A Representation-Oriented Taxonomy of Gradation

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Abstract
Gradation, the presence of gradual rather than abrupt boundaries around geographic entities, is one of the many complexities of geography which is beginning to be investigated for representation and analysis in formal models. Much of the research to date has been focused on specific applications, but some are starting to look at the underlying theory behind this phenomenon, leading toward better understanding and better models. This work extends this theory with a taxonomy which describes and explains gradational situations, focusing on issues related to formal representation. This taxonomy has been beneficial in developing methods of representing this phenomenon in GIS and maps.

1 Introduction
By definition, geographic models are not perfect. The spatial representations of the world which are used in the mind, in geographic information systems, and on maps, are not duplications of reality, but are homomorphisms of it (Robinson & Frank 1985, 441). They need only to be “good enough” that the processes in the model yield results which are analogous to the results of real-world processes. The geometries, attributes, structures, and processes which are required to be “good enough” depend entirely on the situation at hand.

One of the primary goals of the research in spatial information theory to date has been to identify these required model elements, and develop methods to incorporate them into formal systems such as GIS, cartography, and spatial analysis. As research has progressed, the repertoire has expanded to include temporal change, three-dimensional entities, scale-dependent geometries, and other complexities.

Another complex phenomenon of reality which has begun to be addressed is gradation. This is a situation where the boundary of an entity is gradual rather than crisp. In a gradational entity, there is an area which is definitely included (called the core), an area which is definitely outside (called the exterior), but also an area that is only somewhat a part of the entity (called the boundary zone or gradation zone).

Contrary to what might be inferred from most GIS databases and maps, gradation is quite common in Geography, especially in nature. It occurs in a wide variety of forms and situations. Common examples include soil types, climates, landforms, metropolitan areas, cultural regions, and wetlands. All of these entities tend to have gradual boundaries, making them more difficult to formally represent than entities with simple, crisp, boundaries.

1.1 Research to Date
The phenomenon of gradation has been known of for many years. Kimble (1951), Weinreich (1954), Grigg (1967), Soja (1971), Gale (1972), and others recog-
nized that culture groups and other regions tend not to have discrete, absolute, boundaries. Research in this field (which is not generally referred to as gradation, but as "fuzzy geography" or "indeterminate geography," terms which often lead to ambiguity) has progressed considerably in the past ten years. Important works include Leung (1988), Burrough (1989), and Wang et al (1990, 1996). A majority of the research to date has been focused on specific applications, and more often look at the analysis of fuzzy entities than at their formal representation.

While several methodologies and solutions have been proposed for representing gradation (e.g. Lagacherie et al 1996, Altman 1994, Wang et al 1990), a consistent theoretical framework is needed to further develop those solutions and extend them to other applications. Although earlier research began to look at some of the underlying processes manifested as gradation (e.g. Gale 1976, Robinson & Frank 1985, Leung 1987), Burrough & Frank (1996) was the first major development toward a general body of theory. The work presented herein builds on the foundation of that book and other works to further develop this theory.

2 The Taxonomy

A theory of gradation can be used not only to better understand the phenomenon in an esoteric sense, but is also invaluable for developing effective, consistent methods for analyzing and representing gradational geographic entities. While a general theoretical framework involves many elements, a taxonomy which distinguishes the various processes and forms which are at work is usually a good place to start.

The taxonomy presented herein was built on earlier foundations found in Gale (1972), Robinson & Frank (1985), and Couclelis (1996). A wide variety of situations in which one can find gradual boundaries were investigated. By analyzing their differences and similarities, several general principles were discovered.

Three main groups of characteristics are presented herein. The first group consist of natural and cognitive processes which appear to cause gradation in geographic entities. The second set are morphological characteristics which affect the appearance of gradation zones and thus their effective representation. The elements of the third category are not actually characteristics of gradation itself, but are situational factors which must be addressed when making decisions concerning representation.

Although a variety of examples of gradation were used in the development of this framework, only one will be used here for illustration. Gambel Oak (quercus gambeli) is a transitional vegetation cover found in the foothills of the mountains of Utah and neighboring states. Although it is commonly known as "scrub oak," mature plants can actually range in height from 2 to 15 meters (Kearney & Peebles 1951, 219), depending on water availability, temperature, and soil quality. This variability, and the transitional elevation and climactic zone it occupies, produce woodlands exhibiting a great deal of gradation.

3 Causes of Gradation

The first group of characteristics looks at six fundamental reasons why a particular entity may have fuzzy boundaries. This list is likely not exhaustive, but consists of readily apparent processes. While they may explain what can cause gradation to