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Interaction with GIS Attribute Data Based on Categorical Coverages*

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Abstract. The human-computer interface is a crucial element in the design of the next generation of Geographic Information Systems (GISs). We discuss the user interface design process by separating the *formalization* of the problem domain (identifying the objects a user manipulates, and their pertinent operations) from its *visualization* (describing human-computer interaction techniques such as windows and dialog boxes). This framework is used to examine the process of manipulating *attribute data* in a GIS on the basis of the common cartographic concept of a *categorical coverage*. The characteristics of categorical coverage data and the user requirements for interacting with this data are formalized in the form of a set of fundamental objects and operations. A visualization for a windows-icons-menus-pointing devices (WIMP) interface is presented.

1 Introduction

Throughout the history of Geographic Information Systems (GISs), most of the research attention has concentrated on methods to store, retrieve, process, and analyze geographic data efficiently (Maguire *et al.* 1991). Only recently, attention has moved toward the user interaction components of a GIS (Egenhofer and Frank 1988; Kuhn and Egenhofer 1991; Mark and Gould 1991; Mark and Frank 1992). For example, investigations of metaphors appropriate for dealing with geographic data (Gould and McGranaghan 1990; Jackson 1990; Kuhn and Frank 1991; Mark 1992; Egenhofer and Richards 1993) have influenced the design of some GIS user interfaces. In order to implement a successful system, GIS designers must have a clear understanding of the user requirements, including the concepts users will apply when they deal with geographic data. This is a particularly important concern for the design of GIS user interfaces, as it should not just focus on the way people interact with computers, but should be based on how people go about problem solving when interacting with geographic information itself (Mark and Gould 1991).

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GISs are typically thought of as containing two very different, but interrelated kinds of data and information, spatial and attribute. *Data* are measurements of the "real world" that are used to create useful *information* about the world for use in analysis. For this paper, the "real world" is *geographic space.* The term *spatial data* describes position or location within geographic space. *Attribute data* (also known as aspatial or non-spatial data) consist of the descriptive or statistical characteristics of spatial data. Research into modeling the geometry of geographic data has been abundant. For overview articles see (Peuquet 1988; Egenhofer and Herring 1991; Frank 1992). On the other hand, modeling of the attribute-data component of a GIS has been secondary to the spatial component. Attribute-data modeling has been examined primarily within the usual frameworks developed in computer science for general-purpose database management systems such as the hierarchical, network, or relational data model, and most recently also object-oriented methods have been favored (Worboys *et al.* 1990; Egenhofer and Frank 1992). A second perspective of attribute data that has received attention is the classification of attribute data into nominal, ordinal, interval, and ratio (Stevens 1946), for instance to model spatial data quality (Clapham 1992). While these views of attribute data modeling are useful for a discussion of some aspects of geographic data, they consider attribute data as separate from the spatial domain. This intimate link between attribute and spatial data, however, is the essence of many geographic applications and its correct modeling is critical for the design of the interaction with attribute data in a GIS.

This paper uses the cartographic concept of a *categorical coverage* (Chrisman 1982) as a basis for interacting with attribute data. Categorical coverages are particularly well suited as a geographic framework for attribute interaction as they organize the spatial domain according to properties of the attribute domain and manipulations of the attribute domain trigger changes in the spatial domain. This is different from the behavior of choropleth maps, which have a similar visual appearance to categorical coverages. They arrange attribute information for enumeration areas on the ground (Robinson *et al.* 1984); however, unlike in a categorical coverage, the zones on a choropleth map are predetermined mapping units for which a representative value (e.g., average or maximum) is measured and depicted.

The user interface design is based on the formalization of the objects and operations present in a *family of categorical coverages* (Frank *et al.* 1992), which provides both a consistent, compact description of the problem and a means of communication of functionality between the user and the developer. This is followed by the visualization of the objects presented to the user at the screen surface and the implementation of the pertinent operations.

The following section introduces a user-interface design paradigm that is tailored to complex applications such as GISs in which an interplay exists between domain-expert knowledge and human-computer interaction methods. It emphasizes the formalization of the problem at hand prior to the discussion about its visualization and interaction concerns. The remainder of this paper documents the design of a GIS user interface for attribute data within this framework. Section 3 describes informally the cartographic concept of a categorical coverage. Section 4 formalizes the relevant parts and section 5 presents one possible visualization/interaction with a WIMP (windows-icons-menus-pointing devices) user interface. The paper concludes with a summary of the results.

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2 Formalization and Visualization

"Current commercial GISs widely disregard fundamental aspects of human-computer interaction. GIS users need extensive and expensive training prior to using a particular system, due to the researchers' and designers' concentration on functionality and implementation rather than usability. Systems tend to evolve from a small set of commands to hundreds of features without the necessary considerations of how users learn them and interact with them" (Frank *et al.* 1991). Exceptions to this trend are the design of Arc/View, parts of which had undergone extensive theoretical investigations prior to its implementation (Jackson 1990; Kuhn *et al.* 1991), and user interfaces that build on Tomlin's (1990) map algebra (Kirby and Pazner 1990; Egenhofer and Richards 1993).

