loss of employment is expressed. Increasingly, levels of permanent sickness and early retirement rose in Britain during the last decade and, in places, these factors resulted in more people of working age being out of employment than did unemployment alone. Figure 14c shows a cartogram of over ten thousand wards in Britain (part-postcode sectors in Scotland) which was used to disseminate some of the statistics collected by the last census. In this figure all wards are allocated to one of sixteen categories depending on the proportion of people of working age who

were either unemployed or were retired or permanently sick in that ward. Thus over twenty thousand statistics are used to colour the cartogram, two for each ward resulting in a bivariate shading scheme (the mixing of two colours, here red and blue, is used to construct the key). Almost twice as many statistics are being used as in the last colour illustration. In some wards over 10% of the working population were unemployed and over 10% were prematurely retired or permanently sick. These are shown by the wards coloured black on the figure (which the key shows contained 7.8% of all people in Britain). These were almost all found in Wales, Scotland and the inner cities of the northern metropolitan counties (excluding West Yorkshire) as well as in some coalfield areas. A very clear north/south and urban/rural divide still separates the people of Britain when shown at this level, despite the equalizing effects of the last recession. The pattern for each of the other fifteen categories of ward shaded in this figure also tells a story about the spatial social structure of this country, but space precludes further discussion here (see Dorling 1995a and Dorling and Woodward 1996 for that).

Figure 14d once again doubles the amount of information included on one A5 page by showing the relative levels of four groups of people within each ward. This is done by using a quadrivariate shading scheme, where each ward is shaded according to the relative proportions of four groups of people living there. The four groups are: people who were working in managerial or professional jobs (light blue), people in supervisory or artisan type jobs (yellow), people in semiskilled or strictly supervised jobs (light-red) and people looking for work who had not been employed in the last ten years (black). Wards where a disproportionate share of the workforce belongs to a single one of these groups are given its "primary" colour. Wards where two groups are disproportionately represented are shaded by the mix of those colours so that a ward with many managers and artisans would be shaded light green, and so on. An excess of workers with no occupation in an area (the long term unemployed and people in the armed forces) changes the shade from light to dark. This mixing results in fourteen possible categories of ward and hence fourteen colours being shown in the key. If different levels of each group were distinguished, rather than just over- or under-average levels being used, then many hundreds of shades would be needed; but already with this minimal number the pattern which is revealed is complex. Around almost every city in Britain are localities containing disproportionate numbers of single groups. A majority (61%) of the population live in areas where either one or two of the three groups in employment are over-represented and the other two or three groups are under-represented (this can be calculated from the percentages given in the key to the map). This cartogram contains a detailed picture of the way in which people in Britain are spread over the country according to the kind of work they do or have done.

On a conventional map the red, purple and black would appear to occupy very little space.

What is unusual here is the level of detail which is included in this series of colour cartograms. However, these show detail which is still nowhere near the limit possible with high quality colour printing and computer animation. Population cartograms are, almost by definition, economical with space, but it is still surprising to see how much land area in a country like Britain is sparsely populated and hence how much detail can be afforded to the cities when the countryside is shrunk. Whatever you choose to use cartograms for, from studying participation in elections, to the spread of a disease, or the social structure of a country, the very different perspectives they show are likely to alter the way you imagine the processes behind these patterns to be operating. In human geography, mapping with population cartograms changes the perspective from concentrating on the populations of the countryside to the inhabitants of towns and cities where most of the people live. The last cartogram to appear in the Times newspaper was drawn on April 4 1966 following the Labour victory which was orchestrated from the cities. When the Conservative party regained power at the following general election the newspaper reverted back to a conventional projection which made the result appear like a landslide for the party of the right (Times 22 June 1970). Claiming space on maps is as much a political process as a technical one. People who are seen not to matter are often neither counted nor shown in studying society.



Figure 15 British counties transformed after 128 iterations of the cellular algorithm (Author).

