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Object-Oriented Representation of Environmental Phenomena: Is Everything Best Represented as an Object?

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A geographic space must be partitioned into a finite number of discrete pieces, such as points, lines, polygons, and grid cells, to accommodate the finite computing environment. Because these discrete geometric primitives can be implemented as software objects, the object-oriented computing paradigm might have encouraged the tendency to "objectify" spatial phenomena, regardless of whether they are best represented as objects. A critical review is necessary to assess whether object-orientation, a concept first developed outside geography, is suitable for spatial representation. This article reviews object-oriented spatial representation in the context of environmental modeling. The review is organized into four topics: (1) the principles underlying object-orientation, (2) the categorization of environmental phenomena, (3) GIS data models and their object-oriented implementation, and (4) the compatibility between these three sets of concepts. The discussion argues that spatial objects, regions, and fields represent three categories of phenomena that are well represented, reasonably represented, and not well represented by the objects, respectively. *Key Words: environmental modeling, object-orientation, spatial representation.*

The concept of object-orientation was first introduced into the geographic information systems (GIS) community in the late 1980s (Egenhofer and Frank 1987), and since that time has appeared frequently in the literature (e.g., Worboys 1994; Westervelt and Hopkins 1999), textbooks (e.g., Lo and Yeung 2002; Clarke 2003), and software packages (e.g., Zeiler 2001; Burke 2003). The adoption of the object-oriented approach in GIS reflects the influence of the rapid development of information technology in the 1990s. Since the beginning of this era, object-orientation has been the computing paradigm and software industry standard (Nierstrasz 1986; Khoshafian and Abnous 1990; Wegner 1990; Kim 1991; Rumbaugh, Blaha, and Premerlani 1991; Cook and Daniels 1994; Worboys 1994). Because of the common use of GIS in geography and other disciplines, the object-oriented approach has become familiar, though to varying degrees for different researchers.

Because the computing environment is finite and discrete, a geographic space must be partitioned into a finite number of discrete pieces before the space can be represented in a computer (Egenhofer and Herring 1991; Worboys 1994; Raper and Livingstone 1995). Geometric primitives, such as polygons, lines, and points in the vector data model, and cells in the raster data model, are examples of these pieces. The spatial partition is due to the discrete nature of computer representation and is independent of the object-oriented paradigm. Because these discrete geometric primitives can be implemented as software objects, the object-oriented paradigm might have encouraged the tendency noted by Couclelis (1992) to "objectify" spatial phenomena, regardless of whether they are best represented as objects.

The concept of object-orientation originates in computer science. A review is necessary to assess whether a computing concept first developed outside geography, which has subsequently been adopted by the discipline, is suitable for the representation of spatial phenomena. This article reviews object-oriented spatial representation in the context of environmental modeling and focuses on whether all spatial phenomena are best represented as objects. For the purposes of this discussion, environmental models are loosely defined. They include those that describe physical processes through mathematical expressions, those that predict environmental outcomes through statistical probabilities, and those that evaluate environmental suitability through knowledge-based weighting scores. These models address a broad range of issues relevant to the environment surrounding humans. The primary reason for focusing on environmental modeling is that it deals with a rich set of phenomena that are spatially distributed and temporally dynamic.

The review is organized into four topics: (1) the principles underlying object-orientation, (2) the cat-

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egorization of environmental phenomena, (3) GIS data models and their object-oriented implementation, and (4) the compatibility between these three sets of concepts. For the first topic, the basic principles of object-orientation are first reviewed; then the distinction between object-orientation as a means of representation and as a programming technique is discussed. For the second topic, criteria to identify spatial objects are discussed. Using these criteria, three categories of spatial phenomena, spatial objects, spatial regions, and fields, are identified. For the third topic, GIS data models and their object-oriented implementations are discussed for spatial objects, regions, and fields. For the last topic, the object-orientation principles and software object models are evaluated for their compatibility in representing spatial objects, regions, and fields.

First, however, it should be noted that the word "object(s)" carries two connotations in this article. When used directly, it refers to those types of environmental phenomena that are perceived as objects in an ontological sense. Ontology is a branch of philosophy that considers "the existence of things in the world. Specifically, it studies the generic traits of every mode of being and becoming, as well as the peculiar features of the major genera of existence" (Bunge 1977). Because the discussion focuses on spatial representation, these ontological objects are referred to as "spatial objects." For its second connotation, the word "object(s)" refers to objects in the context of object-oriented computing. These objects are referred to as "software objects." In addition, this article uses the term "GIS" in the more traditional sense to mean "geographic information systems" in order to distinguish it from "geographic information science."

Object-Orientation

Basic Concepts

The computer science literature has long argued that object-orientation is not meant to be a mere programming technique. Rather, it is intended to be "a representation, modeling, and abstraction formalism"; thus "the object-oriented paradigm is not only useful but also fundamental" (Wegner 1990). The fundamental intention of the object-oriented paradigm is to represent human perceptions of the world. The rise of object-orientation represents a change in computing philosophy, away from a computer-oriented view (how to implement a solution), and toward a knowledge-oriented view (how to represent the perceived world; see Wand 1989). The significance of object-orientation thus lies in its conceptual models, rather than being merely another useful programming technique (Wand 1989; Khoshafian and Abnous 1990; Wegner 1990).

Object-oriented representation involves three levels of abstraction: (1) object-oriented analysis (OOA), (2) object-oriented design (OOD), and (3) object-oriented programming (OOP); see Abadi and Cardelli (1996). OOA is the *conceptual model* of the world and its purpose is to establish facts and relationships about a situation. OOD develops a *formal model* of objects and events according to the conceptual model developed at the OOA level. All aspects of the objects and events are defined at this level for the subsequent implementation of the formal model. OOP deals with the *implementation model* of the objects and events defined at the OOD level. Cook and Daniels (1994) referred to a similar division of abstraction as essential, specification, and implementation models. Rumbaugh, Blaha, and Premerlani (1991) used a slightly different nomenclature with the terms object, dynamic, and functional models. Cook and Daniels (1994) explained that the difference between the three levels of abstraction reflects three distinct viewpoints as that of (1) an observer of the world, (2) a software specifier, and (3) a software implementer.

These views, though in the context of object-orientation, are consistent with the multiple levels of abstraction for spatial representation. These include the conceptualization, function, and implementation levels defined by Peuquet (1988); scientific, logical, and physical models by Worboys (1994); and geographic, spatial data, and data structure models by Kemp (1997). The review presented in this article focuses on the analysis level, the level closest to human perceptions and most removed from software implementation concerns. At this level, objects in the software are expected to have a counterpart in the perceived world. The remaining discussion continues to use conceptual, formal, and implementation models to refer to the three abstraction levels, respectively.

In order to discuss the suitability of object-orientation for spatial representation, the basic principles are reviewed briefly below. Full descriptions of these principles are available in numerous texts. The review presented here is summarized primarily from Wand (1989), Kim (1991), Egenhofer and Frank (1992), and Worboys (1994). The review focuses on two basic principles of object-orientation, among many others, namely encapsulation and composition. Researchers have pointed out that some of the basic principles of object-orientation are conceptual, and others are concerned with implementation issues. Encapsulation and composition tend to be considered as conceptual principles by most researchers

(Wand 1989; Silvert 1993; Cook and Daniels 1994; Worboys 1994).

The basic concept of encapsulation is that the world is composed of objects. Each of these objects has an identity, properties, and behavior encapsulated within the object. The unique properties allow objects to be distinguished from one another. The properties of objects are represented by attributes, the values of which describe the state of objects. The behavior of an object is represented by methods. Objects act on, or they are acted upon by, other objects. Methods can change the state of an object and this change of state is referred to as an event.

