SCALES OF CYBERGEOGRAPHY

Michael F. Goodchild
National Center for Geographic Information and Analysis, and Department of Geography, University of California, Santa Barbara, CA 93104-4060, USA. Phone 805 893 8049, FAX 805 893 3146, email good@geog.ucsb.edu

Abstract

The transition to a digitally based information technology is having profound effects on the role and significance of spatial scale. Four variations are presented on this theme: the need for new metrics of scale that are appropriate for digital representations of geographic information; the implications of such metrics for the sharing of geographic information through the Internet; the emergence of new scales in the production of geographic information; and arguments for and against the disappearence of spatial structure, and thus scale, in the organization of human activities. The last variation is explored with specific attention to spatial structure in the storage of geographically referenced information.

INTRODUCTION

As other chapters in this book will have already made clear, the word *scale* has many meanings -- it is highly *overloaded*. Geographers are of course most interested in *spatial* scale, and less interested in scales of variation in time, or in other dimensions. In this chapter I explore the significance of scale in the context of what I term the *digital transition*, or the conspicuous take-up of digital technology in all aspects of society -- the workplace, the arts, entertainment, and education.

Much has been written in recent years about the digital transition (for discussions with a geographic focus see for example Dodge and Kitchin, 2001; Janelle and Hodge, 2000; Leinbach and Brunn, 2001). We read about the *new economy*, and associated ideas of trading in information rather than tangible goods; a shift from customary patterns of shopping to on-line electronic commerce; a growing disparity in wage rates between those who are able to contribute skills and those who are not; and even the now-discredited speculation that the new economy is somehow free from the traditional business cycle. The information age is said to make it possible for more people to work from home; is widely believed to be more environmentally responsible than the industrial age; and is often said to be conducive to a better-informed citizenry and a higher quality of political debate. On the other hand, many of these optimistic assertions may be false; and to date the new economy has clearly not been egalitarian, but rather has tended to exacerbate existing cleavages, between rich and poor communities, and between developed and under-developed countries. Despite vast increases in the flow of information, the growing digital divide remains one of the most discouraging aspects of the past decade.

The reasons for the digital transition are not hard to find. Although the term *digital* is preferred, the reference to fingers is clearly misplaced, because digital technology is based on a binary counting system, not a decimal one. Virtually all forms of human communication, with the obvious exception of direct communication by voice or gesture, now pass through a digital form at some point. Standard coding systems have emerged to support the representation of numbers, text, graphics and images, music, and even maps in digital form. Digital encoding is attractive because it can be accompanied by simple procedures that identify and remove errors; and because massive economies of scale can be obtained if a single technology can support the transmission of virtually any kind of information. For example, the devices that handle the packets of bits that travel through the Internet are in no way dependent on the specific meaning of the packets to their senders and receivers, since those meanings may range from pieces of music downloaded by high school students to encrypted, top-secret military communications -- both are simply strings of zeroes and ones. In this way the binary alphabet achieves far greater scale economies than were possible with earlier coding systems, such as the Morse code of the telegraph, which was never able to encode music efficiently.

The chapter is structured as a series of four variations on a common theme, the effects of the digital transition on scale. First, digital technology is providing new flexibility in the ways in which knowledge of the Earth's surface is represented. Scale is an important property of any representation, but the ways in which the property is measured are strongly affected by the digital transition. I explore these impacts, and propose measures that are more appropriate for digital representations. Second, the digital transition is enabling sharing of information to an unprecedented degree. Geographic information is voluminous, and I show that it can easily swamp communication networks. But arguments based on scale can be used to show that such concerns are largely unfounded. Third, the digital transition and associated developments in geographic information technology have greatly changed the economics of the production and dissemination of geographic information, which is in the process of being reorganized at novel scales. Finally, it is often argued that the digital transition is reducing or even removing the importance of space in human organization. If this is true, the importance of scale must also diminish. I explore the arguments for and against this proposition.