15. Appendix A: Cellular Cartogram Program

See Figure 8a for the algorithm pseudo-code and Figure 15 for the results:

```

REM>CELLULAR
REM Cellular Algorithm Implemented in BBC BASIC (version 5)
REM Originally developed on a 32K Acom Electron
CLS

REM initialize variables (% = integer variable)
zones% =63: REM number of zones
width%=65 : REM width of grid (should be odd)
length%=100 REM length of grid (should be even)
blocks%=width%*length% : REM size of grid%

REM initialize arrays
DIM colour%(zones%) REM integer array of the map colour of each zone
DIM sorts(zones%) : REM integer array for calculating gini coefficients
DIM areas(zones%) REM integer array of the number of cells in each zone
DIM people%(zones%) : REM integer array of the population of each zone
DIM panics(zones%) REM integer array of inflated zones populations
DIM raster% blocks% : REM array of single bytes to store the grid
DIM awake% blocks% : REM array of single bytes of active parts of the grid
DIM ratio (zones %) REM real array of the population density of each zone
DIM nbour%(8) REM integer array storing off-sets of neighbouring indexes
nbour%(1)=width%+1: nbour%(2)=width%: nbour%(3)=width%-1: nbour%(4)=-1
nbour%(5)=-width%-1: nbour%(6)=-width%: nbour%(7)=-width%+1: nbour%(8)=1

REM clear the grid area array (set all cells to 0)
FOR I%=1 TO blocks%
  raster%?I%=0
NEXT

REM read map data from the end of the program into the grid area array
FOR Y%=0 TO lengths-1
  READ line$
  FOR X%=1 TO widths-1
    raster%?(Y%*width%+X%)=ASC(MID$(line$,X%,1))-ASC( )
    area%(raster%?(Y%*width%+X%)) += 1
  NEXT
NEXT

REM mark cells which are not in the sea as being awake in byte array
FOR I%=1 TO blocks%
  IF raster%?I%=0 awake%?I%=FALSE ELSE awake%?I%=TRUE
NEXT

REM initialize populations in people array and calculate densities &
REM read in the map colours and initialize the sort positions in arrays
pop%=0
space%=0
FOR I%=1 TO zones%
  READ index$,character$,name$,colour%(I%),people%(I %)
  sorts(I%)=zones%-I%+1
  ratio(I%)=people%(I%) / areas(I%)
  pop%=pop%+people%(I%)
  space%=space%+area%(I%)
NEXT

REM Calculate and print Gini coefficient of density inequality
last=FNGINI REM FN=function call
PRINT;INT(last*10) /10

REM begin main loop of the algorithm, calling the main procedure
REPEAT
  REM proceeding through grid in a chequerboard fashion
  PRINT; INT(last*10)/10
  FOR block%=1 TO blocks%-1 STEP2
    IF awake%?block% PROCFUTURE(block%): REM PROC=procedure call
    IF awake%?(blocks%-block%+1) PROCFUTURE(blocks%-block%+1)
  NEXT

  REM Update and print Gini coefficient of density inequality
  next=FNGINI