As encapsulation describes what an object is, the principles of composition describe how objects are related to each other through several relationships. These include inheritance, aggregation, and association. All objects belong to object classes, and all classes are organized into a class hierarchy. A subclass is a *kind of* its own superclass, from which a subclass inherits all attributes and methods, and may have additional attributes and methods in its own right. Besides the inheritance relationship, an object may belong to an aggregate object as a *part of* the aggregated whole. An object can also belong to an association object as a *member of* the associated set. An object can simultaneously maintain all these relationships with other objects (Kim 1991; Egenhofer and Frank 1992).

A Means of Representation versus a Programming Technique

The distinction between *conceptual* and *implementation* considerations is important. Implementation concerns should be independent of conceptual models because the implementation may change according to the computing environment (Egenhofer and Herring 1991; Worboys 1994; Raper and Livingstone 1995; Abadi and Cardelli 1996). Object-orientation requires a clear framework before the implementation can begin. Technically, everything can be implemented as a software object. Further, attributes and methods can be considered objects in an implementation and, thus, each in turn can have its own attributes and methods (Wand 1989). These situations can easily cause confusion if the development is not guided by a clear framework. The conceptual models of object-orientation can lead to implementation advantages. For example, the principle of inheritance leads to the reusability of software components (Nierstrasz 1986; Meyer 1987; Wand 1989), which has been one of the most lauded implementation advantages of the object-oriented approach. The implementation advantages should apply to object-oriented programming in general, but the conceptual advantages of object-orientation may not be as widely applicable.

Definition of Objects

In contrast to a rather clear set of principles, object-orientation lacks a clear definition of objects (Leung, Kwong, and He 1999). This may be because object-orientation has been intended to be a generic model for all disciplines, and the definition of objects is left to the discretion of researchers in a particular discipline. This tendency is reflected in several aspects in the practical use of the object-oriented approach. First, objects in object-orientation can represent an almost unlimited range of phenomena. Second and consequently, the definitions for properties, behavior, and relationships of objects seem to be open to various interpretations. Finally, there is no specification whether the properties, behavior, and relationships may be used individually or in combination to define an object. In practice, it seems that anything can be programmed as a software object, as long as it can be assigned either an identity, attributes, or methods, or can be put into a hierarchy. Such an open definition may leave room for error, especially a mismatch between the software objects and perceived spatial phenomena.

One definition of objects that has seen widespread acceptance is that objects are discrete (Wand 1989; Egenhofer and Frank 1992). In environmental investigations, a great number of spatial phenomena are perceived as having a continuous nature. A continuous phenomenon can be divided indefinitely without changing its essential nature, however, a discrete phenomenon most likely cannot be divided without altering its nature. For example, the water in a bucket may be continually halved and yet remain water, but half a bucket is no longer a bucket (Bell 1999). The contradiction between a discrete definition of objects and the perceived continuous world may affect the applicability of the object-oriented approach in spatial representation. To take full advantage of this approach, it is paramount to understand the conceptual model of various spatial phenomena.

Identification of Spatial Objects

Criteria

In spatial studies, certain phenomena are easily perceived as objects. The identification of objects has been discussed in contrast with the identification of fields as two opposing conceptualizations of space (Goodchild 1992). The object-field dichotomy has offered a profound framework to examine the representation of spatial phenomena. However, as Couclelis (1992) has pointed out, these two concepts are not exclusive. A phenomenon can be conceptualized as either an object or a field depending on several considerations, such as the spatial scale of an observation, the purpose of an investigation, and convention (Couclelis 1992). The two conceptualizations can coexist as well (Cova and Goodchild 2002). The characteristics of spatial objects and fields have been actively discussed in the geographic information science literature (Couclelis 1992; Goodchild 1992; Worboys 1995; Burrough and Frank 1996; Peuquet, Smith, and Brogaad 1999; Bian 2000; Yuan 2001; Cova and Goodchild 2002; Peuquet 2002; Galton 2004; Mcintosh and Yuan 2005). This section reviews the criteria that have been used to identify spatial objects. Using these criteria, the types of spatial phenomena of environmental considerations, such as spatial objects, spatial regions, and fields, are discussed prior to evaluating whether object-oriented representation is appropriate for them.

A spatial object possesses certain properties. The following discussion synthesizes five such properties discussed in the literature that have been associated with spatial objects and object-like spatial regions. These five criteria include spatial scale, boundary, attributes, process, and mobility.

Spatial scale is one of the most widely used criteria in the categorization of spatial phenomena. Using this criterion, Zubin (1989) proposed four types of spatial phenomena that have been further elaborated on by Couclelis (1992), Montello (1993), and Frank (1996). This categorization uses the human body as the reference scale and human experience as the basis of the categorization process. The first type of spatial phenomena includes everyday objects that are smaller than the human body and can be moved or manipulated. The second type is an extension of the small objects into large-scale space and includes phenomena that are perceived as objects, but are larger than the human body. The third type of spatial phenomena refers to things in large-scale space, such as landscapes, that cannot be experienced completely all at once. These phenomena are perceived as fields. The fourth type is an extension of fields and refers to large-scale things that are beyond the range of direct human experience. The spatial scale criterion corresponds well with those environmental phenomena that can be easily perceived as objects (e.g., animals) and those that cannot (e.g., an energy continuum).

Another important criterion used to identify spatial objects and regions is the existence of *boundary*. From an ontological perspective, boundaries are as essential as the internal content to the ontological makeup of a spatial object. Boundary is a concept inseparable from that of spatial objects (Smith and Mark 1998; Montello 2003). Small-space objects (i.e., the first type in Zubin's category) tend to have well-defined boundaries and can be readily manipulated. Couclelis (1992) and Frank (1996) believe that this concept is often translated into large-scale space. Objects in the large-scale space include those that are well-bounded, such as a building, and those that are not so well bounded, but are perceived as objects. For the latter, a region is extracted from continuous space by arbitrarily assigned boundaries. These boundaries create the perception that these regions are objects that can be manipulated, as if they were small-scale objects. In the following discussion, the small-space objects and the well-bounded large-space objects are referred to as spatial objects, and the regions extracted from continuous space are referred to as spatial regions.

Smith and Mark (1998) have categorized boundaries into two types according to their origin. These are boundaries that correspond to genuine discontinuities in the world (bona fide) and those that do not exist physically, but are projected onto space as a reflection of human intention or cognition (fiat). This categorization of boundaries presents a seminal approach to the identification of spatial objects and spatial regions in an environment. In the physical environment, boundaries for both small-space objects (e.g., animals) and well-bounded large-space objects (e.g., a lake) can be directly observed and, therefore, correspond well to the bona fide definition. The most typical of the fiat type is the administrative boundary that can be precisely placed but is physically nonexistent. The fiat boundaries were extended by Montello (2003) to identify spatial regions with imprecise boundaries. For example, boundaries of tall grass prairie cannot be placed as precisely as administrative boundaries because tall grass prairie gradually changes into either forest or short-grass prairie. Further, certain other boundaries can be precisely placed, not by human intention or cognition, but by measurement (or estimation), such as that of a hurricane system (e.g., a minimum wind speed of 75 mile/hour). All of these types of boundaries, such as the genuine, the gradual, and the precise, are abundant in environmental models.

Attributes have always been considered a criterion for identifying spatial objects or spatial regions. From the ontological viewpoint, things are known to the world through their properties (Rosch 1973; Wand 1989). For the identification of spatial phenomena, the importance of attributes is widely recognized in the geographic information science literature. The identification of spatial objects can rely on their intrinsic boundaries (Couclelis 1992; Peuquet 1994, 2002; Kemp and Vckovski 1998; Yuan 2001; Montello 2003; Mcintosh and Yuan 2005), but when identifying spatial regions from continuous space, attributes are essential. These views are described in Goodchild's (1992) formal definition of spatial objects $< i, a_1, a_2, \ldots, a_m >$, where i is an object and a_1 through a_m are attributes of the object. This model has important implications for the application of the object-oriented approach in environmental modeling. The identification of spatial objects and, especially, spatial regions in environmental studies often depends on the spatial distribution of attributes because it describes the state of phenomena. Several rules are common. These include homogeneity of attribute values (e.g., land cover patches), thresholds of attribute values (e.g., climate zones), dominance of a prototype (e.g., vegetation zones), or spatial association of several prototypes (e.g., soil associations).

