Commentary: A Conceptual Framework for Integrating Remote Sensing, GIS, and Geography

The term "integrated geographic information system (IGIS)" has appeared increasingly to signify the technical integration of image processing and geographic information systems (GIS). In this essay I distinguish between the technical aspects of linking image processing with GIS, and the conceptual framework for linking remote sensing with geography and the rest of science. Technical accomplishments are an important part of the remote sensing community's contribution to science and technology. The conceptual framework is equally important because it governs the value of remote sensing to geography and the rest of science and because technical elements emulate conceptual elements. My purpose here is to suggest a conceptual context that makes explicit the contribution of remote sensing to science, consistent with the principal definitions of remote sensing documented by Fisher and Lindenberg (1989). My perspective is that of a geographer (Jensen *et al.*, 1989; Curran, 1987), a GIS specialist, and a remote sensing specialist in this order of allegiance. My intent is a synthesis, a reminder rather than a review, of some key concepts that were well established in the early part of this century, but are rarely prominent in remote sensing and GIS literature of today.

Inside the remote sensing community IGIS may be a useful technical concept to connote a bridge between familiar hardware/software systems and GIS. Outside this community, however, the term implies more than intended and reveals much about how remote sensing specialists view their field. At a minimum, the term indicates that they consider this particular integration to be special, somehow, in comparison to myriad other types of integration accomplished, ongoing, or anticipated in GIS. At a maximum, the term suggests limits on geography and GIS that are inconsistent with common definitions of both "geography" and "geographic." Clearly, the features addressed by remote sensing are an important part of the geography of the land and are of fundamental interest to geography as a discipline. Who would argue, for example, that land cover—a major focus of remote sensing—is not an integral part of geography? Even from a technical standpoint, GIS functionality has grown so relentlessly that it is difficult to say what functions are *not* implied by "GIS" alone. Indeed, most GIS developers would characterize the history of GIS as a constant challenge to integrate disparate hardware systems, disparate software systems, disparate databases, and disparate concepts of space—not one of which rated an "I" of its own.

Technical Integration

Much excellent work has been done on technical integration of image processing and GIS. Themes range from an early emphasis on raster/vector conversion to current exploration of data integration (Bolstad and Lillesand, 1992; Zhou, 1989), data access (Ehlers *et al.*, 1991), equipment (Faust *et al.*, 1991), standards, education/training, institutional issues (Lauer *et al.*, 1991), and error propagation (Lunetta *et al.*, 1991). Improvements in commercial software and the advent of the Global Positioning System (GPS) have accelerated the pace of progress in the 1990s.

Technically and conceptually, the linkage of remote sensing information with GIS and ultimately with environmental transport and process models remains a major challenge for the next plateau of GIS advancement (Price and Hodgson, 1993; Ehlers *et al.*, 1989). Most current literature focuses on applications that directly incorporate remote sensing information. Forest management, for example, benefits from inventories classified and measured directly from aerial photographs or satellite images (Archibald, 1987; Goodenough, 1986). Similarly, cartographic feature extraction, topographic mapping, automated digital elevation model (DEM) extraction, and planimetric facility mapping (Ehlers, 1990) derive valuable products only a generation or so removed from source imagery (Case, 1992). Davis *et al.* (1991) explicitly depict this principle as a conceptual diagram listing the steps leading to geographic databases that can be entered into environmental analysis. The diagram contains a box labeled "analysis models," but the box and its contents are not elaborated.

Lauer *et al.* (1991) suggest the need for a broader perspective of spatial data in decisionmaking processes. The National Center for Geographic Information and Analysis (NCGIA) is pursuing a broad research agenda on Integration of Remote Sensing and GIS Technologies (Initiative 12) (Star *et al.*, 1991). Simultaneously, NCGIA is developing a research agenda for integration of GIS and environmental modeling through two international conferences (Goodchild *et al.*, 1993). True integration of remote sensing into environmental and other types of analysis will require a scope covering both these NCGIA initiatives and more. Stoms *et al.* (1992) illustrate such a scope in their investigation of the sensitivity of habitat models to uncertainties in a remote sensing database. Smith *et al.* (1992) attest that derived remote sensing databases can be useful input to complex environmental analysis models, and Trotter (1991) examines their role in a GIS for natural resource management.

