Generalizing GIS:
Development of Spatial Grammars for Landscape Planning

Kevin Mayall
Department of Planning
Government of Bermuda
Hamilton, Bermuda

G. Brent Hall
Faculty of Environmental Studies
University of Waterloo
Waterloo, Ontario N2L 3G1

ABSTRACT

The use of spatial data technologies in urban and regional planning is something of a paradox. While conventional spatial data tools represent specific, real-world objects (whether existing or proposed), local planning agencies are charged with creating generalized, non-specific statements that are applicable across all properties within their jurisdiction and that are, in specific instances of regulatory planning, intended to produce a desirable landscape character. This paper describes an approach to digital landscape modeling that allows these generalized statements about landscapes to be encapsulated within ascribed *landscape grammars* and then visualized by generating scenes of landscape objects for both current and future landscape characters.

Keywords: landscape character, landscape modeling, landscape grammars, generative 2 and 3-D visualisation

1. Background

The high value attached to the visual landscape character of a region by its residents renders that character a resource. The need for the careful planning and management of this resource is underscored by the perceived threat of the homogenization of landscapes by globalization and mass development. Planning agencies are increasingly required to plan for the preservation of existing (or creation of a new) distinctive landscape character. This is especially true of jurisdictions that have small and limited land areas that embody a distinctive and valued character. Such places value highly the visual appearance of their landscape, not only for reasons of cultural identity but also for the economic purposes of a marketable and appealing image for the attraction of tourism and other business.

In order to manage the preservation or creation of a distinctive and pervasive landscape character, planning authorities must be able to define those features that contribute to the local visual character. Such a landscape character definition describes not only the types of physical landscape objects that are visually significant but also their typical characteristics and relationships to one another in space. By identifying these recurrent qualities of the local visual character, planners articulate their knowledge of the landscape in terms of a generalized definition of landscape objects and patterns. Such generalized definitions of a landscape are embodied in the application of heritage planning, in instances, for example, where historical building façades are retained to portray the legacy of the past even although their interior may have been totally renovated to modern form and function. On a broader scale, expressions of vernacular architecture and function are expressed in large scale landscape canvases, such as the American casino city of Las Vegas, or the Chinese city-state of Macau, which combines elements of its Portuguese colonial past, with its post-colonial Asian presence, combined with the same type of casino culture as Las Vegas. Further examples are not difficult to find, as they occur to varying extents in almost every urban, rural and even wilderness landscape.

In addition to defining expressions of their local 'landscape knowledge', planners must write policies that will influence development in such a way as to maintain or produce the desired character of a landscape without dictating the specific form of each feature. Planning regulations are seldom defined on a site by site basis but instead written to be generally applicable to sites across a region. Regulations governing landscape form often define the bounds within which physical development should occur. Therefore, like the description of a local landscape character, planning mechanisms, such as land use zoning regulations, are written in a generalized form rather than specific to actual physical objects. We may even regard planning policies and regulations as an articulation of planner's knowledge as to how the landscape *should* be formed in order to maintain a desirable landscape character.

Because regulations governing form are applied iteratively across a landscape during the life of a plan, they influence the local landscape's visual character over time. The visual impacts of policies and regulations on the landscape should therefore be of concern to planning agencies that govern a valuable visual landscape resource. There is therefore a need for local planners to define a desirable visual landscape character, write policies and regulations that maintain it and then examine whether those regulations are effective in producing the intended physical consequences in the landscape. While there has been much study of the aesthetic quality of particular landscapes, the development of methods to define a generalized landscape character and ultimately to test its consequences in the landscape have not yet been forthcoming.

Geographic information systems (GIS) have become principal planning tools for the storage and analysis of information regarding local landscape features. In serving the above purposes, GIS can be consulted to identify those features that exist in the local landscape and to perform descriptive analyses of those features. For example, a spatial database containing records of the locations and shapes of buildings, roads and woodlots can be queried to describe the proximity of buildings from the road and to identify which buildings are located within or nearby a woodlot. GIS data layers may even be modified to include hypothetical features, such as new buildings, and then analyzed to determine the proximity or other relationship of these new features to existing ones.

