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DIGITAL GEOGRAPHIC WORLD

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Abstract

The representative fraction, the metric traditionally used by cartographers to characterize the level of geographic detail in a map, is not well-defined for digital geographic data. Increasingly complex and unsatisfactory conventions are needed to preserve this legacy of earlier technology. A series of requirements is defined for replacement metrics. For digital representations of fields six cases can be identified, but in only two cases is there a straightforward solution to the requirements. For digital representations of discrete objects, representative fraction can be replaced with any ordinal index of specification. We conclude that simple metrics having dimensions of length are preferable to the complex conventions required to specify representative fraction for digital geographic data.

Introduction

In times of rapid technological change, it is frequently observed that the first uses of a new technology emulate those of an old one. An oft cited example is the first "horseless carriage", which simply replaced the motive power of the horse with that of the internal combustion engine, and left other aspects of the traditional mode of transportation largely unchanged, at least initially. It would have been very difficult at the time of the first horseless carriage to have anticipated the eventual form of the automobile, or the impacts that it has had on urban structure, land use, or human spatial behavior.

Recently, much attention and popular writing has been devoted to the long-term impacts of the very rapid advances being made in digital technology, particularly digital computing (Negroponte, 1995; Toffler and Toffler, 1995). Human society is in the midst of a transition to digital technology in all aspects of information transmission, storage, and use. Almost all information communicated between individuals, with the notable exception of communication by direct personal contact (but see

supported collaborative work; e.g., (Camp, 1995), now adopts a form of digital data in its existence. Some digital data is structured in highly formalized ways--tables of information in spreadsheets are one example, or vectorized maps--while other information uses very general forms of representation, such as those associated with facsimile transmission, digital encoding of voice phone communication, or remotely sensed images of Earth.

When the first digital computers appeared in the mid 20th Century they were designed as responses to well-defined needs, and the inadequacies of older technologies. The digital computer's powers of numerical calculation vastly exceeded those of mechanical calculators or analog devices like the slide rule, and were quickly applied to the massive computations needed by nuclear research. Similarly, the computer's abilities to process large amounts of information rapidly and to examine vast numbers of alternatives were of very substantial benefit to the cryptographic community. But in both cases the applications of the new technology reflected those of the old, or tried to solve its perceived problems and inadequacies, and it was not until many years after the advent of digital computers that new ideas began to emerge about their long-term significance. Ideas of graphic user interfaces, artificial intelligence, individual empowerment, electronic games, virtual realities--all of the ideas we now routinely associate with digital technology--would have been largely irrelevant and perhaps almost inconceivable to the developers of the 1950s.

Without embarking on a discussion of the varied meanings of the term, it is useful to think of these technological transitions as occurring in a social and institutional context which we will refer to as "culture". These examples illustrate the short-term role of technological change in serving the needs of an existing culture (for general discussions of the interactions between technology and culture see Hardison, 1989; Marx, 1988; Ross, 1991; Street, 1992; Volti, 1995). But in the longer term, technological change stimulates cultural change, as institutions, societal expectations, and a wide range of social activities adjust in response. In this model, it is implicit that cultural change occurs more slowly than technological change--the technology to support our modern patterns of land use was available long before those patterns emerged in response to changing cultural practices.

The term "legacy" has a useful meaning in this context; legacy ideas are those aspects that are inherited from previous technologies, and tend to guide how we think about new ones. In other words, legacies are embedded in the old culture, but persist in the short term as one technology is replaced by another. Legacies help us to adopt new technologies by giving

of old ones--for example, the laptop computer may be presented on the familiar electronic calculator. The electronic calculator's interface may not be optimal in any sense, but its familiarity allows the user to master the new technology quickly and to overlook its awkward aspects.

While legacy ideas have benefits, they also tend to constrain thinking, and impede the emergence of new ideas. Although the metaphor of the desktop and its graphic icons was defined by the Xerox Palo Alto research laboratories in the late 1960s, it was not until the Macintosh was announced by Apple in the mid 1980s that it reached widespread application, and not until Microsoft released Windows 95, or arguably Windows, that it achieved its current status as the dominant paradigm for interaction in the general computer user community. The appropriate balance between new ideas and legacies is an important question for the research community, as it tries to push the "cutting edge" of technology while at the same time ensuring that its results are useful enough to be widely adopted. In other words, there are good reasons why new technology should be embedded simultaneously in both the old and the new cultures.

Much of the information now being collected, manipulated, communicated, and stored using digital technology is geographic--we define geographic information here as collections of facts and other evidence about places on, above, and below the surface of the Earth. As with other information types, almost all geographic information now passes through one or more forms of digital representation at stages in its life, making use perhaps of digital remote sensing and image processing (e.g., Jensen, 1996), the Global Positioning System (GPS; Leick, 1995), geographic information systems (GIS; Maguire, Goodchild, and Rhind, 1991), and a range of alternative representation schemes or data models (Peuquet, 1984; Molenaar and de Hoop, 1994). We may choose to think of a geographic information system (GIS) as a container of maps, with a database that is built by digitizing maps, and outputs that frequently emulate the appearance of maps, because again these ideas and metaphors are familiar, and encourage adoption of the new technology by a wide base of users. But such legacies tend to constrain our ability to think about the long-term future of geographic information technologies, and their impacts on society's activities.