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Conceptual Integration

When I first heard "integrated geographic information system," my reaction was, "Redundant!" If geography doesn't mean "integrated," what does it mean? Many who approach remote sensing from geography and GIS have long felt the need for better integration and easier access to remote sensing information. Our wish list, however, includes a plethora of items, such as better statistics and modeling capabilities, that would help us link together a multitude of variables available from *in situ* as well as remote sensing sources. An extreme view has been that remote sensing information is just one database (or a few databases) among many in a GIS or database management system. My personal view is that remote sensing constitutes far more than a collection of databases, but much less than a linchpin of the integration we seek. My intent here is to explore the principal relationships among geography, remote sensing, and GIS and to speculate on their integral future.

Geography as Spatial Logic

To most geographers, integration is essential to the function and purpose of geography, but to non-geographers this fact may not be obvious. Many attempts to define geography have been made, and all have failed. No single definition has achieved a consensus among geographers, and no definition has truly imprinted the consciousness of the public or our peers in other sciences. Much of the argument among geographers has occurred because each existing definition captures a part of geography, but not the whole. A crucial need exists for a more comprehensive and comprehendible definition. There is no surer way to alienate geographic and nongeographic audiences, alike, than to discuss the definition of geography, so please bear with me as I offer the definition I favor, based on methodological literature modified by my own observations of what geographers say and do.

Geography is the pursuit of spatial logic, a form of reasoning in which morphology, landscape, spatial coincidence, spatial distribution, spatial association, and spatial relationships are considered to be primary evidence of both physical and cultural processes. As theory is developed, it must concur with temporal and process evidence as well, but the primary focus of most investigators tends to be on spatial evidence. With this definition, it is clear why GIS was named after geography. It is clear that integration is an essential element of GIS, especially when the evidence involves spatial relationships and when multiple physical and cultural processes are involved, and that geography, like mathematics or linguistics, is a part of practically everything we humans do from routine cognition in basic processes (e.g., finding our way across town) to complex analysis of comprehensive processes (e.g., global change).

Most realms of science today, however, are dominated by process logic, a form of reasoning in which each scientist and each discipline studies a selective set of physical or cultural processes, synthesizes general theory, and then tests for spatial and temporal consistency. With both definitions established, it is clear why other disciplines, accustomed to dividing science into topics defined by content, often view geography as unfocused. Yet, both spatial and process logic are necessary to solve complex Earth problems.

Geography as Landscape

To this point, I have been speaking of geography as a science, discipline, intellectual activity, or field of endeavor (i.e., study). Much confusion has derived from the fact that the same term is used to mean the features of the Earth (i.e., place). In both senses (study and place), geography has always suffered from a dearth of synonyms. Note how many times I have repeated the term in order to make my meaning clear. In the study sense, we often substitute "spatial," not very satisfying because spatial does not necessarily imply integration of multiple phenomena. A sculptor, for example, is thinking spatially, though probably not geographically, when working in only one medium. In the place sense, a term that comes close to the same meaning is "landscape." As far as I can determine from Hartshorne (1939) and my own observations of general usage in literature, landscape and geography (place) mean precisely the same thing except that landscape usually refers to a small area while geography can refer to any area-landscape, region, planet. Independent of area size, I would define both terms as the zone of interaction and convergence of the atmosphere, the hydrosphere, and the solid Earth. The vertical bounds are determined by the frequency and extent of interactions pertinent to a given field of inquiry. The biosphere, for example, is the portion of this zone (i.e., of landscape) of primary interest to disciplines focusing on living organisms. Horizontally, landscape may be divided into areal units defined on the basis of physical or cultural features pertinent to a field of inquiry. Physical geographers and ecologists, for example, may choose watersheds or physiographic provinces, while human geographers and sociologists may choose administrative boundaries. The implications of this definition will become more clear as we explore how to represent landscape with digital information technologies.

GIS as the Digital Representation of Landscape

The evolution of remote sensing and GIS bears a striking resemblance to the evolution of an earlier geographic movement toward understanding landscape, a focus of geography (Hartshorne, 1939), landscape architecture (Newton, 1971), and landscape ecology (Forman and Godron, 1986). Landscape formed a central theme in geography from the 1880s to the 1930s. During that time, landscape cognition underwent a gradual change from a simple focus on the visible Earth to a sophisticated concept of three-dimensional, functional landscape units with complex interactions of multiple phenomena in space and time with order. Both the English term "landscape" and the German term "Landschaft" evolved erratically through lively debates that led to an ever more inclusive and compatible concept. By 1930 landscape was comprehended and appreciated as an intellectual and philosophical concept more extensively than it is today, but implementation was impractical, often infeasible, with the information technologies of the day. Landscape's demise as a focus of geography and related disciplines followed, largely due to frustration over the difficulty of implementation. Paradoxically, information technologies have now developed to a state in which implementation of many landscape concepts is feasible, but the depth of landscape understanding attained in the early part of this century is not conspicuous in current remote sensing and GIS literature. It is time to revisit both movements—landscape and GIS—and merge them into a cohesive capability for comprehension *and* implementation.