```

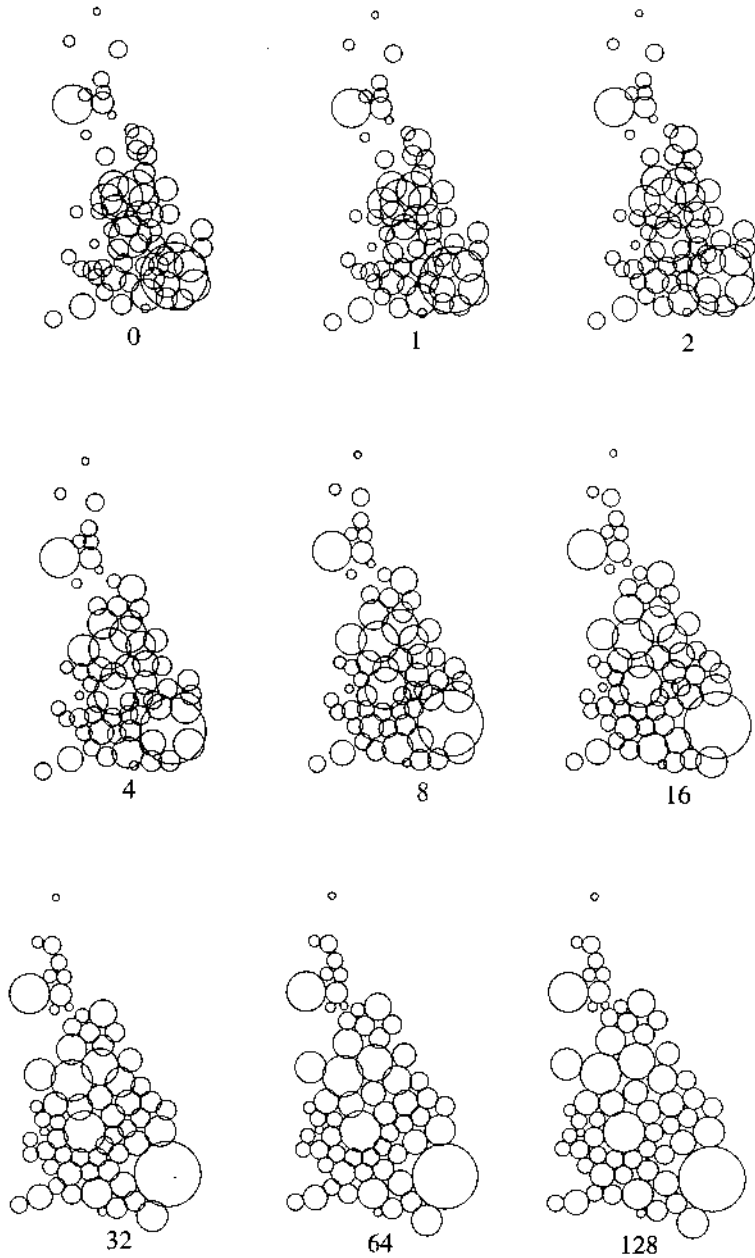



Figure 16 : British counties transformed after 128 iterations of the circular algorithm (Author).

16. Appendix B: Circular Cartogram Program

See Figure 9a for the algorithm pseudo-code and Figure 16 for the results. The Pascal implementation of the code is listed in Dorling (1995b).

```

/* C program to make county cartogram. */
/* I. expects a file called county.in to exist */
/* and produces a file called county.out */
/* bodies is set to be one greater than the */
/* I. current number of areal units, ie 64+1 */
/* graphics commands commented out */
#define bodies 65
#define friction 0.25
#define ratio 0.4
#define pi 3.141592654
#define screen scale 0.001
#include <stdio.h>
#include <math.h>
#include <pixrect/pixrect hs.h>
int body, number, end_pointer, distance;
int x[bodies], y[bodies];
double radius[bodies];
int list[bodies];
/*arestructutgallosysoverlappMgirclestobekkmifiedefficiendy.1
struct leaf
{
id ;
int xpos;
int ypos;
int left;
int right;
};
struct leaf tree[bodies];

/* this function add circles to the tree to build it recursively */
void add_point(pointer, axis)
int pointer, axis;
f(tree[pointer].id == 0)
{
= body;
tree[pointer].left = 0;
tree[pointer].right = 0;
tree[pointer].xpos = x[body];
tree[pointer].ypos = y[body];
}
else
if (axis == 1)
if (x[body] >= tree[pointer].xpos)
{(tree[pointer].left == 0)
= 1;
tree[pointer].left = end_pointer;
}
add_point(tree[pointer].left, 3-axis);
}
else
((tree[pointer].right == 0)
{+ = 1;
tree[pointer].right = end_pointer;
}
add_point(tree[pointer].right, 3-axis);
}
else
if (y[body] >= tree[pointer].ypos)
{(tree[pointer].left == 0)
f++ = 1;
tree[pointer].left = end_pointer;
}
add_point(tree[pointer].left, 3-axis);
}
else
{(tree[pointer].right == 0)
{0 = 1;
tree[pointer].right = end_pointer;
}
add_point(tree[pointer].right, 3-axis);
}
}
}