The impacts of the transition from older geographic information technologies such as manual cartography have been the subject of several studies and essays (Tomlinson and Petchenik, 1988). In this paper we examine one specific and important aspect of this legacy--the description of the level of geographic detail characteristic of a given geographic data set. We assume for the sake of argument that the level of detail is uniform for

...the interesting implications of
...corporate varying levels of detail (as
...the National Spatial Data
Infrastructure; NRC, 1995). "Scale" is the term most often used
to describe level of geographic detail, but we show that its
meaning is confused in a digital geographic world. Its primary
metric, the cartographer's "representative fraction", compares
distance on a map or image to the same distance on the ground--
but in a digital world, there is no equivalent of map distance,
and thus the measure is not defined. This failure of the most
commonly used metric of geographic detail as a legacy of earlier
technologies is our main motivation for this paper, and the need
to replace it with metrics that better survive the digital
transition.

In this paper, the "old culture" is that of manual
cartography, paper maps, and photographic images--the "new
culture" is that of digital geographic information technologies.
We show that in the old culture a tension existed between the
cartographer's view of geographic detail as representative
fraction, and that prevailing in the general scientific
community, but argue that in the new culture this tension is no
longer necessary, or founded on rational argument. We show
nevertheless that it has persisted as a legacy into the new
culture.

The next section of the paper expands on the importance of
the concept and its metaphors, and gives examples of its
applications. This is followed by an analysis of the term
"scale" and its surrogates and correlates, first in the
cartographic world, and then in science generally. We then
present a series of requirements for metrics of geographic
detail, and metaphors suitable for use in interacting with
digital databases, and examine various alternatives. Finally, we
present our suggested resolution.

Levels of Geographic Detail

Many geographic phenomena are almost infinitely complex, so any
attempt to capture their patterns in geographic information must
involve approximation. Even the 1:1 map demanded by Lewis
Carroll's imaginary emperor (Muehrcke and Muehrcke, 1992) would
have failed to satisfy the test of providing a complete
description of his domain. Thus most geographic information must
have an explicit or implicit level of geographic detail. By
limiting the level of detail of a data set, we ensure that
description is possible, at reasonable cost, and that the volume
of data gathered will be manageable.

The idea that the Earth's surface and near-surface revealed
more detail the closer one looked, apparently ad infinitum, was

prot (1982), who gathered together a
visions and ideas, and showed how they
broad umbrella of the concept of
fractals. While a true fractal has additional properties that
allow the rate at which additional detail is revealed to be
predicted, the concept is nevertheless useful in studying a wide
range of geographic phenomena (Xia and Clarke, 1997).

Cartographers and others have attempted to formalize the
reverse process--the loss of detail as one looks at the Earth's
surface less closely--through theories and methods of
generalization, convolution, and aggregation (Buttenfield and
McMaster, 1991; Müller, Lagrange, and Weibel, 1995). Clearly the
level of geographic detail in data affects the outcome of
analysis, in ways that may be hard to predict, and there is a
large literature on this issue, particularly in quantitative
geography (Openshaw, 1983).

A recurrent question in cartography concerns the degree to
which a generalization can be said to be accurate, or true
(Salgé, 1995). In one view, the task of the cartographer is to
represent the world at a specified level of geographic detail,
using models and specifications defined for that level. At
coarse levels of detail, for example, we may believe that a
village is truly described as a point, because it would be
perceived as such by a human observer looking at the Earth from a
long distance away. The specification of the entity "village"
would require us to define a procedure for locating the point,
perhaps at some geometric center of the village's area, or at the
location of its principal intersection. The opposing view is
that all generalization reflects a loss of information, and in
this case a degree of uncertainty about the true position of the
village, since the point might lie anywhere within the area
occupied by the village. One way to resolve the debate is to
define accuracy as the difference between the entity as
represented in the database and its specification, where the
latter is specific to a level of geographic detail. In this
view, all geographic entities, with a few exceptions, have
specifications that include a level of geographic detail. In the
example, there are two implicit and distinct specifications of
the village entity, one at a relatively fine level of geographic
detail as an area, and the other at a coarser level as a point,
and thus two different measures of accuracy. But the example
begs the question of what exactly one means by "level of
geographic detail".

Everyday language uses many metaphors for geographic detail.
The proximity of the eye is often used, as it was above in
phrases such as "look closer", since the amount of detail seen is
determined by the fixed density of cells in the retina and the
optics of the eye. Moving the eye further from the subject

graphic detail perceived by the observer, retina cells that receive information from the ground. If the metaphor is applied to the Earth, it suggests an observer flying above the surface, or located in a space vehicle; detail is revealed as the observer comes closer to the surface, and lost as he or she moves away. The metaphor is exploited in the user interface of Microsoft's Encarta Atlas (Microsoft Corp., Redmond, WA), where the level of geographic detail shown in displayed maps is reduced by moving a slider representing the observer's altitude. However, while the relationship between altitude and detail may be intuitively meaningful to many users, it is not precise enough to satisfy the demands of scientific research, which requires more objective and replicable methods.

Another metaphor readily related to geographic detail is the convex lens, the basis of the magnifying glass and other optical tools. Many graphical user interfaces for GIS identify the zooming function with a simple icon showing a caricature of a magnifying glass (e.g., ArcView, ESRI Inc., Redlands, CA). Others have gone further by exploiting the metaphor for any increase in detail--the "magic lens" can be used, for example, to expand the definition of a term to a full explanation, or to expand a person's name to a mailing address, biographical sketch, or photograph.