While GIS tools are undoubtedly powerful, they are not suited for the purposes of defining and maintaining a general landscape character. Their deficiency lies mainly in the fact that the technology is designed to provide an inventory of specific object records, including their spatial locations and non-spatial attributes, while landscape character is defined by generalized statements that are not location-specific. A GIS, as its name implies, records object-specific information rather than generally applicable knowledge pertaining to landscape form.

This deficiency is also the source of a paradox relating to the use of GIS in urban and regional planning. As established above, planning devices, such as official plans, regulations and codes, most often refer to objects in the abstract rather than specific instances and locations. Consider typical regulations such as "buildings may have no more than three storeys", "woodlots greater than 100 square metres may not be encroached upon by development", or "a development setback of 25 feet must be maintained from a shoreline". Despite their widespread use, GIS tools do not allow the definition of such commonplace spatial statements, other than through simplistic and mechanistic use of functions such as object buffering, nor do they allow the examination of their visual impacts on the physical landscape.

In the following section, we outline an approach to new geographic systems that allow their users to define their idiosyncratic, yet generalized knowledge about a landscape character. For planning agencies, generally applicable regulations may be incorporated into these systems. While these systems provide the capacity for storing this landscape knowledge, they also provide the mechanism to test this knowledge by generating hypothetical landscape data that conform to the stored landscape character definition.

2. Landscape Knowledge as Grammar

In codifying landscape knowledge, we can use a metaphor comparing landscape to language. The landscape-language metaphor is well established by observers of landscape form, especially built form, in the recognition of local architectural "vernacular" forms. We draw on this metaphor more formally to provide a model for describing landscape character. In this model, a particular landscape scene may be composed of objects (words) that are arranged in a meaningful way to form an ordered collection of objects (sentences/phrases) that evokes meaning for the landscape viewer. In generalizing about all landscapes scenes, we define types of objects that may occur (a vocabulary) and rules as to how they may be combined (syntax). The vocabulary and syntax rules together comprise the landscape's *grammar* which can be used in analyzing existing or constructing new landscape scenes (sentences). The complete range of possible constructions comprises the entire 'language' of the landscape character, that is all possible scenes that conform to that character. A *landscape grammar* therefore defines a visual landscape character using a spatial vocabulary and syntax rules.

The idea that grammar rules can be used constructively to generate new sentences is attributed to the linguist Noam Chomsky and his introduction of generative phrase-structure grammars (Chomsky, 1957). The application of this idea to landscapes necessitates the extension of grammatical structures from linguistic structures to spatial concepts. Stiny and others have explored the use of 'shape grammars' that define and combine shapes in various ways to produce geometric patterns (Stiny, 1980a, 1980b; Chase, 1989; Krishnamurti & Stouffs, 1993). Architectural researchers adopted this approach to define styles of architecture in terms of the types of building details used and how they are arranged together in space (Stiny & Mitchell, 1978; Koning & Eizenberg, 1981; Flemming, 1987; Mitchell, 1990; Seebohm & Wallace, 1998). Cellular automata are closely related to this concept as they operate in a grammatical manner, albeit defining space as a grid of cells instead of discrete shapes (Wolfram, 1994). In this paper we extend these grammar applications to landscape in general and find particular potential for the use of landscape grammars in planning a landscape character.

3. Formal definitions

As suggested above, a landscape grammar is comprised mainly of a vocabulary and a set of grammar rules. The *vocabulary* defines the types of objects that may typically be found in a landscape. In defining a type or class of landscape object, a spatial type must be specified (e.g. point, line, polygon) and each attribute that would be associated with such an object must be described. For example, we may define a Tree class as comprising a point and the attributes height, age, species, and trunk and branch radius. We also apply a hierarchical inheritance structure to the landscape object classes. A Building class, for example, may be defined as a super-class of Shop, Church, House, and Garage sub-classes, each of which inherits the spatial type and attribute definitions of the Building class. This hierarchical inheritance feature is adopted from the object-oriented data model which has become well established in knowledge representation methods from artificial intelligence research.