```

```

I* this function retrieves circles from the tree, recursively *I
void get_point(pointer, axis)
int pointer, axis;
((pointer > 0)
if (tree[pointer].id > 0)
((axis == 1)
{(x[body]-distance < tree[pointer].xpos)
get_point(tree[pointer].right,3-axis);
if (x[body]+distance >= tree[pointer].xpos)
get_point(tree[pointer].left,3-axis);
}
if (axis == 2)
{(y[body]-distance < tree[pointer].ypos)
get_point(tree[pointer].right,3-axis);
if (y[body]+distance >= tree[pointer].ypos)
get_point(tree[pointer].left,3-axis);
}
if ((x[body]-distance < tree[pointer].xpos) &&
(x[body]+distance >= tree[pointer].xpos) &&
(y[body]-distance < tree[pointer].ypos) &&
(y[body]+distance >= tree[pointer].ypos))
{+ = 1;
list[number] = tree[pointer].id;
}
}
}

main()
{ *infile
FILE *outfile;
int itters, done, bodys, itter;
int nb, other, boundary;
int people[bodies], nbours[bodies], nbour[bodies][22];
double xvector[bodies], yvector[bodies], border[bodies][22];
double widest, displacement, closest, perimeter[bodies];
double xrepel, xattract, yattract, scale;
double dist, xd, yd, overlap, tradius, t_dist;
double atrdst, repdst, xttotal, yttotal;
/*intab,c4;*/
1. Pixrect.screen:*I

I* screen = pr_open("Idevlfb"); *I
infile = fopen("county.in","r+");
outfile = fopen("county.out","w+");

I* set number of iterations to do etc *I

itters = 100;
bodys = 65;
done = 0;

read in the data *I

t_dist = 0.0;
tradius = 0.0;
for (body = 1; body < bodies; body++)
{ fscanf(infile, "%s %1 %1 %1 %1",
&people[body], &x[body], &y[body], &nbours[body]);
perimeter[body] = 0.0;
for (nb = 1; nb <= nbours[body]; nb++)
{ fscanf(infile, "%1 %1", &(nbour[body][nb]), &boundary);
border[body][nb] = (float)boundary;
perimeter[body] += border[body][nb];
if (nbour[body][nb] > 0)
if (nbour[body][nb] < body)
f= (float)(x[body] - x[nbour[body][nb]]);
yd (float)(y[body] - y[nbour[body][nb]]);
t_dist += sqrt(xd*xd+yd*yd);
t_radius += sqrt(people[body]/pi) + sqrt(people[nbour[body][nb]]/pi);
}
}
}

```

```

scale = tdist / t_radius;
widest = 0.0;
for (body = 1; body < bodies; body++)
I= scale * sqrt(people[body]/pi);
if (radius[body] > widest) widest = radius[body];
xvector[body] = 0.0;
yvector[body] = 0.0;

printf("Scaling by %1f widest is %1f\n",scale,widest);

I. start the big loop creating the tree each iteration *I

for (itter = 1; itter <= itters; itter++)
{(body = 1; body < bodies; body++)
tree[body].id = 0;
end_pointer = 1;
for (body = 1; body < bodies; body++)
add_point(1,1);

displacement = 0.0;

I. loop of independent body movements *I

for (body = 1; body < bodies; body++)
ff "Italic" on)/* get <number> of neighbours within <distance> into
<list[]> */

number = 0;
distance = widest + radius[body];
get_point(1,1);

((body==1)
printf("body I number %i, distance %i, radius Vor,
number, distance, radius[body]);
/* initialize a few vectors *I

xrepel yrepel = 0.0;
xattract = yattract = 0.0;
closest = widest;

I* work out repelling force of overlapping neighbours *I
if (number > 0)
{(nb = 1; nb <= number; nb++)
{ - list[nb];
if (other != body)
{ = x[other]-x[body];
yd = y[other]-y[body];
dist = sqrt(xd * xd + yd * yd);
if (dist < closest)
closest = dist;
overlap = radius[body] + radius[other] - dist;
if (overlap > 0.0)
if (dist > 1.0)
xrepel = overlap.(x[other]-x[body])/dist;
yrepel = yrepel - overlap*(y[other]-y[body])/dist;
}
}
}

I. work on forces of attraction between neighbours. I
for (nb = 1; nb <= nbours[body]; nb++)
{ = nbour[body][nb];
if (other != 0)
1- (x[body]-x[other]);
yd = (y[body]-y[other]);
dist = sqrt(xd * xd + yd * yd);
overlap = dist - radius[body] - radius[other];
if (overlap > 0.0)
f-- overlap border[body][nb]/perimeter[body];
xattract = xattract + overlap*(x[other]-x[body])/dist;
yattract = yattract + overlap*(y[other]-y[body])/dist;
}
}
}