In traditional cartography, the level of geographic detail is most often specified by the representative fraction, or the ratio of distance on the map to distance on the ground, otherwise known as the scale, or the metric scale (for clarity, we will use the first term in this paper). We discuss the concept at length below, and have already pointed out that it fails to transfer meaningfully to digital geographic information. There are other problems also--representative fraction can never be exactly constant for any map of the Earth's surface, because of the projection of the curved surface onto a flat medium.

A final useful metaphor for level of geographic detail is suggested by the ability to identify objects of given size, and implied by phrases like "the whites of their eyes", or "so close you could see people on the ground". While we have no precise methods to relate the distance between observer and subject to the size of the smallest object visible (any relationship must depend on the quality of the observer's vision), we nevertheless establish conventional relationships between the representative fraction of a map and the entities shown.

In addition to these more abstract concepts, the contents of a paper map are also determined to some degree by more mundane, technological constraints embedded in the process of manual cartography. For example, the need to work with a pen, and the

On a map medium, make it difficult to show a feature whose size on the map would be a millimeter across (0.5mm is a commonly used estimate), although smaller features can of course be made visible by appropriate symbolization. By contrast, the size of the smallest detectable feature is explicitly identified in raster images through the pixel size, but only implicitly in photographs because of limits imposed by the grain of the emulsion.

The technology of manual cartography also makes it necessary to impose constraints on the amount of information that can be shown per unit area, independently of the actual density of features on the ground. Excessive "clutter" can easily make a paper map unreadable, while an excessive density of mapped features can lead to an impossible level of "overposting" of labels and other annotation. In the context of manual cartography, therefore, generalization must serve a dual purpose--to create a view of the world at a particular level of geographic detail, and also to satisfy the various constraints of the paper medium.

Level of geographic detail is clearly an important property of any geographic data set, whether digital or not. In the digital case, it is a major determinant of the volume of a data set, and thus of the time it will take to transmit the data set through a communication channel of a given bandwidth. It is a major determinant of the cost of collecting the data, since coarse detail can often be captured less expensively. It is also a determinant of the cost of processing the data; although it is often assumed that the costs of computing cycles have fallen to zero in recent years, there are nevertheless always practical constraints on the volume of information that can be processed. For example, Maidment (1996) identifies rules of thumb for determining the volumes of data that can reasonably be processed in environmental models. The costs of collecting and processing data with a given level of detail can be weighed against the benefits of detail--it might be assumed, for example, that benefits of decisions made using GIS are monotonically increasing with geographic detail.

One of our main motivations in writing this paper is to find ways to deal effectively with the specification of level of geographic detail in systems designed for managing heterogeneous collections of geographic data. We have now reached the point where vast amounts of digital geographic data are potentially available through technologies such as the World Wide Web, and there is great interest in finding effective techniques for locating or discovering data that meet a given requirement. The U.S. Federal Geographic Data Committee (FGDC) has established the National Geospatial Data Clearinghouse

) with the objective of facilitating sharing, and many similar efforts are in progress, the Alexandria Digital Library (<http://alexandria.sdc.ucsb.edu>); the Global Change Master Directory (<http://gcmd.gsfc.nasa.gov/>); and the ERIN environmental data catalog (<http://www.erin.gov.au/erin.html>]. The FGDC's Content Standard for Geospatial Metadata (<http://www.fgdc.gov/Metadata/metahome.html>) is an effort to codify the description of geographic data, and is being widely adopted for that purpose both inside and outside the U.S. Federal Government. Since level of geographic detail is a critical element in determining a data set's fitness for a given use, it is important that effective methods be found for its characterization.

"Scale" in cartography

We now turn to the term most commonly used by the general scientific community to refer to level of geographic detail, but which we have largely avoided to this point because of its inherent ambiguity. The term is used to refer to two distinct aspects of geographic information--the level of geographic detail, and the extent of geographic coverage. Thus a "large scale" can refer to the large geographic extent of the study; or to its level of geographic detail.

Unfortunately there are two distinct interpretations of scale as a description of level of detail. To a cartographer, scale is measured by representative fraction, and thus large scale implies a large representative fraction, and a fine level of detail. To the general scientific community, a large scale implies either a large extent of geographic coverage, or more commonly, a coarse level of geographic detail. Both concepts are important, the first particularly so in studies of processes and patterns that are not geographically stationary in the statistical sense, and thus where the results depend directly on the choice of study extent (Anselin, 1989).

If both extent and level of geographic detail are expressed numerically in linear measure (the large characteristic length of a geographic data set, and the small characteristic length, respectively), their ratio is a dimensionless number. We term this number the LOS (large over small) ratio. The technology of manual cartography limits the extent of a map to the largest sheet that can be conveniently drafted, copied, printed, shipped, or stored, and in practice to about 2m. Similarly, the level of geographic detail is constrained to about 0.5mm as noted earlier. Thus it is very difficult for any geographic data set whose preparation has involved a manual process, including manual digitizing, to have an LOS that exceeds about 10^4 . Similarly, a single Landsat scene has an LOS of the same order of magnitude,

dimension of its extent to the linear in the digital world, screen display about 10^3 for the area that can be simultaneously displayed. Although the effective LOS of digital data can be increased by combining geographically adjacent data sets, the volume of data that can be effectively handled is still limited, by storage devices and processing speeds, and here the square of LOS is an effective measure of the amount of data contained in a data set of given extent and level of geographic detail.