Process is another important criterion for the identification of spatial objects and spatial regions. It is interpreted interchangeably with operation, activity, and function, among other terms. Process leads to changes in the state of phenomena. From an ontological perspective, the information about this change is required to gain full knowledge of things because, simply, all things change (Wand 1989). Process has been discussed in the identification of spatial objects and regions (Frank 1996; Couclelis 1996), but not as extensively as other criteria. Montello (2003) brought process, paired with attribute, onto the center stage of identifying spatial regions. The importance of process, similar to attribute, is more evident in the delineation of spatial regions than in the delineation of spatial objects, due to the lack of genuine boundaries around a region. Environmental process most typically refers to the exchange of energy or mass within systems through time. Similar to attribute, the process-based identification of spatial objects and regions depends on the spatial distribution of processes. Common rules include the dominance of a process (e.g., pollution zones), rate of a process (e.g., hurricane or tropical storm), direction of a process (e.g., drainage basin), and spatial association of processes (source, track, and runout zones of an avalanche). Since process can be represented as attribute change, the attribute and process criteria are often inseparable.

Mobility, as a criterion for identifying spatial objects and spatial regions, can be considered as a special case of the process criterion or a spatially explicit attribute criterion. It has been associated with the definition of small-space or large-space objects (Zubin 1989; Couclelis 1992; Frank 1996). Mobility implies the independence of objects from locations. While moving, objects maintain their identity, properties, and behavior. Many spatial objects in environmental modeling can be mobile or can be moved. Spatial regions can also be mobile, but the movement is represented through a different mechanism. When an animal moves, all parts of the animal move together and maintain their relative structure and functions. In contrast, spatial regions are identified through attributes and process, so their movements are represented by changes in the location of attribute values and processes (Yuan 2001). When, for example, an ocean wave moves, water molecules are in a vertical vibrating motion with zero horizontal displacement, whereas its form (the wave crest) and function (impacts on the shore) move forward. Such a mechanism presents a challenge for object-oriented representation in environmental modeling.

Spatial objects and spatial regions can be identified through any number or combination of the aforementioned criteria. For example, hurricanes can be identified by the criteria of attribute threshold, magnitude and rate of process, and mobility, either individually or combined.

From the perspective of object-orientation, the criteria discussed above roughly correspond to the encapsulation principle because these criteria can be categorized into properties and behavior. The properties include two spatial properties, spatial scale and boundary, in addition to the nonspatial properties. Process and mobility, on the other hand, belong to behavior. In terms of the composition principle, spatial objects and spatial regions can be organized into inheritance, aggregates, or associations.

In summary, the criteria discussed above have been used collectively to identify spatial objects and spatial regions in the context of environmental modeling. The genuine spatial objects exist in both small-space and large-space, have discrete boundaries, are mobile (or movable), and have certain properties and process. Because the identification of spatial objects is deemed straightforward, the identification of spatial regions has often received greater attention. Spatial regions are extracted out of continuous space, mostly in large-space. They have definable, but nonexistent boundaries, and can be mobile. Properties and process are most important for the identification of spatial regions. Both spatial objects and spatial regions can be conceptualized as objects, although spatial regions carry dual qualifications. Each region is perceived as an object, but at the same time it is part of a continuous field.

The identification of fields has remained an active research topic in geographic information science in recent years, and many researchers have sought to identify the ontology of fields (Worboys 1995; Kemp 1997; Kemp and Vckovski 1998; Peuquet, Smith, and Brogaad 1999; Galton 2001, 2004; Cova and Goodchild 2002). Fields are spatially continuous by definition, thus fundamentally distinguishing themselves from objects. Theoretically, this means that a field can be divided indefinitely without changing its essential nature (see the "Definition of Objects" section above). In this sense, fields are viewed as a mapping between attributes and continuous spatial locations (Worboys 1995; Cova and Goodchild 2002; Galton 2004). The formal model of fields was expressed by Goodchild (1992), as $<x, y, z_1, z_2, \ldots, z_m>$, where x, y are continuous locations, and the attributes at the location x, y are represented by the set z_1 through z_m. The measurement scale of the attributes can be any of those commonly used scales such as nominal, ordinal, interval, and ratio. Further, fields can be categorized in several types (Cova and Goodchild 2002), including scalar, vector, and tensor fields. A scalar field presents the scalar value of an attribute for each location (e.g., elevation). A vector field identifies the direction and magnitude of a phenomenon at a location (e.g., wind). A tensor field represents strains at multiple directions through a matrix at every location (e.g., flow direction).

Fields can also be described using the criteria discussed earlier, namely spatial scale, boundary, attributes, process, and mobility. That is, fields occur mostly in large-scale space. They are spatially extended without a boundary or the boundary is not a concern. Attributes and process are associated with each location in a continuous field. The motion of parts or the entire field follows the ocean wave model, as opposed to the animal model (see the "Definition of Objects" section above). The definition and characteristics of fields have important implications for the application of the object-oriented approach in environmental modeling. Spatial regions, as parts of a field and often conceptualized as objects, do not comply fully with the continuous definition of fields or the discrete definition of objects. The dual qualification of spatial regions presents challenges in their representation (Mcintosh and Yuan 2005).

Environmental Objects, Regions, and Fields

Most environmental models, in particular the physical models, are based on continuous theories. Physical models describe the continuous change of state through time, typically expressed as differential equations applied over a continuous space. The actual modeling, however, has almost always relied on discrete representations in terms of discrete temporal and spatial units (Raper and Livingstone 1995; Kemp 1997). The finite, discrete computing environment is one of the major limitations that force the discrete representation (Egenhofer and Herring 1991; Worboys 1994; Raper and Livingstone 1995). In addition, data collected in the field or through remote sensors are not continuous measurements because it is impossible to measure an infinite number of locations in space. Furthermore, it is not even desirable to make observations at all points in space because modeling is a representation, not a replication, of the environment. A finite number of observations at selected locations is effective for both modeling and management purposes.

Environmental modeling deals with a spectrum of spatial phenomena. Some of these are typical of spatial objects, some are spatial regions extracted out of continuous space, and others are continuous fields. Using the five criteria discussed above, namely scale, boundary, attributes, process, and mobility, the following section categorizes the spatial phenomena dealt with in environmental modeling into several types of spatial objects, spatial regions, and fields. With these types identified, the suitability of object-oriented representation for these categories can be evaluated.

1. Mobile Individuals: These individuals exist in small-scale, have clear boundaries, and are mobile. The most typical phenomena in this category are individual or small groups of animals (see Westervelt and Hopkins 1999).
2. Sedentary Individuals: These individuals also have clear boundaries, but are bound to locations. The most typical phenomena in this category include plants and bodies of water (see Mamedov and Udalov 2002). These two types, the mobile and sedentary individuals, are normally conceptualized as objects. Both types are fundamental subjects in environmental modeling.
3. Masses of Individuals: In this category, which is an extension of the first two categories, the individuals are identifiable, but are small in size or large in quantity, or both. The most common example of this type of phenomena includes vegetation composed of individual plants, and a mass of plankton (see Bian 2000). A collection of these individuals is often conceptualized as a field. Their collective behavior and continuous form are important in environmental modeling.
4. Regions of Individuals: The regions in this category are another extension of the individuals in

the first two categories. They are spatial regions extracted from the continua in the Masses of Individuals category. A typical example is a plant biome or landscape patch (see Tischendorf 1997). These regions are often conceptualized as objects in their own right, yet they contain individuals that can also be conceptualized as objects. The uniqueness of properties and behavior of each region is important for environmental modeling.