To overcome some of this *ad hoc* mentality in GIS user interface design, we propose a three-tier framework for the design of GIS user interfaces (Fig. 1). The three steps are interleaved, but different enough to warrant such a separation. Each step requires from the user-interface designers distinct qualifications and command in a number of areas.

- First, formal systems with well-defined behavior and properties are investigated with respect to the problem. This process uncovers the pertinent objects, operations, and behavior of the problem that must be dealt with in the user interface. During this phase, the designers lay the ground for what the system will be able to do and what it will not.

- Second, different interaction procedures are investigated to allow prospective users to perform the intended manipulations. The formalism is used as a consistent foundation from which various user interfaces can be developed according to different interaction techniques such as command-line, windows, and icons. The formalism of objects and operations identifies the core functionality necessary for all the various user interfaces. Therefore, the evaluation of the user interface can focus on the different interface techniques.

- Third, each visualization- and interaction-design is implemented on a particular platform with its operating system and specific user-interface management system, toolbox, graphics library, etc.

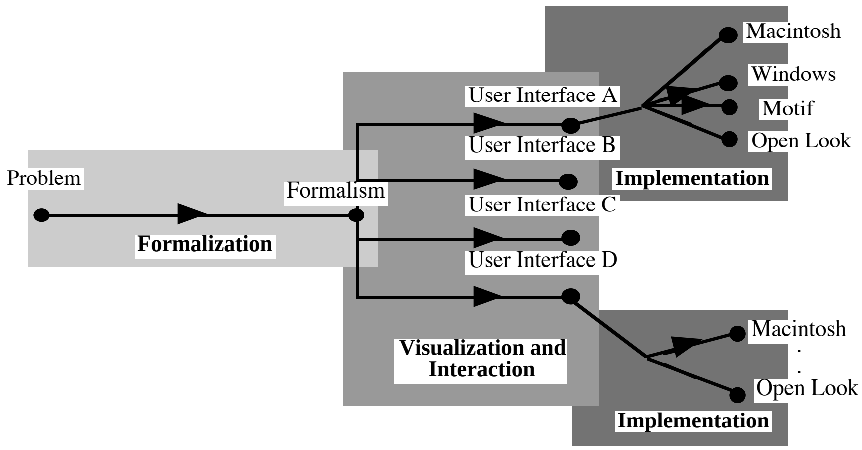

Fig. 1. User interface design process.

The background knowledge necessary in each of the three areas is fairly distinct and the fallacy of many GIS user interfaces is that too often a single user interface designer is expected to master all of them.

- In order to formalize the objects and operations with which a future user will deal, a designer has to know about the problem domain and needs sufficient knowledge of and practice with the formalization tools (e.g., specification languages, algebras); therefore, we will call them the *domain experts.* Without their active involvement in the design process, any user interface will be something made by a designer society for a user society.

- During the second phase, the designer must be proficient in cognitive analysis, psychology, human-computer interaction techniques, and graphics art. This may be what is commonly understood by the *user interface designer* (Mulligan *et al.* 1992). The focus during this phase is on the translation of the domain experts' specifications into a particular interface environment and it involves giving feedback to the domain experts so that they can improve their design in close cooperation with the user interface designers.

- The third phase of the user interface design requires extensive expertise in user-interface programming, graphics packages, and user-interface management systems. We call these experts the *user-interface software engineers.*

We will employ this framework here to design a user interface for the interaction with geographic attribute information.

3 Categorical Coverages

The *categorical coverage* (Chrisman 1982), also known as area-class map (Bunge 1966), is a type of thematic map, which concentrates on the spatial variations of a single attribute (Robinson *et al.* 1984) and shows the relationship of an attribute to a specific geographic area. It depicts a specific bounded area by a set of mutually exclusive and collectively exhaustive regions. The theme and its subcategories are determined initially and the specific area is then evaluated according to the thematic criteria. Every geographic unit is evaluated according to the predetermined classes resulting in regions comprised of homogeneous value. A prototypical example of a categorical coverage is the land use map (Fig. 2), in which a taxonomy of land use classes is determined (Residential, Commercial, Industrial, and Transportation) and then the specific area is evaluated along the values of this theme.

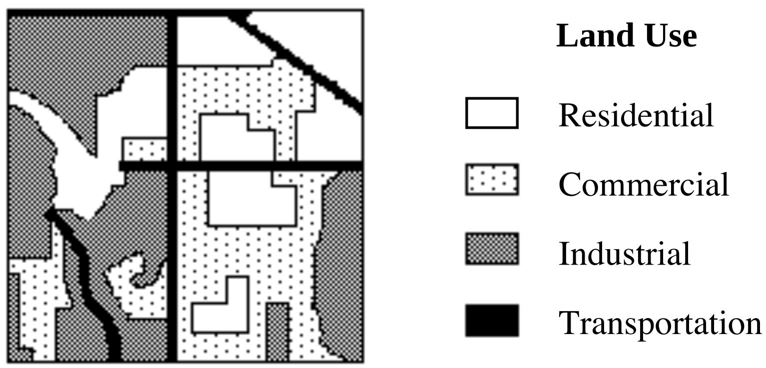

Fig. 2. Simple categorical coverage for land use.