Representative fraction is the measure used by cartographers to characterize level of geographic detail, in part because it has so many correlates, and thus captures so many other dimensions of map-making; we review some of these correlates in this section. First, each mapping agency has established a series of conventions regarding the types of entities shown on maps of a given scale. For example, someone familiar with those conventions would know that individual parcels of land or buildings are typically not shown on maps at 1:25,000, but that some mapping agencies show field boundaries at this scale. At 1:250,000 the skilled map user would know that although major roads are shown, their actual widths on the ground are less than is implied by the width of their symbolizations on maps. These conventions are generally unknown to non-specialists, which creates a problem for systems designed for information discovery--some suitable method would have to be found, for example, to help an unskilled user to specify an appropriate level of geographic detail, in the form of a representative fraction, in searching for a map of buildings.

A second correlate of map scale concerns the degree of detail shown in the geometric form of an entity. At 1:25,000, for example, it is possible to show indentations in coastlines formed by such features as estuaries; but many of these features will disappear at 1:1,000,000. The wiggleness with which a coastline is mapped might be used to discover the original representative fraction of mapping in a data set known to have been derived from a paper map, but the test would be complicated by the nature of the feature itself--less cartographic smoothing is applied to a coastline that is inherently smooth than to one that is inherently wiggly.

For certain types of geographic data, a third correlate of representative fraction is the physical size of the smallest entity shown on the map. We have already identified 0.5mm as a rough estimate of the linear dimension of the smallest feature. This means, for example, that it is difficult to show a riparian zone on a map of vegetation cover at a metric scale of 1:50,000 if the zone's width is less than 25m; or to show a roughly circular area of less than 25m in diameter. In certain areas of

soils, or vegetation cover, it is a minimum mapping unit (MMU; see, for example, Weid, 1988) as the size on the ground of the smallest area one is willing to show on the map; all smaller areas are removed by some process of generalization. Thus we can establish a relationship between representative fraction and MMU--an MMU of 1ha implies a minimum representative fraction of about 1:100,000, since at smaller fractions an area of that size, assumed circular, would be too small to show under normal conditions of manual cartography.

Fourth, representative fraction is correlated with the positional accuracy of mapped features, defined as a measure of the differences between the positions of such features as shown on the map, and their true positions on the ground, or their positions in some source known to have higher accuracy. The U.S. National Map Accuracy Standard (<http://www.usgs.gov/fact-sheets/map-accuracy/map-accuracy.html>) establishes the 90th percentile of the distribution of such differences at approximately 0.5mm, and other mapping agencies have similar standards. Thus a map with a measured positional accuracy of 12m can be said to have an approximate representative fraction of 1:25,000.

Through these four correlates we have established four additional surrogate measures or indicators of representative fraction: classes of entities shown, geometric complexity of features, size of smallest feature, and positional accuracy. The existence and widespread recognition of these correlates among mapping experts led to a complex series of conventions in the old culture. For example, the "representative fraction" of an aerial photograph is established by the representative fraction on the camera's focal plane--but because the grain of the photographic emulsion is potentially high enough to support very substantial enlargement, representative fraction defined in this way clearly does not have the same significance for the sizes of features and other correlates as it does for paper maps.

While it is clearly desirable to have a single measure of level of geographic detail applicable to all forms of geographic data, the example of the aerial photograph demonstrates that use of representative fraction for this purpose created certain difficulties in the old culture of paper maps and aerial photographs. In the digital era, with its much wider range of forms of geographic data, that problem has become even more pronounced. How, for example, should one define representative fraction for a digital orthophoto quad (DOQ)? The entire production process of the DOQ is digital, from the use of airborne digital cameras to the automated correlation of stereo pairs. Nevertheless, by convention a DOQ produced by the U.S. Geological Survey is said to have a representative fraction of

sgs.gov/www/ti/DOQ/spec_accuracy.html).
representative fraction, positional
For DOQs, and 1:12,000 is the

representative fraction that corresponds, in the National Map Accuracy Standards, to the 6m positional accuracy of the DOQ product. On the other hand the quoted representative fraction will be misleading if it is assumed to correlate with the size of the smallest feature shown, since the 1m pixel size of a DOQ is equivalent to a paper map with a representative fraction closer to 1:2,000.

Ideally, the same principles would apply to the definition of level of geographic detail for all types of digital geographic information, allowing a user to specify requirements in simple, robust terms, and to compare the merits of one type of geographic information with another. In an interoperable world (Buehler and McKee, 1996), for example, the distinction between raster and vector representations should not matter, as long as both can deliver the same level of geographic detail. Although representative fraction served this purpose in the old culture of paper maps (problems of aerial photographs aside) it clearly fails to do so in the new culture of digital geographic information. The expedient of relying on complex conventions based on the different correlates of representative fraction that existed for paper maps is clearly problematic, since it limits understanding of level of geographic detail to those familiar with the conventions. Instead, we argue in this paper that a digital world requires a fresh perspective on the characterization of level of geographic detail.

