# FUNDAMENTAL PRINCIPLES OF GEOGRAPHIC INFORMATION SYSTEMS

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## ABSTRACT

The primary goals in GIS design to date have been focused on technical efficiency. The fundamental principles for an information system do not derive from pure laws of geometry or from computing theory, because they must reflect the basic goals of society. While social goals may seem nebulous, they can be described adequately for resolving some of the basic technical choices. Certain fundamentals can be determined by digging deeper into the reasons behind an information system. Important social functions lead to **mandates** that provide the impetus for **custodian** agencies. Even more fundamentally, geographic information systems should be developed on the primary principle that they will ensure a fairer treatment of all those affected by the use of the information (**equity**). Certain solutions, though efficient in their use of computing do not support the effective use of institutions or the equitable results of the analysis.

## WHAT IS A FUNDAMENTAL PRINCIPLE?

GIS has come of age. Over the past twenty years, those inside the community have marvelled each year at the expanding sophistication and power of our tools. Success and expansion are nice, but dangerous. Those who have built the tools know how fragile they are, and particularly how fragile our fundamental understanding. Some of the current success is achieved by exploiting the easy parts of the problems. The tough issues, temporarily swept under the rug, will reemerge, perhaps to discredit the whole process.

This article has a presumptuous title for anything of the length of a proceedings paper. However, as Director of this Symposium, I felt it important to discuss the fundamentals because they may be obscured if the papers concentrate exclusively on specific technical developments.

A number of recent symposia on research needs have emphasized the lack of fundamental theory for GIS and related fields (Smith, 1983; Onsrud and others, 1985). Each report calls for more theory, but without specific suggestions. The field of GIS involves some components, such as knowledge engineering or Geo-Positioning Satellites, that are emerging technologies in the joyful chaos of discovery. The field also involves some of the oldest sciences and professions, such as geometry and land surveying that trace origins back for millennia. It is hard to invent a geometric problem for modern computer displays which was not drawn with a stick on the

Athenian sand three thousand years ago. Any gaps in geometric theory were filled during the eighteenth and nineteenth centuries when a series of great geometers generalized the field far beyond the rudimentary needs of a GIS. This essay will attempt to provide a partial answer to the quest for basic theory for GIS, but the result may be different from the intentions of the above reports. This essay will not enumerate principles in the abstract, but will concentrate on those useful in illuminating the choices behind an overall data model.

AUTO-CARTO is about computers and what they are doing to alter the polyglot disciplines that address spatial information. The primary issues at this symposium are technical ones, since our technology is still far from complete. Technical development requires choices between competing alternatives, and many of these alternatives are completely unexplored in a field like ours. In early exploratory research it is fine to try out a hunch, but as the field matures there is a need to develop more formal and consistent principles to guide the selection. Also, as our technology finds its way into practical use, it must be accountable economically, but also politically, socially and even ethically. The principles developed in this paper are "fundamental" because they try to address the deep issues of why we collect and process geographic information.

To provide a focus for an essay constrained to the proceedings limits, I will focus on the principles that apply most directly to the "data structure" debate, perhaps better known as "raster versus vector". This paper is derived from a seventeen year excursion in automated mapping, but the principles that I now see as fundamental are not the ones that I have expounded at earlier AUTO-CARTOs. At the first two events I presented papers as a partisan of vectors (Chrisman, 1974; 1975). By 1977, I had decided that the argument between rasters and vectors involved such different concepts of space that the proponents could not share the frame of reference required for a true debate (Chrisman, 1978). At that point of development, the debate was thoroughly theoretical, since no complete system had yet been developed. Like many others, I put my energy into building a real system, hoping to resolve the issues by direct demonstration, not theoretical argument. Now that essentially complete systems exist, the debate should be reexamined.

## THE DATA STRUCTURE DILEMMA

Throughout the development of GIS, there has been a competition between data models – a sign of vigor, but also a sign of confusion. For the purposes of this paper, I need not be more specific than three basic alternative models: raster, CAD (originally Computer-Aided Design, but now a term of its own) and topological. The raster model prescribes the geometric elements as cells in an integer space. Epistemologically, this model ties back to the atomic theory of Democritus and the modern inheritors of that approach, such as Ernst Mach (1906). Using the simplicity of enumerating objects in the integer space, many measurements can be treated on a common reference. The raster approach has many proponents, but most of the arguments are based on technical considerations (Peuquet, 1979). The two "vector" models adopt a geometry

of continuous space (the model of Aristotle and his successors) to position points, lines and areas. The CAD model places the primitive objects into separate "layers", but does not introduce any further data structure. The topological model takes the same primitive objects, but places them into a network of relationships.