Categorical coverages describe a subset of space thought of as a 2-dimensional plane, possibly embedded in 3-dimensional geographic space. This space is conceptualized as regular Euclidean space and typically mapped onto $\mathbb{R}^2$. For the categorical coverage, the spatial data model—raster or vector—is of limited importance. Either model can represent the necessities of a categorical coverage. We will proceed with the assumption of a vector model, thereby focusing on the identity of the zones belonging to attribute classes and thus ignoring individual pixel values.

The zones of a categorical coverage (Fig. 3) are an exhaustive subset of space and that not overlap (Beard 1988).

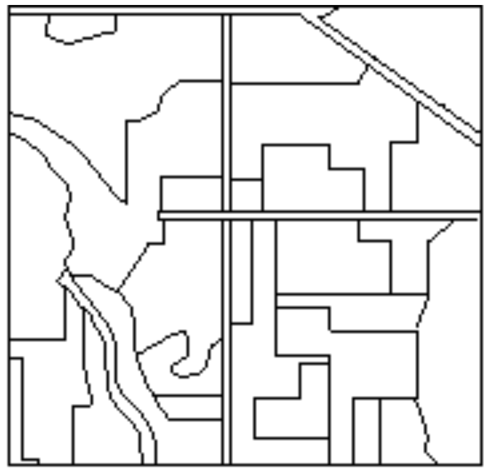

Fig. 3. The zones of the categorical coverage.

Categorical coverages have a theme that is based on the purpose of the examination. The theme of the categorical coverage is a domain of attribute values (categories) that describe the salient properties of a given space. The domain consists of a finite or infinite number of attribute values, which are at least discernible on a nominal scale, but often have more internal structure. The set of values that are differentiated are often called the *categories of the coverage* (Beard 1988). The categories form a partition of the domain of attribute values. Attribute values are often ordered hierarchically, typical for taxonomies.

Conceivably, more than one categorical hierarchy can be built from the same initial coverage in order to address a different map purpose (Fig. 4). The collection of these categorical hierarchies has been called a *family of categorical coverages* (Frank *et al.* 1992). A family of categorical coverages is defined as all possible categorical coverages that can be deduced from a single, most detailed coverage. Each member of the family will preserve various levels of the original categorical detail. The cardinality of the domain of attribute values (finite or infinite) of the theme determines the cardinality of the complete family of categorical coverages.

The operations discussed in this paper for the construction of a categorical coverage apply only to the categories of the attribute values. These operations induce changes in the complexity (the number of zones) of the spatial domain. There are no operations that are directly applicable to the geographic domain except the cartographic viewing operations, such as the selection of symbology, which are omitted from this discussion. However, if we allow that the display of the categorical coverage is only an approximation to its conception then additional operations become necessary to show the coverage on any given display device. These generalizations are better considered as part of the cartographic rendering process than the formation of the categorical coverage.

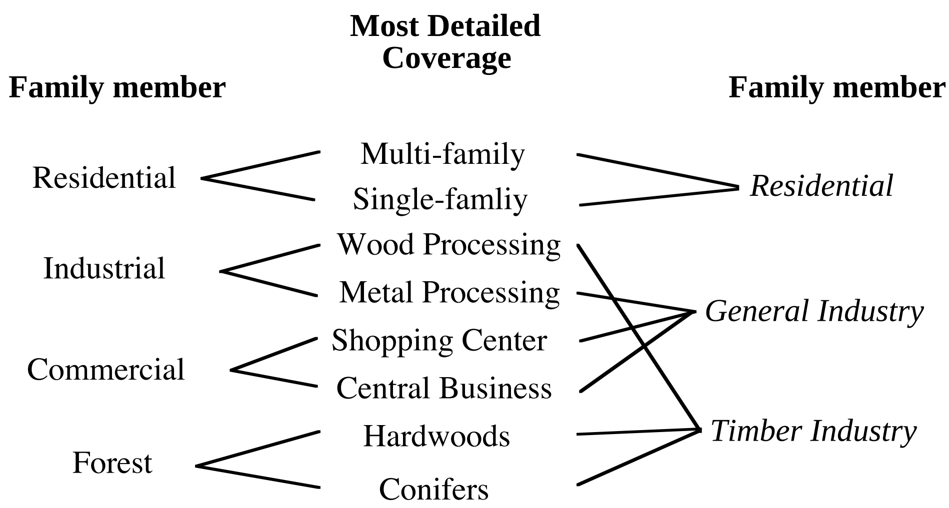

Fig. 4. Partial family of categorical coverages.