```

```

I* now work out the combined effect of attraction and repulsion */
atrdst = sqrt(xattract  xattract + yattract * yattract);
repdst sqrt(xrepel  xrepel + yrepel * yrepel);
if (repdst > closest)
|- closest * xrepel / (repdst + 1.0);
yrepel = closest * yrepel / (repdst + 1.0);
repdst = closest;

if (repdst > 0.0)
|. (1.0-ratio) * xrepel + ratio*(repdst.xattract/(atrdst + 1.0));
ytotal = (1.0-ratio) * yrepel + ratio*(repdst*yattract/(atrdst + 1.0));

else
Hatrdst > closest)
|= closest * xattract/(atrdst+1.0);
yattract = closest * yattract/(atrdst+1.0);

xtotal  xattract;
ytotal  yattract;
}
xvector[body] = friction * (xvector[body] + xtotal);
yvector[body] = friction * (yvector[body] + ytotal);
displacement += sqrt(xtotal * xtotal + ytotal * ytotal);

I* draw body as vector from old position to knew *I
I* a = x[body] * screen scale; *I
I* b = 900 - y[body] * screen scale; */
I* c = a + xvector[body] * screen scale; */
I* d = b - yvector[body] * screen scale; *I
I* pr_vector(screen,a,b,c,d,PIX SET.); *I

I* update the positions *I

for(body = 1; body < bodies; body++)
|+ xvector[body] + 0.5;
y[body] += yvector[body] + 0.5;

done += 1;
displacement = displacement / bodies;
if(done 5 10 == 1)
printf("displacement is %f after %i iterations\n", displacement, done);
}

I*writeouMMenewfile*I

pr close(screen); *I
printf("writing out the new file \n");
fprintf(outfile, "%i %i\n", itters, done);
fprintf(outfile, "%I %f\n", bodies, widest);
for (body = 1; body < bodies; body++)
{ fprintf(outfile, "%f %f %i %f %i %i %f
xvector[body], yvector[body], people[body],
radius[body], x[body], y[body],
nbours[body], perimeter(body));
for (nb = 1; nb <= nbours[body]; nb++)
fprintf(outfile, "%i %f ", nbours[body][nb], border[body][nb]);
fprintf(outfile, "\n");
}