SCALE IN DIGITAL REPRESENTATIONS

Given the profound change represented by the digital transition, it is worth asking whether there are instances of concepts that fail to survive -- that were prominent in the earlier era, but are now losing their meaning and therefore their use. Before the recent growth of technology based on the binary alphabet, one of the primary means of communicating geographic information was the paper map. This is an instance of *analog* representation, since the world is represented not in a digital code, but as a proportional model. Analog representations are the basis of the Bell telephone (electrical signals proportional to changes of atmospheric pressure, now largely replaced with signals encoded in binary form), traditional photography, and many other communication media.

The constant of proportionality is an essential parameter of any analog representation, and in the case of paper maps (and many other analog representations) the term *scale* is used. *Representative fraction* is a more intuitively appropriate term, because it immediately suggests a ratio between the representative model and the real world. But a digital representation is not proportional, and the representative fraction is not meaningful for digital geographic databases -- there is no distance in the representation that can be compared to distance on the ground.

Goodchild and Proctor (1997) argue that the representative fraction has nevertheless persisted through the digital transition, because of its familiarity -- an instance of a more general pattern in which concepts associated with an earlier technology persist into a new era (the term *horseless carriage* is often cited, because it defines the new concept -- the automobile -- in terms of earlier ones). In order for this to be possible, a complex system of conventions has arisen that allows representative fractions to be assigned to databases that do not intuitively have them. The most obvious of these is the convention adopted for databases that originated as paper maps (and were transformed by digitizing). In this case the representative fraction (RF) of the digital version is by convention the RF of the source analog document. It is implicit in this convention that the act of digitizing does not significantly corrupt (or improve) the contents, through omissions or the introduction of positional errors, and thus in effect degrade the RF.

RF is a particularly successful scale parameter of paper maps, because it acts as an effective surrogate for many other properties. Mapping agencies have adopted practices that link the collection of features shown on maps to the RF (e.g., a U.S. topographic map at 1:24,000 shows major streets but not buildings), allowing the RF to act as a surrogate for content. RF also acts as a surrogate for positional accuracy, a relationship that is established through national map accuracy standards which link them directly. For example, the U.S. National Map Accuracy Standard (USGS, 1999) specifies that on maps with an RF of 1:20,000 or larger (more detailed) 90% of points should be within 1/30th inch of their true positions; for maps at coarser scales, the standard is 1/50th inch (e.g., for maps of 1:24,000 the standard corresponds to an error on the ground of 12.2 meters). Thus if positional accuracy is known for a digital database, it is possible by convention to specify an RF, and this convention is often used in the case of digital orthophotos (a positional accuracy of 6 m is linked via the national map accuracy standard to an RF of 1:12,000, because 6 m is the approximate specified accuracy for maps of that RF). But for digital databases there need not be any such precise relationship between positional accuracy, spatial resolution, and content.

RF fails to survive the digital transition except by convention, raising the question of how positional accuracy, spatial resolution, content, and other expressions of level of detail should be defined for digital databases. In the case of raster data sets, spatial resolution is readily defined by the cell size, since this is the minimum distance over which change is recorded. Define the linear measure of cell size (cell width) as S, an index that is useful for both analog and digital representations. Unfortunately vector representations do not provide a similarly rigorous way of defining S, and confuse this property of the representation with properties of the phenomenon (Figure 1). For example, consider an isotherm map used in climatology. Its spatial resolution is related to the spacing of weather stations at which atmospheric temperature is recorded, but there is no obvious way of determining *S* from such a map, either from the observed spatial variation in temperature, or from the spacing of weather stations. It may be preferable to treat *S* as varying spatially, with greater spatial detail in areas where weather stations are closer together. Urban mapping presents similar problems; for example, census tracts are designed to have roughly equal populations, and thus vary in size, being typically smallest in high-density urban cores. But it may also make sense that they are larger in suburban areas because spatial variation there is less rapid, and perhaps also because the attenuating effects of distance on social interactions are less -- in which case variable spatial resolution may have rigorous justification.

[Figure 1 about here]

Besides level of detail, the term *scale* is also used in the sense of extent, or scope. Define *L* as a linear dimension of extent, equal to the diameter of a circular project area, or the edge length of a square project area, or the square root of area for an oddly shaped area. A project covering the entire surface of the Earth has an *L* of approximately 23,600 km (square root of surface area), and the parameter is readily defined for topographic quadrangles, Landsat scenes, etc., whether the data are in analog or digital form.