Other meanings of "scale"

Several other commonly used metrics and correlates of level of geographic detail exist outside the realm of cartography. In geostatistics, the semivariogram is used to characterize the increase of expected variance with distance, by showing how the expected squared difference between observations of some variable measured on an interval or ratio scale increases with the distance between them (Isaaks and Srivastava, 1989). Many empirical semivariograms are observed to show a monotonic rise of variance to a plateau or sill at a characteristic distance known as the range. Thus the range may be interpreted as a characteristic length of the geographic distribution of the variable. Variables with a very short range display patterns with much local complexity--variables with a long range are comparatively smooth, and thus characteristic of a coarse level of geographic detail.

In the fractal literature, the level of geographic detail is characterized by the dimensions of the measuring device (Mandelbrot, 1982). If the length of a shoreline, for example,

measuring stick then the measurement
line level of geographic detail--longer
arser detail. Similarly, if the
shoreline is measured by rolling a ball along it and counting the
number of revolutions, then the diameter of the ball determines
the level of geographic detail detected. Another measurement
method uses square cells of varying sizes. There is extensive
literature on the degree to which such results are dependent only
on the linear dimension of the measuring device, and independent
of the method of measurement.

If geographic variation is represented in the spectral
domain by making a Fourier transform, then the spectral density
function provides a direct measurement of the amount of detail at
any wavelength or frequency. A low-pass filter, which removes
all variation at wavelengths shorter (frequencies higher) than a
defined threshold, provides a formal way of controlling level of
geographic detail, and of generalizing a geographic phenomenon by
removing its finer components. This approach can be used to
generalize and characterize digital topographic data, and these
techniques are widely used in image processing.

Level of geographic detail is readily defined for Earth
images as the ground size of each of the image's pixels. A more
problematic case occurs for geographic phenomena sampled at
irregularly spaced points such as weather stations or soil sample
pits. The mean area per sample point (obtained by dividing total
area by the number of points, and perhaps taking the square root
to create a linear measure) can be misleading if points are more
dense in some areas than others; the shortest distance between
sample points is also easy to criticize as a measure of level of
geographic detail.

For geoscientists, the most important meaning of "scale"
concerns the modeling of processes. An environmental or
geographic process is said to have a characteristic scale if its
successful modeling requires some known minimum level of
geographic detail. Physically, this may occur because the
process involves a convolution or averaging over a finite area,
as is the case for a foraging animal or the nutrient uptake of a
tree. In such cases it is difficult to predict the success of
the individual if the level of detail of the data is coarser than
that indicated by the linear dimension of the convolution. Other
processes possess characteristic scales because some geographic
variable is causally related to another, and thus inherits its
level of geographic detail.

This brief review is far from a complete analysis of the
literature of "scale", even in its narrow meaning of geographic
scale. The interested reader is referred to the many books and
articles on the subject. For the role of scale in environmental

anger and Field (1993); Foody and Curran
ee, and Risser (1988); Schneider
dchild (1997). Lam and Quattrochi
(1992) discuss alternative meanings of "scale" at various stages
in the collection, manipulation, and analysis of geographic data.
Finally, level of geographic detail appears in at least three
distinct ways in scientific research: in the scales implicit in
theories and models of process; in the scales at which reality is
sampled and observed; and in the scales used to represent
geographic variation. For the purposes of this paper, it is
sufficient to note that all of these interpretations of scale
focus on a more or less well-defined measure with linear
dimension, that has little connection with the representative
fraction discussed in the previous section.

Requirements

We now turn to the central objective of the paper, the
identification of metrics of level of geographic detail that are
useful, informative, and readily understood in a digital
geographic world. As noted previously, our main motivation is to
replace the representative fraction, which we see as a useful
legacy concept but one that raises a number of problems--the lack
of rigorous definition of representative fraction for digital
data, with the exception of data sets derived from maps by
digitizing; the reliance on conventions based on one or more of
its correlates; and the need for measures that are readily
understood by users wanting to assess the fitness of a given data
set for a particular use.

The previous paragraph identified several requirements of
suitable metrics, so we now formulate them in detail:

1. The metric should be well defined in both analog and digital
worlds, and invariant under the analog/digital transformation.
2. The metric should be meaningful across a range of digital
representations of geographic information (for example, raster
and vector), and as independent of them as possible.
3. The metric should be readily understood by a user lacking
knowledge of the conventions of any narrowly defined field.
4. The metric's value should be readily determined by analysis of
the data set, and largely invariant under a redefinition of the
data set's extent.
5. The behavior of the metric should be predictable under certain
well-defined methods of generalization.
6. The metric should be defined independently of other



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mic data that are well defined but not geographic detail, such as positional

A seventh candidate rule might be the requirement that the metric is comparatively stable--for example, in a statistical context we might require that the metric possesses such statistical properties as unbiasedness or consistency, under certain assumptions about the method of measurement and the statistical properties of the data. These issues will not be addressed in this paper.

Representative fraction clearly fails the first and second tests above. It arguably passes the third test for analog maps, although one might argue that many users of maps find other indicators of ground distance easier to understand than the representative fraction. For digital data, it is very difficult to predict or control the representative fraction of a screen display because of the wide variation in physical dimensions of display units, and the lack of access to them by software. For example, it would not be appropriate to quote representative fraction for a map being displayed simultaneously on a laptop and an overhead projector screen. In short, unlike traditional paper maps whose representative fraction is permanently fixed, the representative fraction of a digital display is transitory, easily changed by the interaction of the user, and an artifact of the display device. While it may be useful as a characteristic of a display, it is difficult to argue that it has a function as the primary indicator of a data set's level of geographic detail.