```

county.in file:

```

FORMAT: County_number Count) name Population X-centre Y-centre Number_of neighbours [neighbour number common_boundary_lengthi ( repeated )

I Greater_London 6713130 530646 180164 6 0 148618 29 34509 22 69378 43 83111 26 51429 11 17013
2 Greater_Manchester 2595734 381581 400741 5 17 32804 13 70231 7 31232 3 23083 30 87689
3 Merseyside 1511787 339015 394127 4 30 59427 13 55439 0 118730 2 23083
South_Yorkshire 1303948 443348 396895 5 17 85158 37 38906 27 40466 7 62030 36 17918
5 Cyne_and_Wear 1142411 429743 563101 3 20 62292 35 55909 0 97794
6 West_Midlands 2648939 405864 289209 3 25 46985 44 108297 41 88499
7 West_Yorkshire 2037165 421638 427874 5 2 31323 30 25396 36 162115 17 7670 4 62030
8 Avon 915175 361271 171409 5 23 54855 0 90608 46 48745 40 81486 49 3000
9 Bedfordshire 507054 505909 237139 4 26 85322 11 70295 12 57550 34 31481
10 Berkshire 681226 474615 172533 5 46 35405 43 31658 11 58388 24 66342 38 88841
11 Buckinghamshire 567979 487054 209569 7 43 1859 26 70448 34 74279 9 70295 38 112569 1 17013 10 58388
12 Cambridgeshire 578734 536432 274664 7 22 43044 26 29718 9 57550 33 62165 42 97916 34 61149 32 63749
13 Cheshire 929926 361734 371864 7 47 67696 39 42278 41 52552 17 24010 0 104759 2 70231 3 55439
14 Cleveland 567958 450790 521126 3 36 68383 0 92003 20 45654
15 Cornwall 432101 194055 54710 2 18 108675 0 767985
16 Cumbria 487001 334553 516599 7 30 37974 36 52327 20 49797 0 374541 57 29957 55 16754 35 95547
17 Derbyshire 910173 432602 356845 7 41 136255 4 85158 13 24010 2 32804 31 43760 37 80979 7 7670
18 Devon 955785 275303 91475 4 40 125680 0 552750 19 20934 15 108675
19 Dorset 595088 384585 97956 5 40 99145 18 20934 0 263427 24 63117 46 39110
20 Durham 607198 423368 535198 6 36 93981 14 45654 5 62292 35 51555 0 18897 16 49797
21 East_Sussex 657195 555958 113316 4 45 75950 0 94980 29 97689 43 1699
22 Essex 1474126 575778 208817 6 0 628862 12 43044 42 85602 1 69378 26 74370 29 3000
23 Gloucestershire 501673 388500 214177 7 49 34240 25 149770 44 29033 38 50449 46 77831 8 54855 0 83336
24 Hampshire 1462823 455653 126512 6 46 106399 19 63117 45 40760 43 49497 10 66342 0 276397
25 Hereford_and_Worcester 631756 373175 253319 7 52 70989 49 53494 23 149770 39 103287 6 46985 44 62220 41 14054
26 Hertfordshire 956517 520207 211315 5 22 74370 1 51429 11 70448 9 85322 12 29718
27 Humberside 852076 504243 426295 5 32 134390 37 14711 0 287697 4 40466 36 148609
28 Isle_of_Wight 118553 451301 87419 1 0 148028
29 Kent 1467079 588986 154922 5 0 411148 1 34509 21 97689 43 20160 22 3000
30 Lancashire 1376519 358141 433330 6 3 59427 2 87689 0 241629 7 25396 36 84496 16 37974
31 Leicestershire 844825 460251 306874 6 44 49919 41 1970 34 91463 32 68489 37 66728 17 43760
32 Lincolnshire 550725 515753 355439 7 33 14614 12 63749 34 422 0 190436 27 134390 37 100738 31 68489
33 Norfolk 694547 607540 311810 4 0 200577 42 149752 12 62165 32 14614
34 Northamptonshire 528448 478714 268052 7 44 45044 11 74279 38 50377 9 31481 12 61149 31 91463 32 422
35 Northumberland 299457 408129 590413 5 20 51555 16 95547 0 182230 5 55909 55 126366
36 North_Yorkshire 666945 443847 470483 8 30 84496 7 162115 16 52327 14 68383 20 93981 27 148609 0 77411 4 17918
37 Nottinghamshire 985283 460917 352913 5 32 100738 31 66728 17 80979 27 14711 4 38906
38 Oxfordshire 519490 448334 206866 6 46 31890 23 50449 44 56252 11 112569 34 50377 10 88841
39 Shropshire 375715 354623 308197 5 47 67539 52 140163 41 109201 25 103287 13 42278
40 Somerset 427114 336534 132657 5 8 81486 46 39594 0 104236 18 125680 19 99145
41 Staffordshire 1015620 398472 326717 7 39 109201 25 14054 44 26597 6 88499 17 136255 31 1970 13 52552
42 Suffolk 598335 609135 260608 4 22 85602 33 149752 12 97916 0 235846
43 Surrey 1004332 509811 155549 8 21 1699 45 68334 1 83111 29 20160 0 5730 24 49497 10 31658 11 1859
44 Warwickshire 476315 430725 271563 2 23 29033 25 62220 31 49919 34 45044 6 108297 41 26597 38 56252
45 West_Sussex 661816 510603 116981 4 21 75950 43 68334 0 117542 24 40760
46 Wiltshire 518545 405161 160054 7 38 31890 10 35405 24 106399 23 77831 8 48745 40 39594 19 39110
47 Wlwyd 391056 318873 360868 5 50 95325 0 82558 13 67696 39 67539 52 32495
48 Wyfed 330157 235009 230139 4 54 42189 0 634587 52 139653 50 5903
49 Gwent 439875 330812 199867 7 53 9376 51 46369 52 41848 0 70696 25 53494 23 34240 8 3000
50 Gwynedd 230009 255292 357542 4 48 5903 0 575967 47 95325 52 71642
51 Mid_Glamorgan 538474 301922 193307 5 53 65730 0 26425 54 48719 52 34196 49 46369
52 Powys 110555 306394 267684 8 51 34196 54 22680 48 139653 50 71642 47 32495 39 140163 25 70989 49 41848
53 South_Glamorgan 384042 313052 174927 3 51 65730 49 9376 0 68672
54 West_Glamorgan 367554 270902 197300 4 51 48719 0 144666 52 22680 48 42189
55 Borders 99784 351522 634305 6 16 16754 35 126366 57 110088 61 130813 0 32627 62 55766
56 Central 273205 275510 692880 5 0 88525 58 22448 63 165739 62 160682 61 31734
57 Dumfries and Galloway 145101 279498 577341 4 16 29957 0 379520 55 110088 62 204077
58 Fife 326863 6261 7 700173 4 56 22448 0 179875 63 81139 61 7000
59 Grampian 471799 366265 824968 3 0 259579 60 140933 63 141641
60 Highland 199976 229501 848078 4 59 140933 63 115430 0 2988738 62 69662
61 Lothian 738372 324369 670289 5 56 31734 0 96647 55 130813 62 48205 58 7000
62 Strathclyde 2402956 241099 664546 7 56 160682 57 204077 60 69662 61 48205 0 2630274 63 31346 55 55766
63 Tayside 391845 320293 737483 6 56 165739 58 81139 59 141641 60 115430 0 97575 62 31346
64 Islands 78153 305402 933328 1 0 3481274
Note: area number 0 is the sea or external land

```

17, Bibliography

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