5. Continuous Solid Mass: This type has large spatial extents and is continuous. The attributes, as well as behavior in a loose sense, of this type of phenomena vary across space, and the mass is solid and immobile. The continuum of land surface and lithosphere belong to this category (see Kemp 1997).
6. Continuous Fluid Mass: Phenomena of this type are spatially extended, continuous, spatially varying, and mobile. Water, air, and any other fluid belong to this category (see Hunter and Goodchild 1995). Both continuous solid mass and continuous fluid mass are normally conceptualized as fields. The continuous form of these fields is important to the modeling.
7. Sedentary Regions in Mass: In this category, which is an extension of the two categories of continuous masses, the regions are extracted out of the continua in categories of Continuous Solid Mass and Continuous Fluid Mass. Although the constituent materials can be solid or fluid, the regions themselves are immobile (mobility is unrecognizable or average locations are stable). Watersheds identified from continuous land surface and stable pollution zones in a lake are examples of this category (see Band et al. 2000).
8. Mobile Regions in Mass: This is another extension of the categories of continuum. These regions are mobile. Typical examples of this category include pollution plumes and weather fronts (see Mcintosh and Yuan 2005). Both sedentary and mobile regions are often conceptualized as objects in certain modeling contexts. The uniqueness of the properties and behavior of each region is important for modeling.

The eight categories discussed above represent a spectrum of spatial continuity, anchored by the most typical objects on one end and the most typical fields on the other, converging to spatial regions in the middle. The first four of the eight types begin with phenomena that are perceived as spatial objects and then aggregated into spatial regions and fields. The other four types begin with continuous fields, which are then discretized into spatial regions. According to the five criteria for identifying spatial objects and fields, the eight types of environmental phenomena include two categories of spatial objects (1 and 2), three categories of spatial regions (4, 7, and 8), and three categories of fields (3, 5, and 6). These eight categories relate to the typical forms of data used in environmental models, although environmental phenomena can be placed anywhere along this spectrum of spatial continuity, not necessarily in distinct categories (Plewe 1997). The examples used are certainly not exhaustive and each may qualify in a number of categories, depending on the perspective of researchers.

Associated with spatial regions are boundaries, such as ridgelines, shorelines, fault lines, and tree lines. These include the genuine, the gradual, and the precise boundaries as described earlier in this article. On one hand they identify where boundaries of spatial regions should be placed, and on the other hand they are spatial objects in their own right. Like spatial regions, these spatial lines are parts of a continuous space. In environmental modeling, boundaries can dictate modeling strategies. For example, different models, parameters, or modeling approaches may have to be used on different sides of the discontinuity.

The identification of these spatial objects, spatial regions, and fields leads to the discussion of whether object-oriented representation is appropriate for them. Before addressing this issue, it is necessary to review how these spatial objects, regions, and fields are represented in GIS.

GIS Data Models for Spatial Objects, Regions, and Fields

GIS Data Models

This article uses the traditional terms vector and raster to refer to GIS data models. Typical vector data models include points, lines, polygons, and their derivatives; typical raster data models include cells in various shapes, primarily square. The vector representation for spatial objects and regions is rather straightforward. Spatial objects can be represented by various discrete vector data models according to the form of an object; spatial regions are most likely to be represented as polygons. The raster representation for spatial objects and regions is treated in later sections. The following discussion is devoted to data models for the representation of fields.

A continuous field must be partitioned into a finite number of discrete pieces in order to accommodate the finite computing environment. Of various GIS data models that partition the space, six have been discussed specifically in the context of field representation. These are polygons, triangulated irregular networks (TINs), contours, cell-grids, point-grids, and irregular points (Goodchild 1992; Kemp 1997; Cova and Goodchild 2002). Of the six, cell-grids and point-grids are raster data models and the rest are vector models. In terms of how spatial variation in the attributes of fields is preserved, the six models represent two discretization approaches. First, piecewise models, including polygons and TINs, partition space into regions with explicit boundaries. Second, sampled models, including contours, cell-grids, point-grids, and irregular points, are characterized by a "raw" sample form. Attributes' values are presented only at the sampled locations.

In the piecewise models, the delineation of the regions is based on the spatial variation of attributes. The polygon model delineates polygons following a number of rules such as those discussed earlier in this article, namely homogeneity, threshold, dominance, and spatial association of attributes. The attribute values projected from the original field into resultant polygons are assumed to be unique and homogeneous. For environmental modeling purposes, lines and points can also be considered to be piecewise field models. This is because fields can be in one-dimensional linear forms or masses of points, out of which linear or point spatial regions can be extracted, respectively, according to the same criteria for extracting two-dimensional regions. The delineation of triangles in a TIN model is based on the spatial variation of prominent attribute values of a field, such as value peaks, ridges, passes, and valleys. The attribute values in each triangle are either constant (slope and aspect) or varying linearly (elevation) with location. TINs, however, are much less frequently used than polygons in environmental modeling.

Unlike the piecewise models that partition a space according to attribute values, the sampled models partition the space according to the spatial schemes of samples. These include the intervals between contour lines, size of cells, distance between regular points, and locations of irregular points. These sample locations can be determined independently of the attribute values of a phenomenon. For example, the layout of the grid of a 30-m digital elevation model is independent of the spatial variation of the elevation attribute. The identification of spatial regions is not intended in this spatial representation. If any, it is a secondary process after a field is first established. A sample point, a contour line, or a sample cell is only a sample out of all possible samples, instead of an object by itself. Of the sampled models, cell-grids and point-grids are most commonly used in environmental modeling.

In recent years, the aforementioned GIS data models have been implemented in object-oriented environments. The section below discusses some of these implementations.

Object-Oriented GIS Data Models

When using object-oriented GIS, certain researchers choose proprietary software packages, whereas others prefer to develop their own in-house object-oriented GIS applications. The proprietary object-oriented GIS packages normally contain sophisticated object-oriented GIS database capabilities. To be precise, most of these databases use a hybrid object-relational design, rather than a purely object-oriented one (Worboys 1999; Lo and Yeung 2002). For the purposes of discussion, the following sections continue to refer to these databases as object-oriented. The manner in which the GIS data models are implemented in an object-oriented environment, either proprietary or in-house, affects the subsequent GIS applications. This section reviews some of these object-oriented environments as reported in published texts and the literature.

There has been considerable research into the design of object-oriented GIS databases (Egenhofer and Frank 1987; Gahegan and Roberts 1988; van Oosterom and van den Bos 1989; Worboys, Hearnshaw, and Maguire 1990; Egenhofer and Frank 1992; Zhan and Mark 1992; Milne, Milton, and Smith 1993; Roberts and Gahegan 1993; Clementini and Di Felice 1994; Gunther and Lamberts 1994; Worboys 1994). These research efforts sought to represent GIS data models in an object-oriented framework. Presently, both vector and raster data models are supported in proprietary object-oriented GIS databases (Zeiler 2001; Lo and Yeung 2002; Burke 2003). This review focuses on the object model of ArcObjects developed by Environmental Systems Research Institute (ArcObjects 2003) as a case study of a proprietary implementation. ArcObjects is a library of software objects developed to support customized GIS applications and is supported by a number of proprietary object-oriented GIS databases (Zeiler 2001; Burke 2003). Note that this selection is due to the availability of published texts (Zeiler 2001; Burke 2003), and is not intended to endorse a particular proprietary software package.