As an example of the fourth test, consider the case of a vegetation cover map represented as a set of polygonal areas. Calculation of the area of the smallest polygon could provide a measure of geographic detail, and thus a metric of geographic detail that is computable from the data. Measures of the geometric complexity of lines might also satisfy the requirement, though they are clearly also affected by the nature of the phenomenon represented--the curves of large rivers are naturally smoother than those of small rivers. The sixth requirement is intended to deal directly with the problem illustrated by the DOQ example above, where metrics of level of geographic detail and positional accuracy were confused by the connection between them established for paper maps by the National Map Accuracy Standards.

Evaluation of alternatives

To frame the discussion of alternative measures, we examine in turn each of the basic data models in use in GIS to represent geographic variation. While these are not a complete set of all possible methods of representation, they include all of those

to justify inclusion in multipurpose
ly missing from the list are
tral domain, created by the
discretization of the spectral power function, and widely used
for modeling the Earth's atmosphere in global climate models
(GCMs), and for digitizing one-dimensional sound. Also not
discussed here are models for representing variation over one-
dimensional networks embedded in two-dimensional spaces (for
example, the link-node and dynamic segmentation models widely
implemented in GIS), and models for three-dimensional or temporal
variation. However, we suggest that the methods used here could
be readily extended if necessary.

The data models are divided into two broad categories
(Goodchild, 1992). First, entity-based or object-based data
models represent geographic data sets conceived as collections of
discrete objects littering an otherwise empty space, and able to
overlap freely. Field-based models represent variation conceived
as spatially continuous, such that for every point in the plane
there is exactly one value of the field. Examples of field
models include representations of the elevation of terrain, or
point samples of a conceptually continuous field of atmospheric
temperature. Examples of object models include points
representing instances of a disease, or polygons representing
named areas.

The object models can be further divided into
representations of the three geometric primitives: points,
lines, and areas. The field models are instantiated by six
distinct representations (Figure 1):

1. regular tessellations into rectangular cells, with the variable averaged or totalled within each cell, or with the cell showing the dominant class in each cell, e.g., Earth imagery (Figure 1a);
2. rectangular arrays of sample points, e.g., digital elevation models (Figure 1b);
3. irregularly spaced sets of sample points, e.g., weather stations (Figure 1c);
4. digitized isolines, e.g., digitized contours from topographic maps (Figure 1d);
5. irregular tessellations into non-overlapping and space-exhausting polygons, with an average value or dominant class in each polygon, e.g., land cover or soil maps (Figure 1e);
6. tessellation using irregular, non-overlapping, space-exhausting triangles, with variation within each triangle described by a planar surface, e.g., the triangulated irregular network (TIN)

) .
are appropriate only for fields formed by variables measured on continuous scales, we discuss them all simultaneously in this paper.

Object models

For the object models, level of geographic detail is often implied by the choice of objects, and by their definitions. For example, the use of points to represent villages implies first that the level of geographic detail is sufficiently fine that individual villages can be discerned, and second that the level is not fine enough to identify the individual objects of which the village is composed--buildings, roads, or parcels of land. When a road is represented by a single line, there is an implication that the level of detail is not sufficient to identify the road as having width, and associated transverse variation of pavement quality, for example. In other words, level of geographic detail is embedded in the meaning or specification of each object--that is, its semantics.

In other cases level of geographic detail may determine the selection of objects within a class. For example, a data set may include as points all cities and towns of population greater than 5,000, and omit all smaller towns--inclusion of smaller towns would imply a finer level of geographic detail. Sometimes the topological dimension of the object may be indicative of level of geographic detail--a village represented as an irregular polygon implies finer geographic detail than the same village represented as a point.

For the object models, generalization processes coarsen the level of geographic detail in a number of ways, as the examples above suggest. A set of objects may be generalized by formal rules that: 1) reduce the topological dimension of each object; 2) select objects; 3) simplify the geometric form of objects; 4) aggregate objects into new objects (for a more detailed taxonomy see McMaster and Shea, 1992). Given knowledge of the rules and a reference data set of known level of geographic detail, it would in principle be possible to determine the level of geographic detail of a generalized version. But in such processes level of geographic detail serves only to instantiate the rules, which are then applied to the data. It follows that any index could serve as a measure, since the index need have no relationship to the data sets themselves. We could, for example, devise rules that implement a five-point scale of detail, from "very fine" through to "very coarse"; or use a scale that resembles the representative fraction, without the latter's geometric meaning. For display purposes the user could be allowed to specify the level of detail, and rules could be devised to change level of

the display is zoomed.

"c" may not be entirely appropriate in this case, such indices of geographic detail for object-based models satisfy all of the six requirements identified earlier, provided the associated rules are made explicit. In essence, they decouple the specification of level of geographic detail from the representations of the objects themselves. Research into formal methods of generalization (Müller, Lagrange, and Weibel, 1995) and the formalization of cartographic knowledge (Buttenfield and McMaster, 1991) may eventually provide objective and rigorously defined rules, but different formal rules will likely be needed for each class of objects. Until such formal rules can be developed a degree of subjectivity will always be present in relationships between abstract concepts of level of geographical detail and the representations of individual objects.

The complex generalization rules of an object-based data set create problems for the inexperienced user, whose intuition will be of little help in anticipating the effects of any specified level of geographic detail. The representative fraction defines these conventions for paper maps, but unless the digital user is familiar with this legacy we have argued above that any ordinal scale, such as "very coarse" to "very fine", will be as effective in distinguishing between them.