Dimensionless constants are often useful in science, because their values are invariant under changes in units of measurement. Thus the Reynold's Number is one of a number of such dimensionless parameters widely used in hydrology. The ratio *L*/*S* is dimensionless, and equal to the ratio of two scales -- the *large* and *small* meanings of the term -- or the ratio of extent to resolution, both properties that unlike RF survive the digital transition.

Although *L*/*S* can in principle take any value greater than or equal to 1, in practice its range appears to be remarkably limited. The display screens of modern personal computers are typically in the *megapel*, or million-pixel range, a common configuration having 1024 columns and 780 rows, or an *L*/*S* ratio of order 10^3. Although some devices such as digital cameras have higher values, it appears that there is little pressure in the marketplace to increase this value -- that most people find the resolution of computer displays adequate for most purposes. There may be a physiological explanation for this, since the *L*/*S* ratio of the human eye (ratio of the spatial extent of the retina to the diameter of a retinal cell) is of order 10^4, and the computer screen is not expected to occupy the entire visual field. Thus any greater resolution would have little perceptual value. If we take the spatial resolution of a paper map to be defined by the width of a pen, or the size of the smallest symbol that can readily be discerned by the map user, then its *L*/*S* ratio is also of order 10^3. A Landsat scene has an *L*/*S* ratio of approximately 3,000, and other sources of imagery tile their products into similar multiples of picture elements. In summary, although both *L* and *S* vary over many orders of magnitude in geographic data (in the case of *L*, from the 20,000 km of a whole Earth to the 200 m of a detailed biogeographical study), the ratio *L*/*S* appears to be remarkably persistent in practice (Table 1). The reasons appear to be both technical and cognitive. On the technical side, and particularly for raster data sets, *L*/*S* is a predictor of data volume, which tends to rise as the square of the ratio, eventually swamping current technology. On the cognitive side, the relationship between *L*/*S* is related to the eye's sensory limitations and the processing abilities of the eye/brain.

[Table 1 about here]

It is interesting to speculate on whether similar patterns can be found in other forms of information. It is rare to find journal articles with lengths outside the range 5,000 to 10,000 words, and it is rare to find bound volumes with lengths outside the range 50 to 2,000 pages. But in neither case is there an obvious equivalent of resolution, and in both cases there are many reasons, some technical and some behavioral, for limits to extent.

SCALE IN THE SHARING OF GEOGRAPHIC INFORMATION

In this section I relate these arguments to the *scaling properties* of geographic information. The verb *to scale* is frequently used in discussions of information technology, and refers to the behavior of technology under changes in the volumes of information being processed. A technology is said to scale if its performance fails to degrade substantially when volume increases. I first examine the scale of textual information, since textual media still largely dominate scholarly communication, and then move to examine visual and geographic information.

Human speech achieves rates of transmission of order 10^5 characters or bytes per hour. A typical book contains order 10^6 characters or bytes, and a prolific academic might write order 10^8 bytes in a lifetime (easily stored on a removable diskette). An average reader processes order 10^5 bytes per hour, and perhaps order 10^9 bytes, or the contents of order 10^3 average books, in an average reading lifetime. A major research library of order 10^6 books contains order 10^{12} bytes of text information, or 1 terabyte. The fact that such a volume of information can now be stored on a device no larger than a piece of furniture, and accessed simultaneously and independently by thousands of readers, is one of the motivating forces behind current research into digital libraries (Arms, 2000).

Visual information is in general much more voluminous than textual information when represented in digital form, and the limited amount of visual information present in research libraries, in the form of images or maps, can easily overwhelm these estimates. A single Landsat scene contains order 10^8 bytes, depending on the degree of compression, while the replay of a DVD video requires display of order 10^9 bytes per hour. If we take video replay as a crude basis for estimating the processing capabilities of the human vision system, it appears that we process order 10^{13} bytes per year, or order 10^{15} bytes (one petabyte) in a lifetime.