The thesis here is that recent steps in the development of remote sensing and GIS replicate stages in the evolution of landscape cognition (Dobson 1992). I will present this evolution in ten steps that include the elements of landscape and the means of representation. From this review I hope (a) to illustrate how remote sensing, image processing, and other information technologies are connected with the intellectual core of geography; (b) to measure the progress of GIS development; and (c) to gain some insight into the future of GIS and remote sensing. The elements of landscape cognition are:

ELEMENT 1.
The Visible or Sensible Earth.
The earliest concepts of landscape focused entirely on the visible surface, the artist's oblique view of the Earth. This is, of course, the natural human view. For centuries, the primary means of representation was the landscape painting. Later, photographs gained dominance because of their cost, convenience, accuracy, and manipulability. Today, the visible surface might be described more comprehensively as the sensible Earth in recognition of greater sensing capabilities, including active systems such as radar. Heat and light beyond the visible spectrum and forces such as gravity and magnetism are routinely measured. Senses, other than sight, often influence human perception of landscapes, but are rarely communicated as part of the scientific description of landscapes. The sound, smell, feel, and taste (salt in sea air, for example) of a landscape are frequently observed though seldom measured and communicated.

ELEMENT 2.
The Orthogonal Perspective.
As a subject of scientific inquiry, the oblique view was entirely too limiting. Investigators chose an orthogonal perspective that gave a broader view of a continuous horizontal surface. Early in historic times it was possible to conceive of land in this manner, undoubtedly a major milestone in human achievement. Before aircraft, this perspective required considerable imagination, acceptance of a godlike omnipresence above the land, and a graphic transformation from the oblique to the orthogonal. Or maybe the earliest cartographers just stood on a hilltop and looked down! At any rate, this perspective has been a standard of cartography for millennia. Maps drawn in this manner have been employed so regularly in geography that many people, including some geographers, consider geography almost synonymous with the study of maps.

In the middle decades of this century aerial photography revolutionized the orthogonal perspective. In recent decades digital satellite images have gained acceptance, but they have not supplanted aerial photographs, even in many applications better suited to satellite image processing. It is interesting to note that, by the time satellites were developed, the original meaning of landscape had evolved so much that a new term, "land cover," was introduced to connote what landscape meant in 1880 (i.e., the visible surface).

ELEMENT 3.
Two-Dimensional Areal Differentiation.
Landscapes were spatially differentiated and divided into separate units. Hartshorne (1959) even defined geography as the science of areal differentiation. Differentiation of a two-dimensional surface can be accomplished through manual analysis of analog maps and aerial photographs or through digital analysis in cartographic or image processing systems. When only a single phenomenon (usually reflected light) is involved, there is minimal need for the full functionality of GIS. Geometry, topology, and attributes are essential, however, in the ensuing elements of landscape which involve supporting mechanisms and multiple phenomena.

ELEMENT 4.
Supporting Mechanisms, Cycles, and Processes.
Investigators recognized the importance of the supporting mechanisms, cycles, and processes that affect the visible Earth. Many indicators of these phenomena are hidden beneath the surface and many are inherently invisible. Many cannot be sensed remotely and require *in situ* monitoring, measuring, and sampling techniques that can be expensive compared to remote sensing of the sensible Earth (Jensen, 1983). Others, such as gravity and magnetism, can be sensed with special devices, and we have, in effect, extended our definition of the sensible Earth to include these phenomena.

The next logical question for early investigators was "How deep and how high do these phenomena extend?" This question could only be answered with a fuller understanding of the processes themselves. Investigators, thus, sought explanation through functional models of landscape processes, and the landscape unit, itself, was recognized as a functional entity. Early investigators employed analog models, such as terrain tables. Today, the primary means of representation and analysis is the quantitative process model. The charge that GIS is not "analytical" derives largely from the lack of such process models in state-of-the-art GIS systems.