These data models were originally driven by technology. The reason for the grid cell was simplicity of programming, and the related raster pixel was determined by the simplicity of hardware designs for remote sensing. Similarly, the vector approach reduced complex graphics to tractable primitives. At one time, vector devices competed with the raster ones. On the hardware front, the technological gap has vanished. Virtually all "vector" devices use raster displays, including advanced page-description devices like the LaserWriter that printed this paper. In most cases, however, there is still a distinction between the raster and vector levels of implementation that highlights the continuing conceptual gap.

Because the roots of the "debate" are epistemological, there is no chance that the issue will vanish (Chrisman, 1978). There is a need to develop another path to describe the fundamentals of geographic information systems. This paper will attempt to produce these fundamentals from aspects of human society, then to demonstrate their lessons for the data model debate.

### Requirements Studies
There have been a variety of procedures used to justify a particular design for a GIS. Many systems are built as experiments in technology, then are promoted without consideration of alternatives. This deplorable phase has to be expected in the early development of any field. A useful theory of GIS would provide a guide to the appropriate data structure and other characteristics of a system from some more fundamental basis. At the moment, the most prevalent approach is a "user needs assessment" or "requirements study" which provides an approximation to system design through a social survey approach. Similar to a time-and-motion study in industrial engineering, an analyst assembles a description of what is currently done, tabulates the results, then formulates a system to replace the current process. In many respects, the current state of affairs is the appropriate basis for a decision, but it introduces certain limitations. On one extreme, it may simply automate chaos without understanding it or improving it. More typically, the promise of the analysis is a more "rational" system. It seems to be an item of faith that every organization must treat information as a "corporate" resource. The analysis is looking for duplicated effort and redundant information. Yet, these irrationalities all arose for quite specific reasons. Often these reasons relate to the differences between choices which are rational in the narrow framework of a given agency, but irrational from a more global perspective (Portner and Niemann, 1983). The reasons behind the "irrational" components of the *status quo* are likely to be potential causes of failure. Hence a *user needs analysis* has limits in doing too little (replicating a bad system) or doing too much (using system analysis to overrule institutional arrangements and foster political infighting). Another approach is required to develop a theory to cover the whole problem.

# THE CARTOGRAPHIC COMMUNICATION MODEL

One candidate for a theory is the cartographic communication model. This became a central tenet of academic cartography (Robinson and Pechenik, 1976) during the same period that GIS was developing. The communication model attempts to deal with the role of maps as visual communication with some elaboration of the general scheme presented by the diagram below.
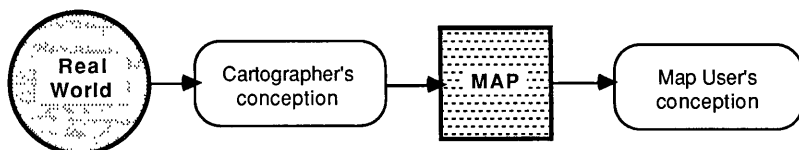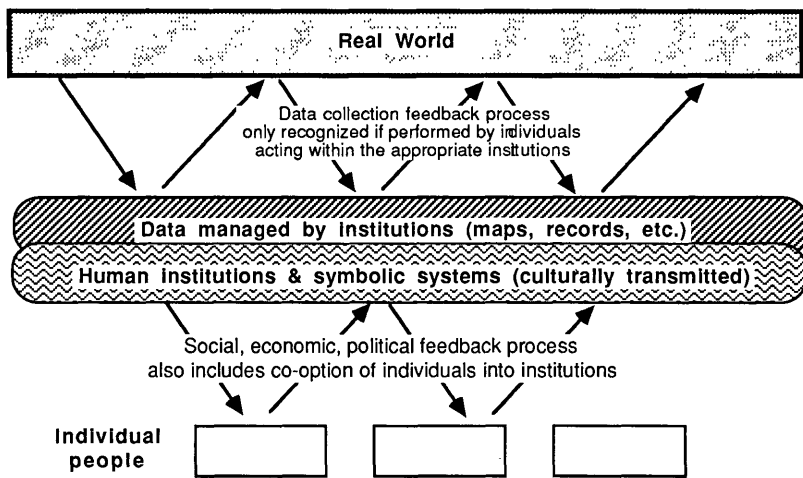