In ArcObjects, vector geometric primitives and their derivatives are implemented as software objects, each of which is anchored on its identifier and encapsulated with attributes and operations (see "Geometry Object Model" in ArcObjects). Particularly, the geometry of these software objects is represented as a "shape" attribute defined by spatial coordinates. The geometric objects are organized into a hierarchy of classes and related to one another in various relationships, such as aggregation and association. The raster data models are organized into three classes, raster data set, raster bands, and pixel blocks (Zeiler 2001; Burke 2003). A raster data set may consist of multiple raster bands (similar to the "band" concept in remote sensing). A raster band refers to a single layer of raster data. A pixel block is an array of cells as a subset of a raster data set or a raster band, defined by the height, width, and origin specified by a user (see "Raster Objects" in ArcObjects). It is an entire data set, a layer, or an array of cells, rather than an individual cell, that is treated as a software object. Further, ArcObjects complies with the component-based modeling standard (Pfister and Szyperski 1998; Kirtland 1999) that helps group objects according to levels of generality and relationships between objects required by an application. The implications of these designs are discussed in later sections.

As opposed to using proprietary object-oriented GIS, many researchers develop their own in-house object-oriented GIS applications. These applications may develop their own spatial databases, but most use raster data models because they are easy to develop in-house. Individual raster cells have often been treated as software objects (Laval 1996; Beecham and Farnsworth 1998; Lorek and Sonnenschein 1998; Ziv 1998; Carter and Finn 1999). Each cell has its identifier, a list of attributes (that may include topology), and operations. These cell objects may be organized into a hierarchy of cell classes for various purposes.

From the perspective of conceptual, formal, and implementation models (see the earlier section of this article, "Object-Orientation"), the proprietary object-oriented GIS databases formalize and implement discrete geometric primitives, but do not usually specify what phenomena these software objects are used to represent. In this sense, these databases embody the formal and implementation models, but are separated from the conceptual model of spatial phenomena despite the recent proposal to integrate conceptual models with a database (Leung, Kwong, and He 1999; Mennis, Peuquet, and Qian 2000). This separation makes a database flexible in order to support generic applications but also leaves room for potential errors. For example, users may compromise conceptual models for the convenience of proprietary databases. In-house object-oriented GIS development is equally, if not more, prone to error. Researchers can be driven by implementation concerns without first considering the most appropriate conceptual models that should precede and guide the technical implementation. In practice, the lack of a clear definition of objects and the inability to discriminate between conceptual and implementation models might increase the likelihood of errors during in-house development (Bian 2003).

Object-Orientation for Environmental Modeling

Technically, it is always possible to implement spatial objects, regions, and all parts of a partitioned field as software objects. The conceptual advantage of object-orientation, however, may not hold unless there is compatibility between the principles of object-orientation, the conceptual model of a phenomenon (spatial objects, spatial regions, and fields), and the object-oriented data models. This section discusses the compatibility between these three sets of concepts. First the principles of object-orientation (i.e., encapsulation and composition) are evaluated to assess whether they are appropriate to represent spatial objects, regions, and fields. Subsequently, an assessment is made as to whether the object-oriented data models support the spatial objects, regions, or fields best at the conceptual or implementation levels. The object-oriented data models are evaluated in both the proprietary and in-house environments wherever available. The discussion is organized by spatial objects, regions, and fields. Table 1 summarizes the two sets of compatibility.

Spatial Objects

The spatial objects include Mobile Individuals and Sedentary Individuals as discussed earlier (types 1 and 2 in the section "Environmental Objects, Regions, and Fields"). Both principles of object-orientation (encapsulation and composition) are appropriate to represent them. Because these individuals have intrinsic identity, properties, and behavior, the encapsulation principle of object-orientation is most appropriate for their representation. The properties may include internal (geometric, biophysical, etc.), environmental, spatial, and temporal attributes of an individual. The behavior may include the action of individuals, their interaction with each other, and the interaction between the individuals and the environment (Westervelt and Hopkins 1999;

Table 1. A summary of the compatibility between the principles of object-orientation, the object-oriented implementation, including both proprietary and in-house, and conceptual models of environmental phenomena

Environment phenomena	Examples	Object-oriented representation	Object-oriented implementation: ArcObjects Vector	Object-oriented implementation: ArcObjects Raster	Object-oriented implementation: In-house Raster
Mobile individuals	animals	yes	yes	no	yes
Sedentary individuals	plants	yes	yes	no	yes
Regions of individuals	plant patches	yes	yes	no	yes
Sedentary regions in mass	watersheds	yes	yes	no	yes
Mobile regions in mass	weather fronts	yes	yes	no	–
Masses of individuals	vegetation	n.a.	–	yes	yes
Continuous solid mass	land-surface	n.a.	–	yes	yes
Continuous fluid mass	air mass	n.a.	–	yes	yes

Note: For the object-oriented representation, "yes" and "no" designate whether they are appropriate to represent the eight categories of spatial objects, regions, and fields. For the object-oriented implementation, "yes" and "no" indicate whether it supports the categories of environmental phenomena. The dash indicates complex situations, depending on specific conceptualization and implementation models. Detailed discussions of these situations are presented in the article text.

Mamedov and Udalov 2002). The dynamics of individuals, spatial and nonspatial, are of great interest in environmental modeling. The encapsulation principle facilitates the representation of these dynamics. Internal changes, such as the geometry of an object, can be accommodated by updating relevant attributes (in this case, the shape attribute) while maintaining the identity of the object. The mobility of an object can be supported by updating the spatial and temporal properties (Raper and Livingstone 1995).

The composition principles of object-orientation support the organization of mobile and sedentary individuals. The inheritance principle of object-orientation is similar to the taxonomy concept in a number of environmental disciplines. The aggregation principle is best suited to the representation of an environmental system when it is perceived as an assemblage of individual parts. It is important to note that the aggregate object can have its own properties and behavior that may not be relevant to its parts. For example, species diversity is relevant to a forest community but not to an individual tree. This is the so-called "emergent property," an important ontological concept well recognized in environmental modeling (Quattrochi and Goodchild 1997). Further, the association principle resembles the social structure concept and is effective in representing interactive relationships between individuals. Note that this discussion adopts the definitions by Cook and Daniels (1994) that aggregation emphasizes the dependency between the parts and the whole, and association emphasizes the role of its members.

Regarding the support of object-oriented data models, the object model of vector primitives (points, lines, and polygons) provided by ArcObjects is compatible with the mobile or sedentary individuals. This is because these software objects have a discrete form and accommodate the representation of identity, properties, and behavior. This compatibility is both conceptual and in implementation. An application requires additional programming tools to assemble the software objects in a working model, whereas these software objects provide the building blocks for modeling individuals in the environment. Since its recent development, the software objects in ArcObjects have enhanced the utility of GIS. Shape change and mobility of an individual are two such examples that have made GIS much more useful in environmental modeling.

The cell software objects have been mostly used in in-house applications. For sedentary individuals, the cell-object representation has its conceptual merit. A cell software object can represent, for example, a single or several plants. Spatially adjacent cells that share certain properties can be organized into classes to represent patches of individual plants (Tischendorf 1997; Beecham and Farnsworth 1998; Mamedov and Udalov 2002). This treatment supports environmental modeling principles, bringing both design and implementation advantages for modeling and analysis. Mobile individuals, on the other hand, are separated from their background environment. The cells, if implemented as software objects, are intended to be parts of the gridded background environment, not the mobile individuals themselves. In these applications, the mobile individuals can be considered "shapeless" and "invisible," and the cells are used to represent the consequences of their behavior, typically mobility. In this sense, there is no conceptual conflict in the representation of individuals as software objects.

The compatibility between the principles of object-orientation and the conceptual models of mobile and sedentary individuals can bring the application of object-oriented vector GIS to its full potential. The core assumption of object-orientation, namely that the world is composed of objects, provides an ideal framework for modeling spatial objects.