4 Categorical Coverages and Partition Formalism

The basic concept of a categorical coverage is such that the attribute categories are defined first and the spatial zones are then constructed corresponding to these categories. There are distinct connections between the attribute and geographic domains of a categorical coverage and partitions. The common objects of this relationship are described in Section 4.1 and followed by a discussion of common operations.

4.1 Objects

An attribute domain or theme, A, corresponds to a "universal set" of attribute categories or values, $\{a_0, a_1, ..., a_n\}$. The set of attribute categories for a categorical coverage defined by the data collection and input procedures is finite and by default, defines the universal set of attribute categories. While in reality additional categories for a particular theme can always be created, they may be deemed unnecessary for the purposes of a particular categorical coverage mapping. The union of all a_i equals A, and the set is said to be collectively exhaustive of A. This must be the case for a categorical coverage because geographic areas of undefined attribute values may occur. Therefore, the attribute domain of a categorical coverage is characterized as follows:

$$A = \{a_0, \ldots, a_n\} \qquad (1)$$

$$\bigcup_{i=0}^{n} a_i = A \qquad (2)$$

For a categorical coverage, the mapping of each unit of the geographic domain is restricted to exactly one attribute category. Therefore, all elements of the set of attribute categories must be mutually exclusive.

$$\forall_{i,j \mid i \neq j} \quad a_i \cap a_j = \varnothing \tag{3}$$

The intersection of all the attribute categories must be empty to insure that there are no geographic overlaps. For instance, reality may show a geographic unit to be both wooded and wet, but it can not be mapped both Forest and Wetland in a categorical coverage. The most distinguishing characteristic must prevail (Forest or Wetland) or a new category, for example Wooded Wetland, must be created.

If these conditions are met, the set of attribute categories form the thematic component, a partition of A of a categorical coverage, denoted by P_A.

The definition of the attribute domain directly affects the representation of the geographic domain, G. The geographic domain corresponds to a "universal set" of geographic positions. Every position (x, y) in G is mapped onto exactly one attribute value that exists in the attribute partition, P_A (Fig. 5).

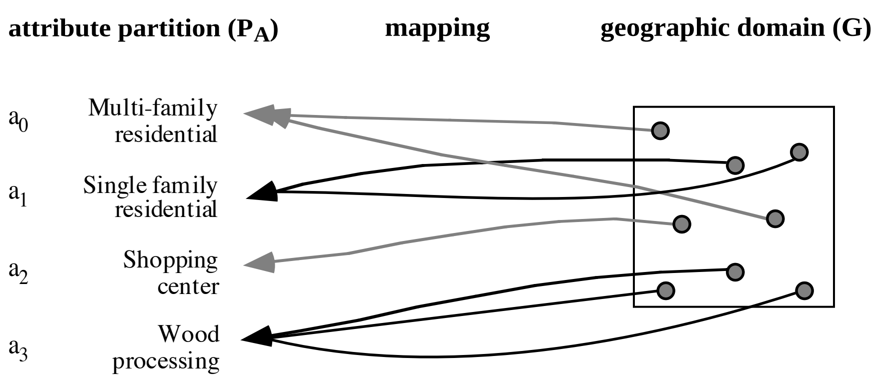

Fig. 5. Creating a categorical coverage.

These points are grouped by equivalent attribute value to form homogeneous zones, $\{g_0,...,g_m\}$ (Fig. 6). These zones become the elements of the geographic domain. The mutually exclusive and collectively exhaustive properties of the attribute category set also hold for these zones. Therefore, the set of zones form a partition of the geographic domain, P_G.

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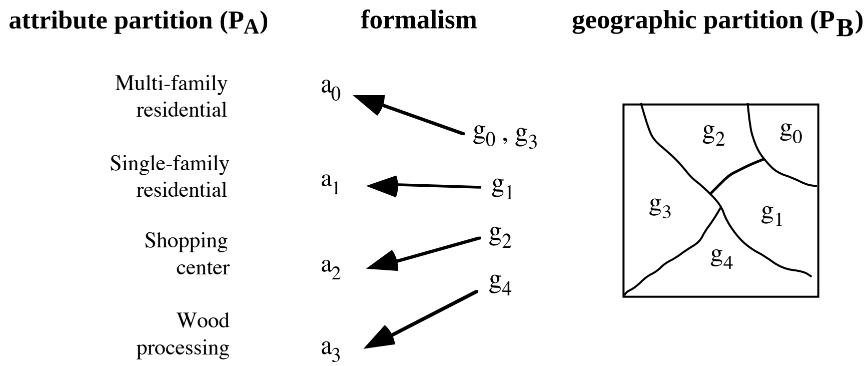

Fig. 6. Formal components of a categorical coverage.

Although, both the geographic and attribute components are essential to a categorical coverage, the geographic domain is only a spatial representation, which is dependent on the definition of the attribute domain.