Finally, consider geographic information. The EOS series of satellites is expected to provide order 10^{12} bytes per day of information. The Earth's surface has order 10^{15} sq m, so a complete coverage at this resolution with one byte per sq m would produce order

10^{15} bytes, before compression. A person viewing such data at a rate of 1 sq km per second, by filling a computer screen every second with 10^6 fresh picture elements, would take approximately a working lifetime to view the entire surface of the Earth.

It is interesting to compare these estimates with statistics for the Internet. The network includes order 10^7 servers, and order 10^8 users. Estimates of the total volume of information accessible via the Internet are notoriously unreliable, but generally exceed order 10^{15} bytes, of which only a fraction are catalogued by the Internet search engines. Bandwidths vary, but take 10^8 bytes/sec as the capacity of a "fat" pipe. Then if all Internet users required access to all information, order 10^{23} bytes would have to be transmitted, requiring order 10^{15} seconds through our fat pipe, or order 10^8 years. Clearly the Internet is capable of massive congestion.

But now recall the result of the previous section, that in practice the L/S ratios exhibited by geographic data sets fall into a fairly narrow range. Although in principle the exchange of such data could quickly swamp the Internet, in practice a user interested in studying the entire Earth's surface (L = 20,000 km) is unlikely to expect or demand a spatial resolution much finer than 20 km ($L/S=10^3$), and conversely a study requiring a spatial resolution of 1 m is unlikely to extend over much more than 1 km. Although volume rises as $(L/\mathrm{S})^2$, such users can be readily accommodated by the bandwidths and storage devices available in most research institutions.

SCALE IN THE PRODUCTION OF GEOGRAPHIC INFORMATION

Traditional methods for the production of geographic information in the form of maps have been highly capital-intensive, requiring the fielding of large teams of surveyors; the acquisition of photography from airborne cameras; massive photogrammetric equipment; and high-resolution color printing systems. Many countries, particularly those with large land areas, have regarded geographic information as a public good, produced by agencies of national governments, often under military control because of the strategic and tactical value of maps. Production of geographic information has thus been centralized at the national scale.

In recent years rapid advances in geographic information technology have led to vast and fundamental changes in the economics of production. These include the development of “soft” or computerized photogrammetry, which allows massive mechanical systems to be replaced by simple computer applications; and the Global Positioning System, which measures position on the Earth’s surface cheaply and directly, and to sufficient accuracy for many types of geographic information. Images from satellites are in many cases sufficiently detailed to replace costly aerial photography. Finally, the digital transition in geographic information has meant that investment in printing is no longer necessary, since the contents of maps can now be disseminated rapidly and essentially without cost.

These changes have greatly reduced the high fixed costs associated with centralized geographic information production, and effectively removed the need for massive economies of scale. Today, it is possible for a local agency, a small corporation, or even an individual farmer (Longley *et al.*, 2001; NRC, 1997) to collect, interpret, and analyze geographic information, and to do so at costs that are low enough to justify the necessary investment and expense. In effect, the production of geographic information has shifted from a centralized system organized at a national scale, to a dispersed network operating at a wide range of scales that correspond to the domains of interest of national, state, or local governments, corporations, or individuals.

THE DIGITAL TRANSITION AND THE BREAKDOWN OF SPATIAL ORGANIZATION

Geographers have long sought explanations for the patterns of spatial differentiation that are observed on the Earth's surface, and have developed theories that attribute them in part to the costs of overcoming separation. Transport costs, for example, are held to be major determinants of industrial location, and travel costs are similarly determinants of market location. Moreover the scales exhibited by human organization on the Earth's surface directly reflect such determinants. The *range* parameter of the central place theories of Christaller (1966) and Lösch (1954) is defined as the distance consumers are willing to travel to obtain a good, while the *threshold* parameter is defined as the number of consumers needed to support the offering of the good. Together, range and threshold define the spacing of settlements offering the good. If the marginal costs of overcoming separation are driven to zero, and with them a major factor explaining spatial differentiation, it is reasonable to ask what the effects might be on the scales of organization of the associated human activities.