The vocabulary provides the vehicle for generalized descriptions of the objects in a landscape. A specific physical object is an instance of an abstract landscape class from the vocabulary. Each object contains an instance of the spatial type defining its geometry and a set of values defining its attributes. A particular landscape *scene* is comprised of a set of specific landscape objects derived from the vocabulary. We extend this definition of a scene to include continuous cellular grids of values such as elevation, slope or soil depth.

Landscape scenes are, however, more than just *ad hoc* collections of objects. The objects are spatially related to one another. Such spatial relationships are defined in the syntax rules of a grammar. A *grammar rule* is therefore a pair comprised of an antecedent and a consequent. A constructive rule may be read generally as "if <antecedent> is true, then perform <consequent>". The antecedent is made up of a set of predicates that refer to hypothetical objects, such as "a building abuts a sidewalk", "a tree is situated between a house and a road", or "a parcel contains an orchard". Such predicates are combined together as a composite predicate function that accepts a set of landscape objects from a scene and returns a true/false result. The consequent is a set of actions that when executed modify a landscape scene in some way. The statements used in the antecedent and consequent of a landscape grammar rule typically make use of spatial functions and refer to the spatial and non-spatial attributes of objects in a scene. The following is an example of what a landscape rule might look like written in pseudo-code. The rule states that if a house is greater than 10 metres from a road, then a moderately sized maple tree is often found between them.

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IF:   is-a(a, House) AND is-a(b, Road) AND distance(a, b) > 10
THEN: insert(Tree, midpoint(a, b) height = 5, species = maple)
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In order to use this grammatical structure in generating new landscape scenes, we utilise a landscape grammar interpreter program that accepts an initial scene of objects, a vocabulary of landscape classes, and a set of spatial grammar rules. The interpreter iteratively uses the grammar rules to modify the landscape scene. With each iteration, the interpreter first begins a process of identifying a set of matching rules, that is, those rules whose antecedent is true for some combination of objects from the scene. Consequently, for each matching rule, the sets of specific landscape objects for which the antecedent is true (the matching objects) are also identified.

Any of the matching rules may be *fired* on the landscape scene, that is, a set of matching objects are inserted in the consequent statements and the consequent is then executed modifying the objects in the scene. Because the firing of one rule may modify the matching objects of another rule, only one rule may usually be fired at a time. This necessitates a mechanism for selecting one rule from the matching rules, as well as one set of objects from the matching objects, before firing the selected rule on the selected objects. With each firing of a rule, the interpreter begins a new iteration searching again for rules that apply to the now modified scene of objects. These iterations continue until no more rules apply to the scene or some user-defined goal is reached.

The end result of a number of iterations of the landscape grammar interpreter is a scene of objects that have been created in conformance with the definitions of classes in the vocabulary and spatial relationships in the rules. The resultant scene can be visualized by displaying graphically (in either two or three dimensions) the shapes of the objects in the scene. For a given initial scene, vocabulary classes and a set of rules, the interpreter can produce the same landscape scene. However, the introduction of random or stochastic elements to the grammar (such as in object locations, dimensions, and attribute values or in the selection of rules) greatly increases the range of possible scenes that can be generated by the interpreter.

We asserted originally that landscape character is made up of those types of objects and spatial relationships that recur through a regional landscape. The landscape grammar structure defines these ideas formally in terms of a vocabulary and rules. The landscape grammar interpreter uses the grammar to generate various scenes of objects. These scenes conform to the grammar and therefore the landscape character as defined in that grammar. By visualizing some of the possible landscapes that embody the defined character, we effectively explore the range of that landscape character. While it would not be feasible to generate the entire range of possible scenes for a landscape grammar, a grammatical interpreter, by automating the construction of landscapes, provides the mechanism to explore more of the possible outcomes than is presently available by manual digital landscape construction methods.