4.2 Operations

The attribute domain and the geographic domain of a categorical coverage are both forms of a set and partition and therefore, share the behavior of a partition. As defined by refinement of partition, a partition of a set can be further refined such that an additional partition is created. Successive refinement of partitions on a set will result in an ordered hierarchy of partitions (Fig. 7).

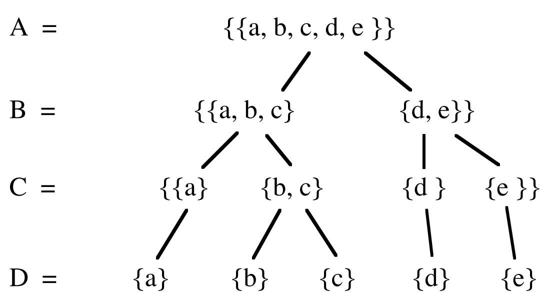

Fig. 7. Ordered hierarchy of partitions.

Spatially, this refinement can be visualized by the decomposition of a space into a set of mutually exclusive and collectively exhaustive polygons (Fig. 8).

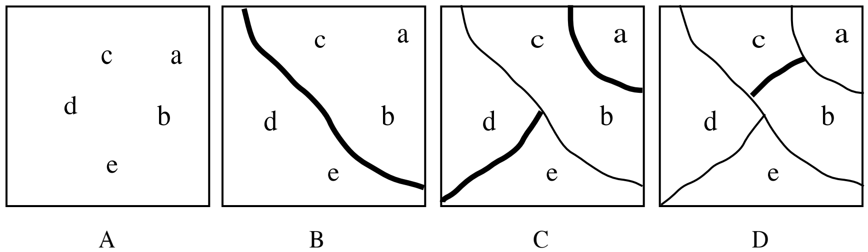

Fig. 8. Corresponding spatial partitions.

Partition *D,* in both the attribute example (Fig. 7) and the geographic example (Fig. 8), which was constructed from *A* through *B* and *C* respectively, is the most refined partition of this set since all the elements of the initial set are themselves blocks of the partition. This partition, *D* in Fig. 7, is analogous to the categories of a categorical coverage. In a GIS, a most detailed partition (a set of most detailed categories) is predetermined by the data stored in the system. This partition is the link to the formal notion of refinement of partitions. This categorical coverage contains the maximum number of categories, which determines the maximum number of zones possible for this coverage.

Additional, less detailed coverages can be created from this initial coverage by classifying the categories into more general categories. This may induce an aggregation of zones in the geographic domain. This classification operation, defined as coarsening, must abide by the same rules as for refinement of partitions. Chrisman (1982) and Beard (1988) have used the term *coarsening* with respect to categorical coverages to describe a spatial operation that is intended to remove sliver polygons generated from an overlay. Their definition of coarsening is meant as a spatial, attribute, and topological generalization tool. Coarsening, as it is used in this paper, is strictly an attribute classification mechanism. For the coverage to remain a categorical coverage, the categories can only be coarsened into one higher category (maintains mutually exclusivity) and all categories must be included in at least one higher category or it becomes one itself (maintains collectively exhaustive property). The categorical coverage that results from a coarsening will have fewer categories and potentially fewer zones. The relationship between set partitioning and attribute coarsening is such that in the case of the categorical coverage, the blocks are built from merging the individual attribute categories (elements), whereas the blocks in set partitioning are built from decomposing an initial set into individual elements.

As refinement partially orders partitions, coarsening partially orders the categories of the attribute domain. Therefore, once a categorical coverage hierarchy is built through coarsening (Fig. 9), it is possible to state that a categorical coverage is a refinement of another.