ELEMENT 5.
Integration of Multiple Phenomena.
Because Earth processes rarely involve only a single element, there was a movement toward integration of multiple phenomena: climate, geology, soils, and vegetation, for example. Traditionally, much integration had been conducted intuitively in the human mind with only the results of the integration represented on a map. During the 1930s overlay maps emerged as a convenient aid to this procedure and as a lasting record of integrative analysis. Analog integration through overlay techniques is practical only with orthogonal data, though digital systems may someday facilitate overlay in a variety of four-dimensional perspectives.

An image processing system or computer aided design (CAD) system may be adequate for the single phenomenon case, but GIS has made its name on the integration of multiple phenomena. To date, most of the market for GIS has been in this niche, and from this niche GIS has earned its reputation for producing maps and inventories. Herein lies the strength and the weakness of GIS. The strength is that GIS offers the most powerful, available tool for integrating spatial *databases*. The weakness is that current GIS technology poorly addresses *interactions among phenomena*. For the most part, spatial analyses of processes and relationships rely on quantitative models that are not well integrated into the GIS framework and are not integrated with each other well enough to represent a functioning landscape. The terminology of the GIS community reflects this two-dimensional, functionally fragmented landscape in its frequent reference to data *layers*.

ELEMENT 6.
Culture.
Culture was first recognized for its importance in impacting the physical surface. Later, "cultural landscape" became a legitimate focus of investigation in its own right. The impact of culture on the Earth surface can be captured in aerial photographs and satellite images, but culture itself is invisible and cultural processes often occur in a decision space somewhat independent of Euclidean space. Again, we must rely on labor-intensive monitoring, measuring, and sampling techniques to obtain information which, at best, inadequately represents culture even after extensive modeling and interpretation. This suggests that there is even more reason to make the best of the information that has been so laboriously

captured and analyzed. GIS will be essential in this pursuit, but it has been underemployed to date. I often hear complaints that the GIS community is biased toward physical resources and away from social concerns. I suspect this is due to the fact that GIS, being costly, requires government and commercial funds which tend to be biased in this way. But there are signs that GIS cultural research is on the rise, especially now that the Topologically Integrated Geographic Encoding and Referencing (TIGER) files offer a key to connect census and other cultural data with cartographic base data.

ELEMENT 7.
The Third Dimension.
The action space of the processes affecting the visible surface demand that landscape models be spatially complete. Today, we still cannot adequately implement this concept because GIS is primarily two-dimensional. Although many commercial systems can generate a three-dimensional plot, no commercial system has three-dimensional geometry and topology so that disparate databases can be integrated in three dimensions as well as they are in two dimensions.

ELEMENT 8.
Temporal Change.
Investigators long ago recognized the importance of landscape change over time. We still cannot adequately represent the temporal dimension (Langran, 1992), because no GIS system currently handles chronology. We typically illustrate the effects of temporal change as vignettes (slices of time) for discrete intervals, but we need to show dynamic change over continuous time. The ultimate solution will be more than a clock, for it must handle change in space as well as change in time. Chronology will have to be treated much like topology; "before and after" taking on the same importance as "left and right" in two-dimensional space or "above and below" in three-dimensional space. The ultimate GIS also may incorporate revolving cycles within cycles, somewhat like the design of an Aztec calendar. Great cycles may represent geologic time; intermediate cycles may represent climatic trends, years, and seasons; small cycles may represent weather, tides, and satellite passes.

ELEMENT 9.
Spatial Interaction among Landscape Units.
Spatial interaction is a fundamental concept in geography. Current GIS systems are of some assistance in the study of spatial interaction, but much development is needed. Weakest performance can be expected in raster systems, non-topological vector systems, and systems without raster-vector integration. Network analysis, which concentrates entirely on spatial interaction, has been weak, but substantial progress is being made in specialized GIS products. Ultimately, transport models, including environmental transport by air and water, will be necessary to link process models with GIS functionality.

ELEMENT 10.
A Unified Landscape.
By 1930 many investigators conceived landscape as the amalgamation of all the preceding elements into three-dimensional, functional units with complex interactions of multiple phenomena in space and time with order. No hardware and software system can adequately represent such a concept today. GIS is woefully inadequate, but progress is being made in representing each of the individual elements.

Early definitions of GIS focused on GIS as a database management system for spatial information (Maguire, 1991). Later, as GIS functionality evolved beyond the role of organizing data, definitions included spatial analysis, modeling, and display. GIS functionality has continued to evolve as did the cognition of landscape in an earlier age. Today, a more accurate and enduring definition would be GIS as *the digital representation of the landscape of a place (a site, a region, a planet), structured to support analysis*. Certain key elements are embryonic in their development, but the development plans for leading GIS systems are conceptually consistent with the full landscape representation goals of the 1930s. With this definition, it is clear why remote sensing provides more than just a database, for the products truly represent a fundamental landscape element, the sensible Earth.