Spatial Regions

Spatial regions include Regions of Individuals, Sedentary Regions in Mass, and Mobile Regions in Mass (the types 4, 7, and 8 listed earlier). Once conceptualized as objects, they have intrinsic identity, properties, and behavior. Both the encapsulation and composition principles of object-orientation are, therefore, appropriate for their representation.

Unlike spatial objects whose representation can be independent of their background environment, the representation of spatial regions is bound to the field where they are derived. The composition principles (hierarchy, aggregation, and association) are spatially more explicit for spatial regions than for spatial objects. For example, the Hydrological Unit Code used to define drainage basins nationwide is a spatially defined hierarchy. Subbasins, as subclasses in this hierarchy, are spatially enclosed within their superclass basins. In addition, a soil association is explicitly defined as the spatial coappearance of several soil series. In this case a soil association is related to soil series through aggregation (parts and whole) or association (members and set) relationships.

Regarding object-oriented data models, the vector object model defined in ArcObjects, assisted with other programming tools, supports these spatial regions conceptually and in implementation. Mobile regions, in particular, require not only the change in location (and possibly shape and size), but the rest of the field also must change accordingly in order to fill the "hole" left by the mobile region. The current object model in ArcObjects can support their representation with an augmented programming effort. Cell-based representation of sedentary regions, on the other hand, occurs mostly in the in-house development through aggregations or associations of individual cell objects, organized according to attributes or spatial relationships. As discussed earlier in this subsection, this design is conceptually justified (Beecham and Farnsworth 1998; Mamedov and Udalov 2002).

The dual qualification of spatial regions—perceived as both objects and parts of a continuous field—poses additional challenges for how they should be represented. Neither the objects nor the field conceptualization alone can sufficiently represent the characteristics of spatial regions. A number of representations have been proposed to accommodate this dual nature (Winter 1998; Blaschke et al. 2000; Yuan 2001; Mcintosh and Yuan 2005). These representations maintain a raster data model for the internal spatial variation that these regions inherit from a field. At the same time, a vector data model is integrated with the raster model to support the identity, geometry, and spatiotemporal relationships required for analysis as these regions move and evolve. Presently, the development of these representation methods is still in the research phase. Neither the proprietary object-oriented GIS such as ArcObjects nor the cell-based in-house developments can support this dual representation.

Fields

The fields include the Masses of Individuals, Continuous Solid Mass, and Continuous Fluid Mass (types 3, 5, and 6). The representation of a continuous field requires it be discretized because the computing environment is finite and discrete. The piecewise field data models discretize a space into polygons or a TIN. Each polygon or triangle is a part of the partitioned field, yet the uniqueness of its attributes allows it to be perceived as an object (or a region) in its own right for certain applications. In this sense, object-oriented principles are appropriate to support the representation of these objects or regions. The vector object model in ArcObjects is most appropriate for this representation, both conceptually and in implementation.

Environmental modeling has a long tradition of using sampled field data models, especially regularly spaced cell-grids and point-grids, in order to discretize a field. Regular sampling is the most common discretization method in environmental modeling because it is the simplest way to reduce a continuous, infinite space to a finite representation. The regular, mostly square, shape of cells (or spacing between points) is the simplest geometry to represent an irregular world. These are simple, yet sensible, ways to represent a continuous space and at the same time satisfy the requirement of a discrete representation. Technically, a cell can have an identity, attributes, and behavior, and these cells can be organized in various ways that may fit the framework of object-orientation. Thus, a cell can be treated as a spatial object. Although this treatment is technically convenient, its conceptual appropriateness is questionable. A square cell in a field is not normally perceived as an object because it does not, nor is it meant to, resemble any environmental phenomena. Only an aggregate of cells can reasonably represent a meaningful spatial object or spatial region. The raster data model can treat either an entire raster layer or individual cells as software objects, but there is no significant difference between the two treatments for representing a field. It is the continuous definition of fields and the conceptual distance between a square cell and an environmental phenomenon that ultimately determine that either one is a mere partition approach, not a conceptual representation of ontological objects. Similar arguments extend to other sampled field data models, such as contours and irregular points.

Based on the arguments above, the raster model defined in ArcObjects, which implements a layer of cells as a single software object, is an appropriate conceptual design for the representation of fields. In addition, the vector object model of ArcObjects supports the representation of contour lines and irregular points as software objects, but only at the implementation level. Many in-house applications implement cells as objects to represent a continuous field, even though a cell is only a part of a field and is not normally perceived as a meaningful object itself. This treatment offers an example of compromising the conceptual model for technical convenience. In addition to the conceptual mismatch, the object-oriented representation of cells does not seem to bring implementation advantages. If not for constructing spatial regions, a large number of cells, each with its own identifier, properties, and behavior, can easily overwhelm available computing resources (Laval 1996; Mamedov and Udalov 2002; Bian 2003). This is because of the storage required for the identifier and attributes and, most critically, the time needed to execute methods for each cell. In this situation, not only the conceptual, but also the technical merit of object-orientation is compromised. The older programming technique of handling cell arrays, as implemented in the raster data model of ArcObjects, is more efficient than the object-oriented one in handling gridded fields.

Composite Structures

Presently, the use of ArcObjects still employs a layered structure. Each layer is defined by an application theme (e.g., soils, land use, or others) and a type of geometry (e.g., either points, lines, or polygons). This structure is kept perhaps for practical reasons. It is theoretically and technically feasible to break away from the layered structure to support a "composite" structure that consists of different themes and geometry. Conceptually, a composite structure is consistent with the intention of object-orientation—that is, to represent the perceived world that consists of different things in different forms. A landscape, for example, is more often perceived as an assemblage of forest and grass patches (polygons), streams (lines), and animals (points), each of which is a part of the landscape. These parts play different, yet simultaneously interconnected, roles in the makeup of the landscape. It is perhaps not often that a landscape is perceived as the combination of a layer of polygons, a layer of lines, and a layer of points. Technical tools, such as object-oriented and component-based modeling, are available and can support the implementation of a composite structure (Pfister and Szyperski 1998; Kirtland 1999).

The dual raster-vector representation for spatial regions is an example of a composite structure employing different geometries, though for a single theme (Winter 1998; Blaschke et al. 2000; Yuan 2001; Mcintosh and Yuan 2005). Cova and Goodchild (2002) recently developed a multigeometry and multitheme "object fields" for environmental management, in which objects of various geometries and themes are integrated with a continuous field of a different theme. Multiple relationships are allowed. For example, one object can occupy multiple locations, and one location in a field can link to multiple objects. Moreover, spatial objects, regions, and fields can be organized into taxonomic hierarchies according to either their geometry, as already implemented in ArcObjects, or their themes. Then, the aggregation principle can support a composition of different geometries (points, lines, and polygons) and different themes (e.g., land use, streams, and animals). The association principle can subsequently represent the roles of each part, spatial or nonspatial. The nine-intersection system developed by Egenhofer and Herring (1994), for example, is a notable development to support the complex topology between points, lines, and polygons. The implementation of a composite structure requires sophisticated vector databases that cannot be easily implemented in an in-house environment. Support from proprietary object-oriented GIS is critical to further broaden the utility of GIS in environmental modeling.

Conclusions

Not all spatial phenomena are best represented as objects nor can they be best supported by software objects. Spatial objects, spatial regions, and fields represent three categories of phenomena that are well represented as objects, reasonably represented as objects, and not well represented as objects, respectively. The power of object-orientation reaches its full potential for the representation of spatial objects whose conceptual model matches the principles of object-orientation. For the most part, object-orientation can reasonably represent spatial regions, but faces challenges to represent their dual qualifications. Object-orientation is not sufficiently developed for the representation of continuous fields, due to the primary conflict between the discrete assumption of objects and the continuous nature of fields.