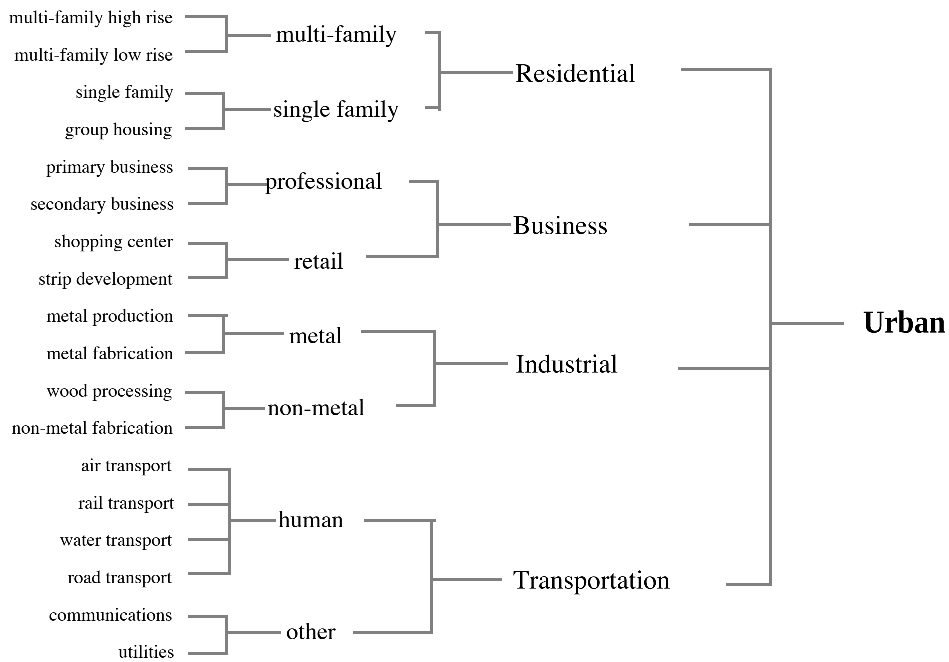

Fig. 9. Multiple attribute coarsenings

By the nature of the coarsening operation, the initial set of attribute values becomes a refinement of the partition resulting from the first coarsening (Residential, Commercial, Industrial, and Transportation) and this partition is then a refinement of the partition resulting from the second coarsening (Urban).

The refinement of a partition relation is such that a partition can be a non-proper refinement of itself if $A \leq B$ and $B \leq A$, implies that $A=B$. Proper refinement, on the other hand, states that at least one subset of the refined partition must be a proper subset of the initial partition. The inverse, or *proper coarsening*, as applied to the attribute domain of a categorical coverage, could then be defined to be any coarsening where at least two elements of the previous attribute partition are classified together to create a "new" attribute category. In this case, it can be said that the geographic representation will contain less than or equal to the number of zones of the previous partition.

The geographic property that determines the number of zones is *contiguity*. If the geographic representation after a proper coarsening does not change (same number of zones) then the zones involved in the attribute coarsening are not contiguous. Contiguous zones are defined as any two zones sharing a common edge such that they exhibit the "1-meet" relation betweeen regions (Egenhofer and Herring 1990). Any two or more contiguous zones whose corresponding attribute values are coarsened to the same category are also geometrically merged to form one zone. This merging operation increases zone areas, which graphically results in a less detailed geographic representation.

Coarsening will usually result in partitions consisting of fewer, but larger zones and fewer and less descriptive attribute categories. This is sufficient for organization of the attribute domain, but is insufficient for proper exploratory analysis of the domains. A selection operator that is be constrained by the rules of refinement, is needed to enhance this analysis ability. Such an operator should provide for varying limbs of an attribute hierarchy to be selected for display, thus allowing varying levels of attribute detail, without explicitly requiring another attribute coarsening.

Once any attribute hierarchy is completely built, an additional operator is needed to directly control the display and facilitate exploration of the hierarchy.

4.3 Family of categorical coverages

In a family of categorical coverages, all family members (M_1, ..., M_f) are attribute hierarchies and are built from the same initial set of attribute values and corresponding geographic zones by coarsening the attribute domain. The complete set of hierarchies constitutes a family of categorical coverages.

Within a member of a family, it is possible to distinguish a refinement without detailing whether it is a refinement of the attribute domain or a refinement of the space partition (it is automatically a refinement of both). However, this is only true for refinement, not proper refinement: a partition of the attribute domain, which is a proper refinement of another one, only induces a refined partition of space (not a proper refinement of the partition of space).

5 A Visualization

The previous section detailed the objects and operations that linked the categorical coverage to the mathematical concepts of the partition. This section discusses the visualization of a user interface based on the principles set forth by the formalism. The user interface presents the objects and operations of the categorical coverage concept to the user through the framework established by the formalism.

5.1 Objects

The separation and dependence of the attribute domain and the geographic domain fit nicely to the user interface concept of a dual representation. An example of this concept using two windows of the respective components of a categorical coverage is shown in Fig. 10. This example of a dual representation using windows is continued throughout the remainder of this section to illustrate additional elements of the categorical coverage interface. The attribute domain is shown textually by attribute category. The geographic domain is shown geometrically. Since the categorical coverage is based solely on attribute manipulation, the attribute window will be where all the user interaction takes place. The geographic window is simply a passive window used for viewing the attribute interaction.