4. Grammar Uses

The power of landscape grammars becomes evident when we consider the grammar to be not an authoritative definition of a landscape character, but rather the formal expression of someone's *ideas* about a landscape character. Hence, the landscape grammar is effectively a knowledge-base pertaining to the spatial and visual characteristics of the landscape. The knowledge it represents is most likely imperfect to some degree. By visualizing the outcomes of applying the grammar in a virtual landscape, we are able to identify imperfections and consequently revise the classes or rules that produced them. The grammatical spatial system therefore allows the user to define their landscape knowledge, test it, and enter a cycle of knowledge refinement based on the visual results.

Landscape knowledge articulated in a grammar does not have to be limited to the superficial description of arrangements of objects. There are often explanations behind the observed traits and patterns of objects in a landscape. We may know that the reason a species of tree is only found in low-lying areas is that it needs the greater depth of soil in order to root itself there, or that the reason for a proliferation of front porches on houses is that members of the community regularly engage in evening activities there. To extend the landscape-language metaphor, we say that landscape patterns have *semantic* content therefore including not only how objects are arranged but why they are so arranged. The semantic content behind patterns of natural landscape objects may have an ecological basis, while that of built structures may have a cultural basis, as the examples above imply. The inclusion of semantic content in a grammar causes us to articulate better our understanding of landscapes.

In planning activities, the adoption of landscape grammars presents an opportunity to define idiosyncratic knowledge of a local visual landscape character, examine it by generating scenes and thus improve the knowledge-base. In addition to natural and cultural forces, the character of a landscape is also subjected to regulatory influences from planning agencies. In the first section of this paper, we described planning regulations in terms of general statements that are applied to sites across a landscape. Such statements, which could relate to, for example, site layout, architectural vernacular, or forest management, are often amenable to representation in a grammar. New regulatory spatial elements, such as setback lines, building envelopes or sightlines, may be added to the landscape vocabulary. Many planning regulations can be expressed as rules stating permissible characteristics or relationships between objects, for example using materials requirements, functional requirements or minimum/maximum quantities, distances, areas or volumes. By expressing planning regulations as vocabulary classes and spatial rules, we transform them into the same grammatical format as the existing knowledge-base of natural and cultural patterns. Through the interpretation of the grammar and generation of scenes, the interplay and effects of planning regulations and natural/cultural phenomena can be visualized in a virtual landscape scene.

We have concentrated here on generative landscape grammars, that is those that construct landscape scenes. Landscape grammars may also be analytical, deconstructing a complete landscape scene according to syntax rules. This is, in effect, working in the opposite direction from a generative grammar. Analytical grammar rules infer their antecedent based on whether their consequents are applicable to the scene. Processing a landscape scene with an analytical landscape grammar interpreter iteratively removes elements from the scene. If the scene can be 'undone' in this way, then it is considered an example of the landscape character embodied by the grammar. Such a tool would be useful for planners attempting to describe whether a development proposal conforms to the local character. Writing an analytical landscape grammar is not, however, a simple matter of reversing the direction of the generative spatial rules mainly because there are usually several ways in which a complex landscape may be deconstructed.

5. Implications for GIS

Technologies that represent landscapes (specifically, GIS and CAD) have been in use for approximately three decades. These technologies are designed to store large amounts of landscape data but not to reason about them. They are 'information-rich' but 'knowledge-poor' in the sense that when landscape professionals such as planners and architects use them to construct digital versions of landscapes, any general knowledge of how the objects relate to one another is held in the mind of the designer and not explicitly stated in the modeling activity.

A landscape grammar system makes that knowledge explicit. A grammatically generated scene is an instance of the defined landscape character, including its vocabulary of class definitions and rules of spatial relationships. In this sense, the grammatical scene carries knowledge. By comparison, the typical GIS database contains information but is not formally linked to a body of knowledge (even though general statements may be inferred from the data). Existing spatial technologies still prove useful within a landscape grammar system. GIS/CAD techniques are needed to store, manage and graphically display the scene of landscape objects created by the interpreter. Existing spatial analysis techniques help to identify particular instances of the landscape patterns that we wish to generalize in grammar rules.