**Schematic outline of cartographic communication model**

This model provides a mechanism to understand the role of a master artist-cartographer, like Erwin Raisz, who created a whole style of maps to communicate his ideas about the landscape and the processes that formed it. Beyond this rare case, the model is less help. The basic communication model offers little help to understanding non-academic cartography, even those in its manual form. Few manual cartographers have design control over the series that they produce. Maps are defined by a system of conventions and standards that have developed over many centuries.

To understand the purpose of a modern geographic information system, the role of the map is an inadequate guide. The map product serves as a visual channel of communication, but it must be interpreted inside its frame of reference to impart meaning. Most communication models recognize the role of a frame of reference – a common system of symbols, values and interpretations. The system of these beliefs comprise the complex that is called **culture** by anthropologists. While the communication model places the individual person in the key role of sending or receiving messages, the cultural frame of reference exists without an explanation. From the anthropological point of view, culture exists and is transmitted through procedures of acculturation where individuals in a society learn roles, symbols and interpretations. In some cases, the culture is all-encompassing, but there can be substantial diversity in the package of beliefs that a particular individual receives. For example, the term *culture* might conjure up the idea of a simple society of hunter–gatherers with a unitary set of beliefs shared by all. The modern anthropologists would be the first to point out a less unitary reality even in the simplest societies. In our modern society, culture is fragmentary and subdivided. To apply the cultural perspective to spatial data handling, disciplines (geographers, cartographers, etc.) and guilds (lawyers, property surveyors, etc.) represent groups that maintain their identity over time. The individuals recruited into the group are trained to adopt the shared system of values. This explains, for example, how plat maps can be so uniform across the country without direct communication amongst the county agencies that do the work. The sense of what a plat map should

look like is transmitted through the discipline and persists no matter which person does the drafting. In short, the person has little control over the data content. The long-lasting and culturally transmitted structure of disciplines is more central than the issues of perception.

In the context of a GIS, the communication model must be modified to accept a cultural kind of transmission. The diagram below is an attempt to present the coherence of most processes over time.



**Real World**

Data collection feedback process
only recognized if performed by individuals
acting within the appropriate institutions

**Data managed by institutions (maps, records, etc.)**

**Human institutions & symbolic systems (culturally transmitted)**

Social, economic, political feedback process
also includes co-option of individuals into institutions

**Individual
people**

The diagram, though much more complex than the original communication model, does not portray the existence of many competing disciplines and institutions. These distinct units are unlikely to share the same goals and directions, leading essentially to a multidimensional diagram. It is important to refine the notion of culture as it applies to information systems, for example, Hardesty (1986) provides a useful overview of one aspect, cultural adaptation, for the geographic audience. However, for the purposes of this essay, a nuanced theory is not crucial.

It is important to understand the primary motivation for the collection and distribution of spatial information. The existence of a given guild or discipline in a society is not fore-ordained, despite the convention blather common in any social group that claims a central role for themselves in the universe. We can discount as cute or presumptuous a society whose name translates as "THE People", but we tend not to apply this filter to the statements of disciplinarians who claim GIS as their exclusive preserve (references deliberately excluded). There must be some larger motivation that can help clarify and adjudicate.

## TOWARDS ANOTHER MODEL

The first conclusion of the cultural argument is that geographic information is a human, social commodity. It is not strictly empirical and objective. This conclusion is dangerous. If taken too far, there is no consensus, and all opinions are equally valid. Fortunately, though each

human perception may vary, they are submerged in a cultural system which cannot permit such extremes of relativism. Social structures provide the basic framework of meaning for geographic information.

A set of fundamental principles cannot attempt to be universal. This essay applies most specifically to the polity of Wisconsin, but it applies fairly closely to other states of the US and the provinces of Canada. The general principles presented are transportable to societies that share the same European roots, with adjustment for divergences of legal, political or social systems. This argument will actually apply less to a corporate geographic information system (such as one maintained by a forest products company) than it will inside a socialist planned economy.