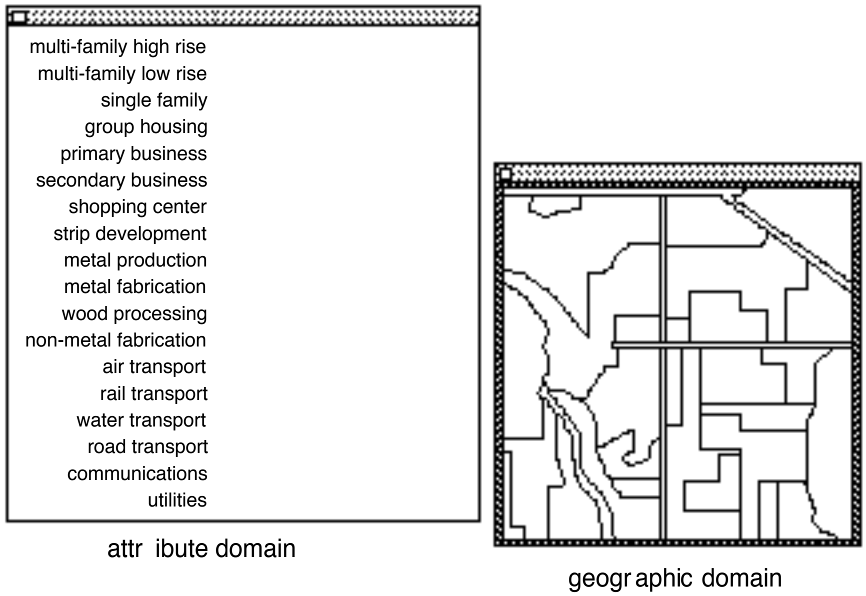

Fig. 10. Window interface for categorical coverage.

5.2 Coarsening

The primary attribute manipulation operation is the coarsening operation. Fig. 11 visualizes this concept of attribute coarsening in the context of the window interface shown in Fig. 10. In this example, “new” attribute categories are created to lessen the thematic or geographic complexity of the categorical coverage.

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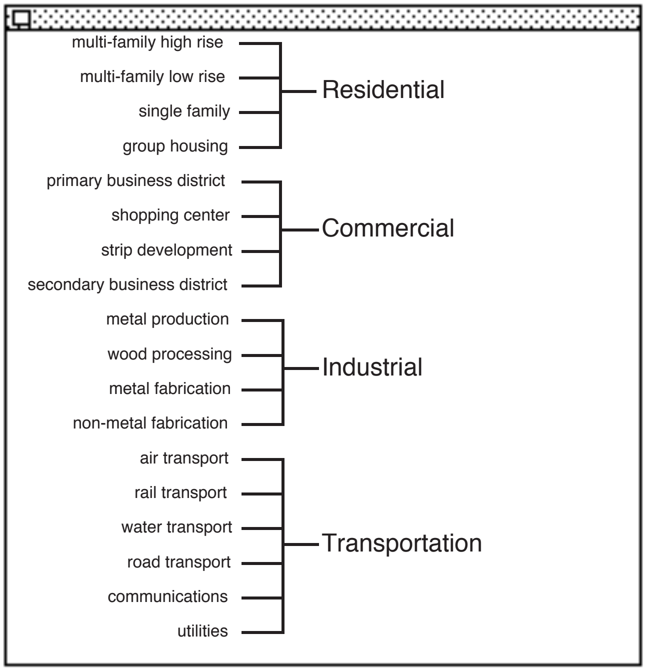

Fig. 11. Attribute coarsening.

In order to enhance exploratory analysis of an existing categorical coverage partition hierarchy, a selection tool can be added to the interface. Such a tool could select/unselect a portion of the hierarchy for viewing. In Fig. 12, the higher level category of Transportation has been selected and hidden in favor of the more detailed categories of air transport, rail transport and so on. This operation carried out by a pointing device is shown progress on the category Residential. This operation allows a user to quickly obtain the desired level of complexity of an existing hierarchy without the nuisance of coarsening the coverage from the initial set of attributes for each session.