Broadly speaking, we propose an extension of existing spatial technologies, beyond the management of landscape data and the derivation of information by means of spatial and non-spatial data analysis, that leads towards the articulation of landscape knowledge providing spatial relationships and semantic meaning to conventional databases. For GIS, this means a richer framework in which to model landscape phenomena, whether natural, cultural or regulatory. The adoption of digital spatial technology in recent decades has already meant greater convenience and ability in the maintenance and visualization of specific proposed changes to a landscape. The incorporation of geographic knowledge and a generative interpretation mechanism extends this capability to include the automated construction of landscape models according to a set of principles. An analytical interpreter allows spatial technologies to deconstruct a landscape to determine if it 'makes sense' according to the knowledge captured in the landscape grammar.

Some encouraging precedents already exist that can contribute toward this extension to spatial technologies. Knowledge-based GIS have been attempted in the past although they have largely been focused on the automation of data analysis routines within an expert system. CAD-based expert systems in mechanical engineering and architecture have more typically focused on generative design although at a smaller scale and with more regularly shaped features than landscape objects. Cellular automata are spatial rule-based models of the spread of phenomena such as urbanization or disease over a continuous surface, although their capacity for representing landscape objects is limited by the raster data structure. Research in cartographic generalization has provided examples of the generative placement of objects (in this case, symbols and annotation on a map) according to the nature of an existing spatial database. These examples provide some experience in the GIS/CAD community that can be drawn upon to effect the implementation of landscape grammar systems.

Our experience with implementing landscape grammars thus far suggests that there is still much research to be done before a landscape grammar is utilized in a local planning agency. There is first a need for the GIS research community to establish formal definitions of basic spatial relationships and then make them available in spatial tools. Topological relationships between objects in a GIS are highly useful in landscape grammars but not enough. The automated construction of landscape models also requires a richer and more flexible array of spatial functions than typically exists in spatial data technologies. In the processing of landscape rules, the transition between vector, network and grid operations is required to be more fluid than in a typical analytical GIS. A body of 'common sense' landscape rules could ease the burden of constructing a grammar. Because landscape rules are processed literally by the interpreter, there is no accommodation of the unstated, common-sense rules that humans assume in their dialogues on landscape form. Even with a diversity of spatial functions available, it is often difficult to translate personal landscape observations into more formal and computational spatial rule statements.

In our research at the University of Waterloo, we have formalized the landscape grammar framework and mechanism described in this paper. We have also implemented a prototype landscape grammar system that contains a GIS with full functionality for object classes and spatial rules. The interpreter mechanism constructs two-dimensional scenes that are then exported to CAD software for three-dimensional visualization. The experience gained with this landscape grammar system prototype will likely be used to develop a new version of the system in a more robust environment.

6. Conclusions

The concept of landscape grammars addresses the deficiency of conventional spatial data technologies in accommodating generalized statements common in landscape planning activities. Spatial rules can generalize about how objects are typically located in relation to one another in a particular landscape character. The types of objects themselves are described generally using vocabulary classes. These comprise the definition of a visual landscape character in a form which can be applied to a particular site to produce a scene embodying the defined character. In addition, planning regulations can be encoded using the same structures and incorporated into the processing of the landscape grammar to visualize the impacts of planning policies on a virtual landscape before they are implemented officially.

Landscape grammars constitute a powerful concept for the definition and testing of our spatial knowledge of the landscape. Development of the grammar concept and its implementation could make it more feasible for planners to explore the spatial and visual consequences of the limitations of their landscape knowledge and the implementation of their policies. Using the knowledge-base to automate the construction of landscape models can help planners to explore more landscape futures and identify unforeseen scenarios.

More broadly speaking, there is a need for a movement in geographic data management to facilitate not just the recording of geographic objects digitally, but also to include the modeling of an organization's knowledge of how geographic objects relate to one another. Although there are still technological and design challenges in order to actualize the concepts presented in this paper, such enhancements will place spatial technologies in a better position to increase the role of learning in landscape planning and management.

7. References

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