The Internet achieves a close-to-zero marginal cost of distance not through the low costs of laying fiber, which are high, but through the enormous economies of scale that are possible because of the massive capacity of fiber links (some of the major backbone links in the U.S. network now have capacities of over 2 gigabits per second, equivalent to 2 million average email messages of 100 characters per second). In addition, there are few mechanisms for passing any marginal costs on to the consumer, and thus affecting consumer behavior, because the Internet has evolved as a service that is essentially free to its users -- few users pay the costs associated with sending packets, whatever the distance over which the packet is sent.

The breakdown of spatial organization that accompanies a decreased role of distance is easy to visualize. Consider a large array of picture elements, such as a remotely sensed scene. Select pairs of picture elements at random, without respect to location, and swap their contents. Spatial patterns begin to disappear, and after an appropriate number of swaps it is difficult to detect any residue of the original image (Figure 2). A screen filled with picture elements of random colors would be meaningless, and would be perceived by the eye as a uniform gray. In essence, much spatial organization results from connections between metrics of space, such as distance, and the behaviors of actors. When those connections are broken, a major cause of spatial organization is removed.

[Figure 2 about here]

Although the Internet reduces the marginal cost of transporting information to close to zero, nevertheless all human activities must be located somewhere, including the electronic bits that represent information. Transport of commodities other than information still incurs marginal costs, and thus continues to result in scale effects. Other activities such as mining and agriculture are tied to properties of places, and display spatial patterns and scales that derive from the spatial distributions of the underlying resources. But with respect to information, spatial metrics are now essentially irrelevant -- there are no longer real costs to the communicator associated with distance, no significant time delays, and no significant bandwidth constraints that are distance-related.

Consider a complex biological organism, such as the human body. Its central nervous system allows messages received by the brain to be associated with specific locations -- we sense where pain signals originate. On the other hand the immune system has functional rather than spatial organization; an infection in one place must be fought by dispatching large numbers of white blood cells throughout the system, only a small fraction of which will actually be needed to fight a localized infection. In the very early stages of fetal development cells are somehow capable of sensing their spatial locations as they differentiate, but these interactions extend only over a few cells, and an adult cell in the foot has no way of knowing or responding to its distance from a cell in the head.

Complex biological systems thus exhibit aspects both of *spatial* organization at different scales, and of *functional* organization. The Internet similarly exhibits aspects of spatial organization in the processes by which a packet is directed from a sender to a receiver. From the user's perspective, however, there is very little evidence of spatial organization at any scale. The earliest domains, such as .edu, differentiated on the basis of function. National domains are widely used outside the U.S. (and some U.S. state governments use both state and national domains, as in .nc.us), but a proposal to build a consistent geographically based system of addresses under a new .geo domain failed to be adopted by the Internet domain authority ICANN (International Corporation for the Assignment of Names and Numbers) in 2000 (see http://www.sri.com/news/releases/10-23-00.html). While earlier systems of communication such as the postal service and wired phone service have strong spatial organization (postal codes and telephone area codes are predominantly spatial), the Internet has clearly moved sharply in the direction of functional organization.

Arguments for a continued importance of spatial organization

Nevertheless, several arguments support the continued presence of a degree of spatial organization in the sharing of information on the Internet, and in related activities; and in turn support the persistence of scale effects in related activities. First, although the marginal cost of transporting information has been driven almost to zero, certain limitations remain that are significant in some circumstances. Cost is only one form of potentially distance-related impedance, and several others are important to users of the Internet. People further apart are more likely to speak different languages, and to experience related difficulties of communication. *Latency* measures the delays associated with transmitting packets between points, and although it is typically distance-related, most packets travel at close to the velocity of light. But latency is also related to the degree of congestion due to excessive traffic, which can be distance-related. Murnion and Healey (1998) have analyzed patterns of latency on a global basis, and shown weak correlations with distance that are in part due to the crossing of international boundaries. *Reliability* is also distance-related, since the potential for service interruption clearly increases with the distance separating the sender and receiver, and with the number of nationally based telecommunication networks encountered en route. Large web sites are sometimes *mirrored* at a very coarse, intercontinental scale, particularly when the user base is strongly multinational, because of specific bandwidth limitations. There have been periods, for example, when bandwidth between the U.S. and the U.K. was significantly impacted during certain hours of the day, notably when U.S. and U.K. working hours overlapped in the U.K. early afternoon. Such effects are capable of introducing coarse-scale differentiations of activities related to information exchange.