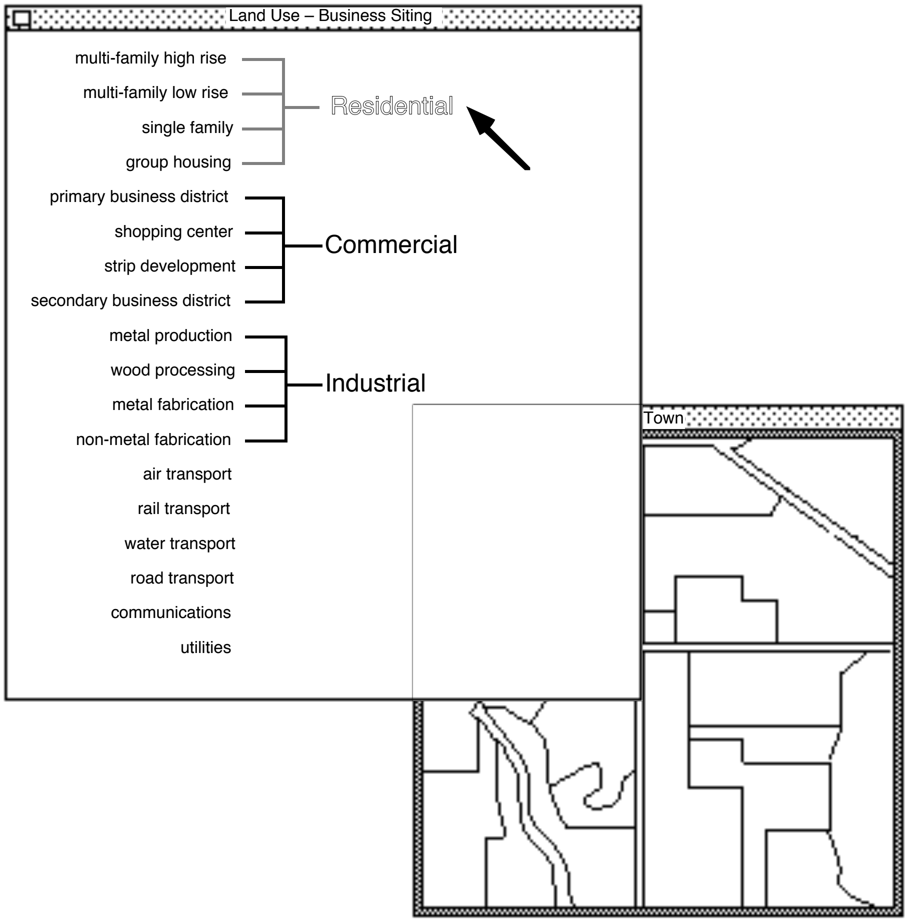

Fig. 12. Selection of attribute detail.

5.3 Family of categorical coverages

The user interface for the family of categorical coverages incorporates all of the above functionality and must also provide the means to choose a family of coverages and a particular coverage. In Fig. 13, another window is added to handle this functionality. The family of coverages is chosen by a click and select of a "pop-up" menu. Other families of coverages for the geographic location of Old Town could be Soils, Parcels and so on. The number of initial attribute values of any particular family is given as ancillary information. Within any single family, many coverages may exist. A similar "pop-up" menu is provided for this operation as well. The number of existing partitions and zones is given in this case to aid the user in the selection.

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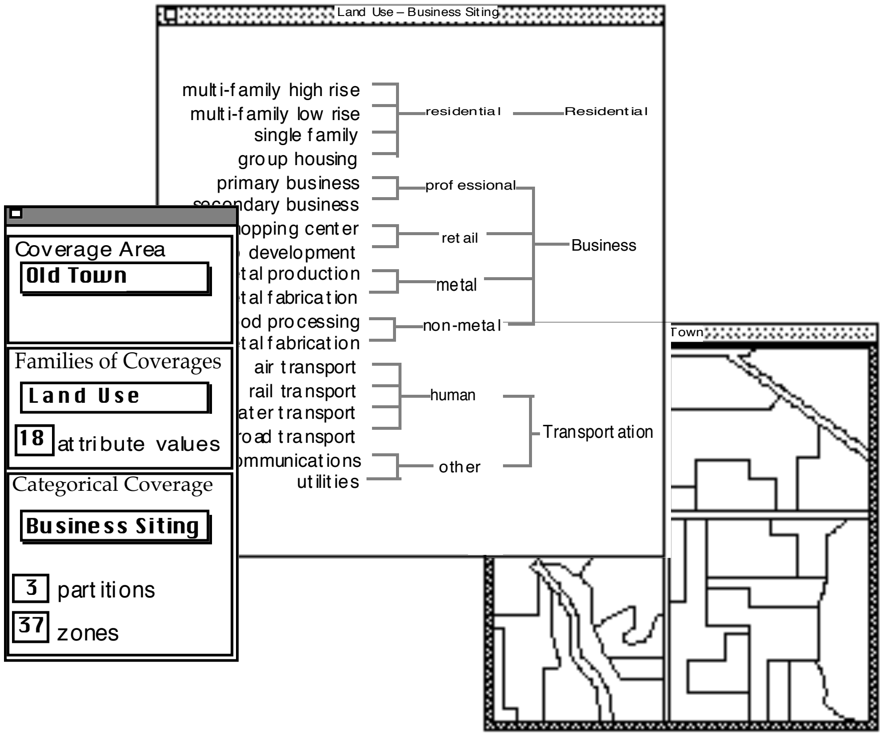

Fig. 13. User interface to select family of coverage and member.

6 Conclusions

This paper discussed GIS user interface design. The novel approach was the conceptual separation of the entire process into *formalization, visualization/interaction*, and *implementation*. During the formalization, designers identify the objects and pertinent operations a user wants to perform. Of particular importance is here the intense knowledge of the application domain and what prospective users will do with the planned system. During a second phase, designers identify interaction techniques that are best suited to implement the intended users interface. Here, particular considerations of cognitive and ergonomic issues are important for the successful design of a user interface. Finally, user interface designers who master the particular software implementation aspects will implement one or more user interfaces on a variety of hardware and software platforms. There is some overlap among the three steps and certainly members of the different subsets of the design team will interact and provide feedback to each other.

Within this framework, we discussed the design of a user interface for interacting with attribute data in a GIS. First, the well-known cartographic concept of a categorical coverage was formalized for the purpose of designing a human-computer interface. The formalism relies heavily on partition theory found in mathematics and serves as the conceptual model for functionality of the intended user interface. It was shown how the geographic zones in a categorical coverage are induced by the creation of the attribute categories. The refinement operation in set partitions was found to provide the fundamental rules for expanding the functionality of the categorical coverage in a GIS environment to include a hierarchy of categories, each step in the hierarchy itself a partition in the attribute and geographic domains.

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