A second observation is that geographic information systems are not new at all. Some kind of system has functioned for centuries. The new technology offers many improvements of efficiency, speed and analytical accuity; I do not mimimize these advantages. The new technology disrupts many of the constraints that determine the structure of the old system, which makes it odd that *user needs assessment* is a common path for systems design. The current way of doing things is a useful guide, but perhaps it shows some features of a social and institutional nature often ignored in the systems design approach.

For example, the analysis of the existing system in a municipality will uncover terrific duplication of parcel base maps of varying vintages. The modern technologist, quite rightly, wants to sweep the slate clean and adopt the more rational "normalized" approach to data where only a single true copy is maintained. Technically, this approach is defensible and necessary. Unfortunately, most system design stops with the facts of data management, ignoring the reasons behind the duplication.

### Mandates
The important data collection functions of society are not carried out for technical reasons. The creation of property maps, zoning maps and all the other municipal functions are not driven by a benefit/cost ratio. Each record is collected and maintained in response to a social need as expressed in the legal and political system. The search should not be for the flow of data, but for the **mandates** that cause the flow. A mandate, which may be a law, an administrative rule, or even simply a customary practice, provides the definitions of the objects of interest along with the procedures for processing and implications for use of information. In place of the social survey approach, mandates provide a deeper view of why information is collected by certain actors. The legal library may be a better guide to what is intended. Of course, every society has some dissonance between the formal rules expressed in laws and the rules that actually govern conduct. In some societies this gap can seem large to an outsider (when the issue of bribery comes up). Still, the gap is a predictable part of a cultural system. In the case of North America, the rule of law is a very major cultural value, and consequently, the gap should be mimimized.

**A case of duplication.** There is a need to distinguish types of duplication using an example drawn from experience in Dane County, Wisconsin

(Sullivan and others, 1985). On the surface, there is a clear-cut case of duplication of parcel maps involving the County Surveyor and the Zoning Administrator. The zoning mandate does not include an authority over parcels, but parcels are depicted to show the zoning so that the citizens can interpret zoning relative to their holdings. Originally, the zoning maps were made by copying the parcel maps (quick and easy), but since then all changes to parcels have been drafted independently on the two copies. For some particular reason long forgotten, the zoning maps happen to be the only ones that record the tax identification numbers used to collect the county's main source of revenue. The Surveyor's parcel map attempts to portray both the locations described in textual information recorded by the Register of Deeds and the spatial units used in the official tax list. There is not a direct correspondence of these definitions, because they derive from independent mandates. The manual system attempts to handle both needs, but imperfectly. A system which merely removes the duplication between zoning and surveyor will miss the real problem of two groups with independent mandates to define ownership parcels.

Mandates, as formal rules, are implemented by people acting inside institutions. In addition to the external mandates, any institution develops its own internal rules. Some of these are disciplinary, because the people share a common basis of training and language. Sometimes professional ethics can override the mandate or divert its intention. For example, although the property records are maintained for the citizens, the banks effectively require the citizen to use a lawyer or title company to perform the work.

The people inside institutions are important to consider, particularly if a new technology threatens their system of values. As Stein Bie (1984) pointed out at AUTO-CARTO 6, we have to construct systems that serve more goals than simple technical efficiency. His point concerned the personal satisfaction of the workers, but it should be extended.

### Custodians
Mandates lead to institutions that carry them out. These institutions have a strong stake in self-preservation, which the agents of technical change might easily interpret (in a surprisingly self-centered point of view) as opposition to progress. There is another solution by recognizing that certain institutions, through their mandates, are **custodians** of their particular records. Instead of opposing progress, the modernized system could become their prime agenda. The modern system provides a much better mechanism for an agency to carry out its fundamental charge.

### EQUALITY AND EQUITY

Both the concepts of mandate and custodian were presented, in initial form, as part of the "Institutional Reasoning" for a GIS presented at AUTO-CARTO 7 (Chrisman and Niemann, 1985), but they were not tied to the underlying goals of society. That paper called for a balance between technical reasoning and institutional concerns in the design of data bases, as if the two were equal. Technical efficiency is measured most commonly as the ratio of benefits to costs. Some recent work (Bernhardsen and

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Tvietdal, 1986) claims remarkably high ratios, presumably with the idea of influencing public judgement. However, many potential projects have favorable ratios of benefits and costs. The actual decisions taken rely on other principles. There are many possibile principles that transcend technical efficiency, but the most important one to geographic information systems is a complex involving equality and equity.