Although fiber-optic links achieve massive economies of scale between their endpoints, the Internet is far from uniformly accessible across space. The so-called "last mile" problem refers to the high cost of providing the low-volume links between high-volume endpoints and distributed business and residential customers, and their high marginal cost of distance. Wireless technology has the potential to reduce this marginal component, but remains largely unimplemented, with limited geographic coverage. Let $c(\boldsymbol{x})$ represent the cost of connecting to the Internet from location $\boldsymbol{x}$, a function that shows extreme local variability over short distances; neighboring houses on the same street can differ by as much as a factor of 1,000 in communication bandwidth. The fixed cost of two people at $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ connecting and communicating, $c(\boldsymbol{x}_1)+c(\boldsymbol{x}_2)$, is largely independent of the total distance between $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, but highly dependent on the local spatial variation of c. Intense local variation in access can lead in turn to intense local variation in activities that involve information exchange, such as the prevalence of telecommuting. Internet access retains a spatial organization, but of a particularly complex and fine-scaled kind.

Second, many patterns of Internet interaction reflect acquaintance networks that were established through physical contact, or require physical contact. For example, people who met in high school may continue their interaction by email. In a related example, Wheeler and O'Kelly (1998) have shown that Internet traffic from the Ohio State University servers is strongly distance-related at the scale of the state, because it is determined to some extent by the locations of students, most of whom are from the state and attend OSU in person. Telecommuting patterns will be strongly influenced by distance if workers are required to spend part of their time at the employer's site. In all of these examples the pattern of information flows is linked to a pattern of physical flows at regional scales that incur distance-related costs.

Finally, much Internet interaction is driven by activities that are tied to physical locations and impacted by transport costs. For example, locations of retail stores remain largely tied to local-scale residential distributions of consumers, and the information services that they require are similarly tied.

Storage of geographically referenced information

Many of these arguments can be exemplified by the case of geographically referenced information, or information that is associated with a particular *footprint* on the Earth's surface. Such information includes not only the contents of maps, but also reports, photographs, books, and even musical compositions associated with particular places. In this section I consider the question of where such information is likely to be found following the digital transition (see Goodchild, 1997, for a more detailed analysis of this problem).

Prior to the digital transition geographically referenced information was associated with specific physical media (bound volumes, map sheets, photographic film). Because the use of such media required physical access, it was necessary for each user either to acquire a copy, or to travel to a central facility such as a library. The scale of organization of libraries was dictated by the spatial distribution of users, and by the ranges and thresholds associated with the library's services.

In principle, the Internet allows a user located anywhere to access information stored anywhere, at costs that are unrelated to distance. Spatial organization in library services becomes a thing of the past, and it is no longer necessary for libraries to duplicate each others' contents. A user searching for a particular item of information might find it anywhere; and would have no way to predict where the information would be found, and no rational basis for deciding where to search.

However, geographically referenced information has properties that argue strongly for spatial rather than functional organization, and for persistence of scale as an organizing principle. First, interest in geographically referenced information is often related to distance: a street map of Paris tends to be of much more interest to a user located in Paris than to a user located in Los Angeles -- unless the latter is planning a trip to Paris, for example. Second, in discussions of national spatial data policy (e.g., NRC 1993) it is often argued that such information is best maintained locally, because of easy access to ground truth. Thus a street map of Paris is more likely to be up to date if produced and maintained by a Parisian agency, than if produced and maintained by an agency in Los Angeles. Third, in the previous section I argued that changes in the economics of data production have enabled cheap, rapid, and local production by much smaller groups and even by individuals.

These three arguments together suggest that after the digital transition geographically referenced information is most likely to be found physically located near the information's footprint; and that this process operates over scales comparable to the extent of the footprint (e.g., internationally for data sets with national footprints). For example, an analysis of the more than 1 million such information items in the Alexandria Digital Library, a major online collection of geographically referenced information, shows that the abundance of items declines globally with distance from the library's physical location at the University of California, Santa Barbara (Goodchild and Zhou, in press).