Early investigators insisted that a landscape was smaller than a region, but they were never able to define rigorously what the size limits should be. Conceptually, it is difficult to understand why there should be an upper or lower bound for either term. "Geography" (in the place sense) has been a covering term because it can be used in the same sense as "landscape" and "region" and has no size limit. It would be scientifically correct to define geography (study) as the study of geography (place) and GIS as the digital representation of geography (place), but such terminology would give the appearance of circular reasoning. Fortunately, modern usage has tended to remove the size limitation on landscape. This is a reasonable step today because much of the earlier logic for limiting landscape size was based on limitations of analog representation which no longer apply. It is now technically feasible to represent regional landscapes more comprehensively and with more detail than was formerly possible in representations of local landscapes. Current investigators can conceive of local landscapes grading to regional landscapes and even to global landscapes.

The ultimate GIS will represent three-dimensional functional landscape units with complex interactions of multiple phenomena in space and time with order. It will be a comprehensive representation of the real world and will provide the controls necessary to analyze significant portions of the real world. But now, to some extent, we are back where we were in 1930. We have a sophisticated concept, but the information technology of the day will not yet support full implementation.

Building a Better Macroscope

For more than a century, science has been dominated by the concept of the microscope. We have sought more and more detail about everything, and integration has suffered through neglect. Now with remote sensing and GIS, we have, for the first time in history, a rudimentary macroscope.

The remote sensing community is firmly committed to the goal of improving the "microscope." Ask remote sensing specialists what improvements are needed in the next generation of satellite sensors, for example, and the highest priorities invariably will include greater spatial and radiometric detail (i.e., finer resolution, more spectral bands). Examine any issue of a major remote sensing journal, and the majority of articles will discuss techniques for improving the categorical or spatial detail of land cover and other sensible landscape features. This development is essential and must continue, but I would urge a comparable, major thrust to improve the macroscope, as well. The macroscope will be as technically difficult as the former and will require a collaborative effort by some of the best people in remote sensing, GIS, and geography.

The macroscope must progress in two directions—larger areal coverage and better integration with the other elements of landscape. Areal coverage must extend to regional, national, and global. Databases, delivery systems, and processing capabilities all must support large-area analysis in a manner accessible to individual researchers. Integration makes a substantial leap forward whenever remote sensing data are incorporated into GIS, but true landscape integration will require major advancements in GIS and in our understanding of landscape. In particular, we must develop a new class of geographic models that incorporate the spatial analysis capabilities of GIS, the process analysis capabilities of traditional quantitative models, and the interconnectivity provided by transport models. I would call these "place models" to indicate that they characterize a place, no matter how large or small, and its landscape, unbounded by topic or discipline.

The challenge to develop a macroscope, composed of remote sensing and GIS, is an unspoken requirement of the grand challenge to monitor global change. In an ideal world, we would make tentative steps toward improving the macroscope. We would build simple models to connect the sensible Earth with the other elements of landscape and apply prototypes to larger and larger regions. The global challenge, however, drives us directly to the most difficult of all applications, an area of planetary size with landscape elements bounded only by political and scientific consensus as to which global issues are crucial to a sustainable future.

Place models will be computationally demanding, even in the simplest form for a small region. Clearly, the computational requirements of place models combining full landscape representation with macroscopic view (regional, national, global) far exceed the capacities of current hardware and software systems.

True Integration

Remote sensing characterizes the sensible Earth, and the image processing/GIS integration of today focuses on linking this element with other geographic databases. Remote sensing and GIS have made and will continue to make valuable contributions to science even without true integration, but they will not be understood by the rest of the scientific community until they are conceptually linked with transport and process models. Remote sensing and GIS will not be fully appreciated until technically linked with the models used in process-oriented science. The immediate technical requirement is to facilitate the exchange of raster image data and other GIS data (raster and vector) in order to access the functionality already available in GIS. True integration, however, will require (a) a revival of landscape concepts last prominent in the 1930s, (b) an enhanced macroscopic view, (c) development of place models unbounded by topic or discipline, and (d) massive computational capability. Until these objectives have been reached, integration will be a crucial goal, but "integrated" will be a poor label. Technical integration will remain an illusive target not likely to be achieved for decades. If true integration is ever achieved, the term "integrated" will still be conceptually redundant when combined with the terms geography or landscape.

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