Equality and equity derive from the same root, and may be easily confused. However, in social science usage, these terms have developed two usefully distinct meanings. Equality refers to rights and other concepts which are allocated to all citizens identically. By contrast, equity is used to refer to a less absolute sense of fairness. Social concerns for both equality and equity are fundamental. Each political philosophy essentially derives from a different operational definition of one or the other. A properly acculturated person will insist that their particular system follows obvious logic, while others are curious aberrations.

The American political system places great value on certain political rights, distributed with strict equality. However, the system of equality does not extend into economic matters very far at all (in contrast to socialist theories). The American capitalist system is founded on the principle that economic production depends on *inequality* to provide incentives to promote efficiency. Okun (1975) describes the unavoidable conflict in his monograph *Equality and Efficiency: The Big Tradeoff*. Okun characterizes many of the political battles in American life as quarrels over the distinction between the rights which are equally shared and the economic goods which are unequally distributed for reasons of efficiency. The barrier is never absolute. For example, no mattter what the theory of equal political importance, the rich can effectively buy greater access to decisionmakers. Also, society will not tolerate the pure capitalist markets that would leave some unfortunates literally to starve.

In the field of geographic information systems, certain activities require strict equality. Rights of access to information must be universal or they are too easy to abuse. However, the line between equality and efficiency is not as difficult as it is in the general economy. The less stringent issue of equity becomes quite crucial. It is through the concept of equity that society tries to deal with the unequal distribution fairly. As a simple example, a strictly equal tax (each citizen pays the same) is not equitable, since the citizens have different economic means. Throughout the country, one prime political issue about land is equity in property taxation. Hence, any information system that deals with property will not be judged simply on its technical performance, but on its contribution to equity.

From my experience with local governments, officials are cautious at first and quite concerned about public expenditure. The initial argument must be one of strict benefit/cost and economic efficiency. However, when the full analytical power of the automated system is available, the results are used to ensure fair treatment that could not be quantified as benefits.

# PRESCRIPTIONS

To carry out the principles presented above, these general rules apply:

Geographic information must be collected and managed by public agencies that have a long term stake in the process, not some *ad hoc* central group. The test of such an agency is the **mandate** that provides definitions, quality standards, and other characteristics.

An information system should be organized on a decentralized model that acknowledges the independent mandates of the contributing agencies. One approach is to declare a **custodian** agency for each element of the whole information system.

Finally, **equity** appears to be a more important goal than technical efficiency and benefit/cost ratios. Geographic information systems should be developed on the primary principle that they will ensure a fairer treatment of all those affected by the use of the information.

## IMPLICATIONS FOR DATA STRUCTURES

Technical alternatives for GIS should derive from these principles. Certain technical solutions, though efficient in their use of computing do not support the effective use of institutions or the equitable results of the analysis. The most crucial decision is the issue of a basic unit of analysis. Any system of arbitrary units, whether raster pixels, quadtrees, or map tiles, imposes a technical construct onto the objects defined by statutory mandate. Society does not define property in convenient regular rows and columns for easy programming. Similarly, natural processes do not limit themselves to mathematically neat descriptions. It may be possible for software to use these technical tricks at lower levels which are isolated from the user level, but the operations should not degrade the integrity of the definitions.

The bulk of definitions implied in mandates fit into the general vector model of points, lines and areas. Topology is a natural part of many systems such as common law, not the abstruse extra that the newly converted sales reps describe. The human eye/mind combination is so used to association by contiguity, that the uninformed cannot believe that the CAD computer knows nothing about adjacency.

Technical concerns may argue for monolithic, completely overlaid databases, of the form propounded as GEOGRAF (Chrisman, 1975) and now implemented for example as TIGRIS and TIGER. My argument for GEOGRAF was flawed because it centralizes definitions. It substitutes technical efficiency for the logic of mandates and displaces authority away from the custodian agencies to programmers much less aware of the requirements. The search for technical efficiency must not be allowed to overturn political choices without careful examination through the political process. The true challenge is to use the increased sophistication of our automated systems to promote equity and other social ends which will never fit into a benefit/cost reckoning. I am convinced that the future of geographic information systems will lie in placing our technical concerns in their proper place, as serious issues worthy of careful attention. These technical concerns must remain secondary to the social

goals that they serve.

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