CONCLUDING COMMENTS

If distance is now irrelevant to many aspects of human organization (Cairncross, 1997), particularly those that are mediated by electronic communication, then the future human geography of the planet's surface will be vastly different. There are many technical and behavioral reasons to believe that distance will continue to be important to many human activities, as I argued in the third section of this chapter. However, the *parameters* of those distance effects will almost certainly be different, and consequently the scales associated with the organization of the associated activities will also be different.

The chapter has concentrated on scale in two distinct senses: as a measure associated with a representation, and as a parameter associated with a process. In principle the two senses are intimately linked, since it is impossible to understand a process by examining a representation unless the scale of the representation is at least as detailed as the scale of the process. For example, understanding the journey to work as a spatial process clearly requires much more detailed data than understanding international migration as a spatial process. But in practice the acquisition of data often proceeds somewhat independently of the investigation of process, and judgments often have to be made about the fitness of a data set for a particular use, based on metrics of scale. The first section of the chapter proposed metrics that are more appropriate for digital geographic information than the traditional representative fraction.

The dimensionless ratio of extent to resolution, or L/S, appears to be approximately invariant across a wide range of types of geographic information and forms of representation, for a combination of technical and cognitive reasons. This suggests practical constraints on the usefulness of large volumes of geographic information, and the possibility of design principles that can be used to anticipate data needs across a wide range of applications.

In the third and fourth sections of the chapter I explored the links between scale and process, with respect to activities that are impacted by the digital transition. The process of restructuring the production of geographic information is already well under way, and novel scales are already emerging. Library services are also being restructured, and offered at new scales. The specific example of geographically referenced information underscored the factors that appear likely to sustain a substantial degree of spatial organization in many human activities despite the pervasive digital transition. In short, distance is not disappearing as a basis for human organization; but the parameters that define its importance are changing, and new scales of organization are emerging as a consequence.

Acknowledgment

The Center for Spatially Integrated Social Science and the Alexandria Digital Library are supported by the U.S. National Science Foundation.

References

Arms W.Y. (2000) *Digital Libraries*. Cambridge, Mass.: MIT Press.

Cairncross, F. (1997) *The Death of Distance: How the Communications Revolution Will Change Our Lives*. Boston, Mass.: Harvard Business School Press.

Christaller, W. (1966) *Central Places in Southern Germany*. Translated by C.W. Baskin. Englewood Cliffs, NJ: Prentice Hall.

Dodge, M., and R. Kitchin (2001) *Mapping Cyberspace*. London: Routledge.

Goodchild, M.F. (1997) Towards a geography of geographic information in a digital world. *Computers, Environment and Urban Systems* 21(6): 377-391.

Goodchild, M.F., and J. Zhou (in press) Finding geographic information: collection-level metadata. *GeoInformatica*.

Goodchild, M.F., and J. Proctor (1997) Scale in a digital geographic world. *Geographical and Environmental Modelling* 1(1): 5-23.

Janelle, D.G., and D.C. Hodge, editors (2000) *Information, Place, and Cyberspace*. New York: Springer.

Leinbach, T.R., and S.D. Brunn (2001) *Worlds of E-Commerce*. New York: Wiley.

Longley, P.A., M.F. Goodchild, D.J. Maguire, and D.W. Rhind (2001) *Geographic Information Systems and Science*. New York: Wiley.

Lösch, A. (1954) *The Economics of Location*. Translated by W.H. Woglom. New Haven, Conn.: Yale University Press.

Murnion, S., and R.G. Healey (1998) Modeling distance decay effects in Web server information flows. *Geographical Analysis* 30(4): 285-303.

National Research Council (1993) *Toward a Coordinated Spatial Data Infrastructure for the Nation*. Washington, DC: National Academy Press.

National Research Council (1997) *The Future of Spatial Data and Society*. Washington, DC: National Academy Press.

U.S. Geological Survey (1999) *Map Accuracy Standards*. Fact Sheet FS-171-99. Washington, DC: U.S. Geological Survey (also http://mac.usgs.gov/mac/isb/pubs/factsheets/fs17199.html).

Wheeler, D., and M.E. O'Kelly (1998) A method for generating cyber trade areas: a case study of The Ohio State University. Presentation at 1998 Annual Meeting, East Lakes Division, Association of American Geographers (October 31).