In the analog world, there is good reason to label the scale of geographic detail with the representative fractions of maps--when a map generalized for "1:25,000" is displayed at that metric scale, the rules ensure that the resulting display will be achievable within the constraints of manual cartographic technology, and not so cluttered as to be unreadable. In the digital world, we suggest that this coupling of level of geographic detail and the representative fraction of the display is no longer necessary--many of the technical constraints are no longer present, and the issue of cluttering is easily resolved in real time by zooming. For the object models, representative fraction provided a convenient scale of generalization in the analog world of paper maps. In the digital geographic world, there is no reason to privilege this scale above any other, given the previous discussion, and good reason to use other, simpler scales that are less rooted in legacy.

Field Models

While the object models are mired in the complexities of semantics and cartographic generalization, the field models are much more amenable to formalization. The following sections discuss each of the six field data models, and possible measures of level of geographic detail. The discussion is abbreviated

become repetitive.

any way of sample points, an appropriate metric that is invariant under the analog/digital transition is the spacing. For rectangular, as distinct from square arrays, two spacings are available, and detail is finer in one direction than the other. We suggest the use of the larger spacing, on the grounds that it is more conservative. We further suggest that this measure satisfies four of the other five requirements: it is readily understood by non-expert users, its behavior is readily predicted if points are resampled, it is distinct from positional accuracy, and it can be obtained through analysis of the data if the Earth locations of the sample points are known. However, it is representation-dependent and therefore not able to satisfy the second requirement.

Exactly similar arguments apply to the use of pixel size in the case of rectangular arrays of cells. For example, we argue that it is clear to the non-expert that an instrument with a pixel size of 1km cannot "see" the Earth's surface as clearly as one with a pixel size of 30m, and that there is a simple and readily understood relationship between pixel size and the ability to discern objects of different sizes.

For irregularly spaced points, level of geographic detail is determined by the locations of points, and is to some extent related to the rules used to determine their locations. If we assume that the variability of the phenomenon is geographically stationary, then we expect the greatest amount of detail to be lost in areas where the sample points are most widely spaced. Thus an appropriate conservative estimate of level of geographic detail can be based on the lowest sample point density. If the area of each point's Thiessen polygon is measured, and a linear measure obtained by taking the square root, then the largest value of this measure would provide a conservative metric of level of geographic detail.

However, a different situation arises if the sample points have been placed using some rule based on observed local complexity of pattern--if points are more dense in areas where there is observed to be the greatest variability. In such cases the previous metric is clearly too conservative, and the square root of the mean Thiessen polygon area, or even the square root of the smallest polygon area, might be used.

The requirement that the metric be readily understood by non-experts argues against metrics based on Thiessen polygon areas, and in favor of metrics based on the distance between each sample point and its nearest neighbor. The maximum value is again the most conservative metric, and the mean and minimum are arguably valid in appropriate cases.

s, metrics might be based on the boundary arcs, or on the minimum polygon area. The term *minimum mapping unit* (MMU) is often used in vegetation mapping to refer to an explicit rule of generalization--any polygon smaller in area than the MMU will have been merged with one of its neighbors--whereas the rules governing geometric detail in boundary arcs are not so easily expressed. We assume that the complexity of the phenomena mapped using these methods is such that the number of polygons mapped is a continuous, monotonic function of the MMU--otherwise, it will not be possible to observe the MMU by measuring observed polygon size. For example, this method would not work to characterize a cadastral data set for which the MMU area was less than that of the smallest parcel. The square root of MMU is a convenient linear metric. However, we assume here that the smallest polygon is roughly circular. If a polygon with area equal to the MMU is long and extended, then it clearly reveals detail at a level defined by its width, which will be much smaller than the square root of the MMU.

The case of triangulated irregular networks reduces to that of irregularly spaced points, since the network is defined by the set of triangle vertices. There appear not to be parallels to the case of irregular polygons, since there is normally no equivalent of the MMU in the construction of a TIN.

Finally, we discuss the case of digitized isolines. Here, the only possible metric of level of geographical detail that might satisfy the requirements listed above seems to be one based on the geometric complexity of the isolines, since the contouring of a complex surface would necessarily produce complex isolines. A level of geographic detail also establishes a minimum possible area for contour loops, but the occurrence of such a loop is also a function of the choice of contoured levels. Several metrics of the geometric complexity of a line have been suggested in the literature, and we propose that one of them be used. There are two counterarguments, however. First, it is difficult to argue that any of the methods for measuring geometric complexity are readily understood by the non-expert. Second, geometric complexity is clearly also a function of the ruggedness of the landscape. We conclude that the digitized isoline model causes the greatest problems for characterization of level of geographic detail.

Having discussed metrics of level of geographic detail for each of the commonly used GIS data models, we turn now to the question of metaphors for user interaction with digital geographic databases.

Metaphors

It is important that level of geographic detail is a viewing measure that are rigorously defined, replicable, and able to satisfy the requirements specified above. For purposes of user interaction, however, especially if the user is assumed to be unskilled or inexperienced, different criteria apply. Designers of user interfaces often resort to metaphor, or the use of analogy to concepts and processes believed to be familiar to the user, to overcome what might otherwise be problems of understanding and ease of use. It seems reasonable, therefore, to ask what metaphors are most appropriate to a user working with digital geographic data.