In seeking the ontological root of object-orientation, Wand (1989) stated that principles of object-orientation compared well with basic ontological principles defined in Bunge (1977). However, there seems to be a critical difference. The very first principle defined in Bunge, "The world is composed of *things*," differs from Wand's (1989) "The world is composed of *objects*." Not all things in space are best represented as objects. The fundamental assumption behind object-orientation, that the world is composed of objects, is incomplete for spatial representation.

For environmental modeling, object-orientation has allowed researchers to explore new territories that would otherwise be difficult. The rise of individual-based modeling in ecology (Judson 1994) and, recently, in epidemiology (Ferguson et al. 2005) is such an example. In both cases, individuals are represented as objects. The delineation of spatial regions for hydrological modeling is another example. Spatial regions at multiple scales (such as canopy strata, patch, climate zone, hillslope, and watershed) can be extracted as objects and organized into a spatial hierarchy in order to support multiscale modeling (Band et al. 2000). The dual representation of spatial regions in meteorology (Yuan 2001) and the integrated representation of object fields (Cova and Goodchild 2002) for environmental management, especially, have provided insights into the future roles the object-oriented approach may play.

On the other hand, caution should be exercised when adopting a concept first developed outside of geography. Of a computing philosophy, a clear set of principles, and the technical procedures of object-orientation, the latter is the most concretely specified. This, in addition to some researchers' inability to distinguish between object-orientation as a means of representation and as a programming technique, might have contributed to inappropriate objectification of some environmental phenomena.

The arrival of object-orientation has generated active discussions in the geographic information science community. As reviewed above, these discussions address a broad range of issues, such as the applicability of object-orientation to spatial modeling, the design of object-oriented spatial databases, and object-oriented applications in geographic research. The discussion presented in this review focuses on the conceptual compatibility of object-orientation for representing spatial objects, spatial regions, and fields in the context of environmental modeling. More than fifteen years after object-orientation was first introduced into the geographic information science community, this review offers some viewpoints that might not have been fully considered at the time object-orientation was becoming widely adopted.

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References

Abadi, M., and L. Cardelli. 1996. *A theory of objects*. New York: Springer.

ArcObjects. 2003. ArcObjects version 8.3. Environmental Systems Research Institute (ESRI). Redlands, California.

Band, L. E., C. I. Tague, S. E. Brun, D. E. Tenenbaum, and R. A. Fernandes. 2000. Modeling watersheds as spatial object hierarchies: Structure and dynamics. *Transactions in GIS* 4:181–96.

Beecham, J. A., and K. D. Farnsworth. 1998. Animal foraging from an individual perspective: An object oriented model. *Ecological Modeling* 113:141–56.

Bell, J. L. 1999. *The art of the intelligible: An elementary survey of mathematics in its conceptual development*. New York: Springer.

Bian, L. 2000. Object-oriented representation for modelling mobile objects in an aquatic environment. *International Journal of Geographical Information Science* 14:603–23.

———. 2003. The representation of the environment in the context of individual-based modeling. *Ecological Modeling* 159:279–96.

Blaschke, T., S. Lang, E. Lorup, J. Strobl, and P. Zeil. 2000. Object oriented images processing in an integrated GIS/remote sensing environment and perspectives for environmental applications. In *Environmental information for planning, politics and the public*, ed. A. Cremers and K. Greve, 555–70. Marlburg, Germany: Metropolis.

Bunge, M. 1977. *Ontology I: The furniture of the world.* Vol. 3 of *Treatise on basic philosophy.* Boston: Reidel.

Burke, R. 2003. *Getting to know ArcObjects: Programming ArcGIS with VBA*. Redlands, CA: ESRI.

Burrough, P. A., and A. U. Frank. 1996. *Geographic objects with indeterminate boundaries*. London: Taylor & Francis.

Carter, J., and J. T. Finn. 1999. MOAB: A spatially explicit, individual-based expert system for creating animal foraging models. *Ecological Modelling* 119:29–41.

Clarke, K. 2003. *Getting started with geographic information systems*, 4th ed. Upper Saddle River, NJ: Prentice Hall.

Clementini, E., and P. Di Felice. 1994. Object-oriented modeling of geographic data. *Journal of the American Society for Information Science* 45 (9): 694–704.

Cook, S., and J. Daniels. 1994. *Designing objects systems: Object-oriented modeling with syntropy*. New York: Prentice Hall.

Couclelis, H. 1992. People manipulate objects (but cultivate fields): Beyond the raster-vector debate in GIS. In *Theories and methods of spatio-temporal reasoning in geographic space*, ed. A. U. Frank, I. Campari, and U. Formentini, 65–77. Berlin: Springer-Verlag.

———. 1996. Towards an operational typology of geographic entities with ill-defined boundaries. In *Geographic objects with indeterminate boundaries*, ed. P. A. Burrough and A. U. Frank, 45–55. London: Taylor & Francis.

Cova, T. J., and M. F. Goodchild. 2002. Extending geographical representation to include fields of spatial objects. *International Journal of Geographical Information Science* 16:509–32.

Egenhofer, M. J., and A. U. Frank. 1987. Object-oriented databases: Database requirements for GIS. In *Proceedings of the International GIS Symposium: The research agenda*, vol. 2, 189–211. Washington, DC: U.S. Government Printing Office.

———. 1992. Object-oriented modeling for GIS. *URISA Journal* 4:3–19.

Egenhofer, M. J., and J. R. Herring. 1991. High-level spatial data structures for GIS. In *Geographical information systems: Principles and applications*, ed. D. J. Maguire, M. F. Goodchild, and D. W. Rhind, 227–37. London: Longman.

———. 1994. Categorizing binary topological relations between regions, lines, and points in geographic databases. In *The 9-intersection: Formalism and its use for natural-language spatial predicates*, Technical Report 94-1, ed. M. J. Egenhofer, D. M. Mark, and J. Herring, 1–28. Santa Barbara, CA: National Center for Geographic Information and Analysis.

Ferguson, N. M., D. A. T. Cummings, S. Cauchemez, C. Fraser, S. Riley, A. Meeyai, S. Iamsirithaworn, and D. S. Burke. 2005. Strategies for containing an emerging influenza pandemic in Southeast Asia. *Nature* 437:209–14.

Frank, A. U. 1996. The prevalence of objects with sharp boundaries in GIS. In *Geographic objects with indeterminate boundaries*, ed. P. A. Burrough and A. U. Frank, 29–40. London: Taylor & Francis.

Gahegan, M., and S. A. Roberts. 1988. An intelligent object-oriented geographical information system. *International Journal of Geographical Information Systems* 2:101–10.

Galton, A. P. 2001. A formal theory of objects and fields. In *Proceedings of the International Conference COSIT '01, Spatial information theory: Foundations of geographic information science, Morro Bay, California, 19–23 September*, ed. D. R. Montello, 458–73. Berlin: Springer-Verlag.

———. 2004. Fields and objects in space, time, and space-time. *Spatial Cognition and Computation* 4 (1): 39–41.

Goodchild, M. F. 1992. Geographical data modeling. *Computers and Geosciences* 18 (4): 401–8.

Gunther, O., and J. Lamberts. 1994. Object-oriented techniques for the management of geographic and environmental data. *The Computer Journal* 37:16–25.

Hunter, G. I., and M. F. Goodchild. 1995. A new model for handling vector data uncertainties in geographic information systems. *Journal of the Urban and Regional Information Systems Association* 8:51–7.

Judson, O. P. 1994. The rise of the individual-based model in ecology. *TREE* 9:9–14.

Kemp, K. K. 1997. Fields as a framework for integrating GIS and environmental process models. Part 1: Representing spatial continuity. *Transactions in GIS* 1:219–34.