Table 1: Comparison of the approximate extent and resolution of some instances of geographic information, and of the human visual system.

Example	**Extent (*L*) definition**	**Extent (*L*) estimate**	**Resolution (*S*) definition**	**Resolution (*S*) estimate**	***L*/*S* ratio**
Computer screen	Square root of screen area	250 mm	Square root of pixel area	0.25 mm	1000
Landsat Thematic Mapper scene	Square root of scene area	90 km	Square root of pixel area	30 m	3000
Paper map	Square root of map sheet area	1 m	Typical pen width	0.5 mm	2000
Human retina	Square root of retinal area	25 mm	Square root of retinal cell area	0.0025 mm	10000

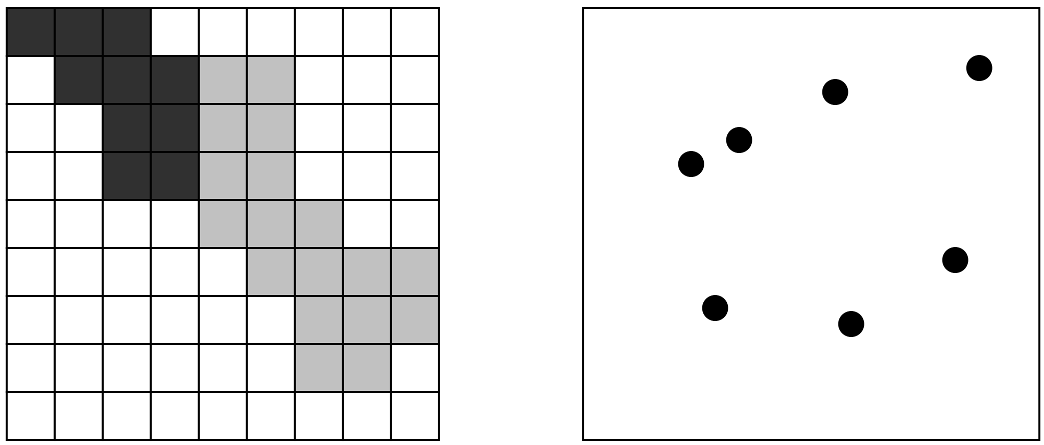

Figure 1: Spatial resolution (*S*) is well-defined for a raster data set (left) as the square root of cell area. But the irregular spacing of sample points in a vector data set (right) implies that spatial resolution is not uniform across the sampled area.

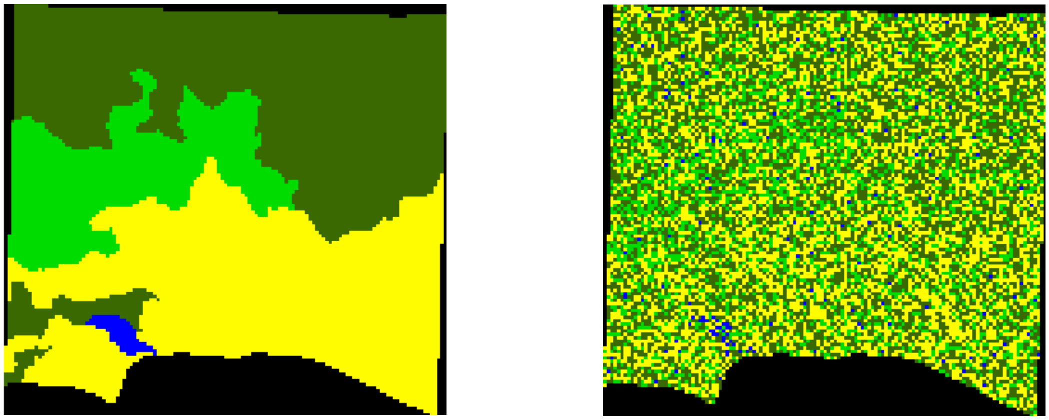

Figure 2: The spatial organization inherent in the left-hand image (classified land cover in part of Goleta, Calif.) can be destroyed by randomly swapping the contents of pairs of pixels (right).