First, we might reasonably ask whether representative fraction provides an appropriate metaphor. In other words, is the parallel between digital geographic data and paper maps sufficiently robust, and the understanding of representative fraction sufficiently widespread, that it could be used as a metaphor in the digital world? The answer clearly must be "no"--there is no reason to suppose that a user encountering a digital geographic data set, or seeing one displayed on a computer screen, would understand the implications of a representative fraction, or be able to relate that concept to what is seen. While some users may be familiar with paper maps, and the conventions that link representative fraction to specification, there is no reason to suppose that an unskilled user has any clear association between representative fraction and level of geographic detail for a digital orthophoto quad, or a scanned aerial photograph.

Another metaphor already discussed is observer altitude. This seems reasonable, at least in an ordinal sense--the user of Encarta is able to understand that by manipulating a slider he or she is in effect positioning the eye further from the Earth, and reducing the level of geographic detail. The magnifying glass also seems to provide a valid metaphor, used in either of two senses: as a device for positioning a small viewing window over the display, on the understanding that its contents will then become the contents of the entire display; or in conjunction with a specified zoom factor, on the understanding that the area around the position of the cursor will become larger by that factor. However, while both of these metaphors are useful for the design of user interfaces for display, they seem not to work as ways of specifying generalization, unless they can be linked explicitly to the generalization rules discussed earlier. For example, we would need to establish a rule to determine exactly how much line detail should be lost, or which feature types, if the eye is raised by an additional 100km above the surface.

In addition, it seems not to be possible to use metaphor as

search or discovery. It is hard to find the Internet for data sets that are located 200km above the Earth's surface, unless rules can be established and widely adopted to link viewing altitude to generalization rules and the metrics of geographic detail discussed above. We conclude that these metaphors are useful as ordinal indicators in allowing a user to manipulate a display, but are not adequate for other purposes. Instead, it seems that information search and discovery must use some combination of the metrics discussed earlier.

Conclusion

We argued at the outset that the transition to a world in which the dominant forms of representation of geographic information are digital requires a systematic approach to the specification of a data set's level of geographic detail. Such an approach seems to have two components: definition of a set of metrics of geographic detail that are appropriate to a digital world, and identification of suitable metaphors for user interaction.

For the object-based data models of GIS, level of geographic detail is embedded in rules of generalization. But such rules are complex and rarely explicit. Thus it seems difficult to find suitable, well-defined metrics, and we conclude that any ordinal scale is appropriate, provided it forms the basis of the generalization and specification rules. There seems no reason to preserve representative fraction into the digital world, except as a legacy whose implications will be familiar to some users. However, the notion of extending representative fraction to cover other forms of data, including DOQs and aerial photographs, seems particularly inappropriate.

For the field-based data models, it is much easier to identify appropriate metrics, and we have identified suitable measures that satisfy the stated requirements in all cases except the digitized isoline data model. However, we have identified potential problems for several other data models that use irregular divisions of space. Nevertheless, all of the suggested metrics are measures with linear dimension, and thus fully compatible with the ways in which the general scientific community has traditionally defined scale. Thus the tension that existed in the old culture of paper maps, between cartographers who expressed scale as a dimensionless representative fraction, and scientists who defined level of geographic detail as a linear measure, and found its expression in a disagreement over what was "large", is resolved in the new culture. In the digital world, according to the arguments presented in this paper, measures of level of geographic detail should always have dimensions of length.

As a measure of geographic detail with extent, the ratio LOS is dimensionless. LOS varies only on the small linear dimension of geographic data in this paper, the large linear dimension of extent is also important, particularly when geographic phenomena are observed to have variances that grow with extent apparently without limit. We argue that LOS, and particularly its square, are useful measures of the volume of a geographic data set.

Because the recommended metrics vary depending on the particular field data model used, it will be necessary to allow for this in the design of metadata standards; for example, TIN representations and rasters require different metrics. Metrics should also take account of the processes used to create or transform the data; for example, if a Landsat scene with a 30m pixel size is aggregated to a vector representation with an MMU of 1ha, the appropriate metric of geographic detail is clearly 100m and not 30m.

We have identified several metaphors of geographic detail that may be useful in user interface design, particularly in the control of displays. However, we have been unable to find a close connection between such metaphors and appropriate metrics.

What is needed is a metaphor that links clearly with the idea of a linear measure. Perhaps aspects of texture provide the appropriate metaphor, as in "grain", or the range of the geostatistician. Perhaps also pixel size is sufficiently well-understood, and the idea of an image as a collection of discrete elements sufficiently linked to the idea of discrete cells in the retina. On the other hand, perhaps it is best to separate the two functions completely, despite their close relationship in the world of paper maps--in the new culture of a digital world, the concepts needed to specify level of geographic detail in searching for suitable data may be necessarily different from those needed to control graphic displays.

Finally, we have argued strongly that the transition to a digital world requires a reexamination of the concept of scale, and a new approach that moves away from the conventions and correlates of the world of paper maps. In the digital world, positional accuracy, level of geographic detail, and extent are all important and potentially independent properties of geographic data, and all have dimensions of length; while representative fraction is in many cases meaningless. If chosen appropriately, the standards and measures used in the digital world to assist in processes of search, browse, and assessment of fitness for use can be much more informative and precise than legacies inherited from earlier technology.

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Figure captions

1. The six digital representations of fields currently implemented
in geographic information systems (see text for
descriptions).