Kemp, K. K., and A. Vckovski. 1998. Towards an ontology of fields. In *Proceedings of the Third International Conference on Geocomputation, Bristol, U.K., 17–19 September*. Bristol, U.K.: University of Bristol, University of Oxford, University College Cork, and Intergraph Corp.

Khoshafian, S., and R. Abnous. 1990. *Object orientation: Concepts, languages, databases, user interfaces*. New York: Wiley.

Kim, W. 1991. Object-oriented database systems: Strengths and weaknesses. *Journal of Object-Oriented Programming* 3:21–29.

Kirtland, M. 1999. *Designing component-based applications*. Redmond, WA: MicroSoft Press.

Laval, P. 1996. The representation of space in an object-oriented computational pelagic ecosystem. *Ecological Modelling* 88:113–24.

Leung, Y., S. L. Kwong, and J. Z. He. 1999. A generic concept-based object-oriented geographical information system. *International Journal of Geographical Information Science* 13:475–98.

Lo, C. P., and A. K. W. Yeung. 2002. *Concepts and techniques of geographic information systems*. Upper Saddle River, NJ: Prentice Hall.

Lorek, H., and M. Sonnenschein. 1998. Object-oriented support for modeling and simulation of individual-oriented ecological models. *Ecological Modelling* 108:77–96.

Mamedov, A., and S. Udalov. 2002. A computer tool to develop individual-based models for simulation of population interactions. *Ecological Modelling* 147:53–68.

Mcintosh, J., and M. Yuan. 2005. A framework to enhance semantic flexibility for analysis of distributed phenomena. *International Journal of Geographical Information Science* 19:999–1018.

Mennis, J. L., D. J. Peuquet, and L. Qian. 2000. A conceptual framework for incorporating cognitive principles into geographical database recognition. *International Journal of Geographical Information Science* 14:501–20.

Meyer, B. 1987. Reusability: The case for object-oriented design. *IEEE Software* 1987:37–51.

Milne, P., S. Milton, and J. L. Smith. 1993. Geographical object-oriented databases: A case study. *International Journal of Geographical Information Systems* 7:39–55.

Montello, D. R. 1993. Scale and multiple psychologies of space. In *Spatial information theory: A theoretical basis for GIS*, ed. A. U. Frank and I. Campari, 312–21. Berlin: Springer.

———. 2003. Regions in geography: process and content. In *Foundations of geographic information science*, ed. M. Duckham, M. F. Goodchild, and M. F. Worboys, 173–89. London: Taylor & Francis.

Nierstrasz, O. M. 1986. What is an "object" in object oriented programming? In *Objects and things*, ed. D. Tsichritzis, 1–13. Geneva: Centre Universitaire d'Informatique, Université de Genève.

Peuquet, D. J. 1988. Representations of geographic space: Toward a conceptual synthesis. *Annals of the Association of American Geographers* 78:375–94.

———. 1994. It's about time: A conceptual framework for the representation of temporal dynamics in geographic information systems. *Annals of the Association of American Geographers* 84:441–61.

———. 2002. *Representation of space and time*. New York: Guilford.

Peuquet, D. J., B. Smith, and B. Brogaad. 1999. *The ontology of fields: Report of specialist meeting held under the auspices of the Varenius Project*. Santa Barbara, CA: National Center for Geographic Information and Analysis.

Pfister, C., and C. Szyperski. 1998. Why objects are not enough. In *Component-based software engineering*, ed. T. Jell, 141–48. Cambridge, U.K.: Cambridge University Press.

Plewe, B. 1997. A representation-oriented taxonomy of gradation. In *Spatial information theory: A theoretical basis for GIS.* Lecture Notes in Computer Science *#1329*, 121–36. Berlin: Springer-Verlag.

Quattrochi, D. A., and M. F. Goodchild. 1997. *Scaling of remote sensing data for GIS*. New York: Lewis.

Raper, J., and D. Livingstone. 1995. Development of a geomorphological spatial model using object-oriented design. *International Journal of Geographic Information Systems* 9:359–83.

Roberts, S. A., and M. N. Gahegan. 1993. An object-oriented geographic information system shell. *Information and Software Technology* 35 (10): 561–72.

Rosch, E. 1973. On the internal structure of perceptual and semantic categories. In *Cognitive development and the acquisition of language*, ed. T. E. Moore, 111–44. New York: Academic Press.

Rumbaugh, J., W. Blaha, and F. Premerlani. 1991. *Object-oriented modeling and design*. Englewood Cliffs, NJ: Prentice Hall.

Silvert, W. 1993. Object-oriented ecosystem modeling. *Ecological Modelling* 68:91–118.

Smith, B., and D. M. Mark. 1998. Ontology and geographic kinds. *Proceedings of International Symposium on Spatial Data Handling (SDH'98), Vancouver, 12–15 July*, ed. T. K. Poiker and N. Chrisman, 308–20. Vancouver, BC: International Geographical Union.

Tischendorf, L. 1997. Modeling individual movements in heterogeneous landscapes: Potential of a new approach. *Ecological Modelling* 103:33–42.

van Oosterom, P., and J. van den Bos. 1989. An object-oriented approach to the design of geographic information systems. *Computers and Graphics* 13:409–18.

Wand, Y. 1989. A proposal for a formal model of objects. In *Object-oriented concepts, databases, and applications*, ed. W. Kim and F. H. Lochovsky, 537–59. New York: ACM Press.

Wegner, P. 1990. Concepts and paradigms of object-oriented programming. *OOPS Messenger* 1:8–87.

Westervelt, J. D., and L. D. Hopkins. 1999. Modeling mobile individuals in dynamic landscape. *International Journal of Geographical Information Science* 13:191–208.

Winter, S. 1998. Bridging vector and raster representation in GIS. In *Advances in geographic information systems*, ed. R. Laurini, K. Makki, and N. Pissinou, 57–62. Washington, DC: Association for Computing Machinery Press.

Worboys, M. F. 1994. Object-oriented approaches to geo-referenced information. *International Journal of Geographical Information Systems* 8:385–99.

———. 1995. *GIS: A computing perspective*. London: Taylor & Francis.

———. 1999. Relational databases and beyond. In *Geographic information systems: Principles, application, and management*, ed. P. Longley, M. F. Goodchild, D. Maguire, and D. Rhind, 373–84. New York: Wiley.

Worboys, M. F., H. H. Hearnshaw, and D. J. Maguire. 1990. Object-oriented data and query modeling for spatial databases. *International Journal of Geographical Information Systems* 4:369–83.

Yuan, M. 2001. Representing complex geographic phenomena with both object- and field-like properties. *Cartography and Geographic Information Science* 28 (2): 83–96.

Zeiler, M. 2001. *Exploring ArcObjects*. Redlands, CA: ESRI.

Zhan, F., and D. Mark. 1992. Object-oriented spatial knowledge representation and processing: Formalization of core classes and their relationships. In *Proceedings, 5th International Symposium on Spatial Data Handling, Charleston, SC, 3–7 August*, ed. P. Bresnahan, E. Corwin, and D. Cowen, 662–71. Columbia, SC: International Geographical Union, Commission on GIS; Humanities and Social Sciences Computing Lab, University of South Carolina.

Ziv, Y. 1998. The effect of habitat heterogeneity on species diversity patterns: A community-level approach using an object-oriented landscape simulation model (SHALOM). *Ecological Modelling* 111:135–70.

Zubin, D. 1989. Untitled. in *Languages of spatial relations: Report on the specialist meeting for NCGIA Research Initiative 2*, Technical Report 89-2, ed. D. M. Mark, A. U. Frank, M. J. Egenhofer, S. Freundschuh, M. McGranaghan, and R. M. White, 13–17. Santa Barbara, CA: National Center for Geographic Information and Analysis.

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