Flexible Patterns of Place for Function-based Search of Space

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Abstract

Place is a human interpretation of space; it augments the latter with information related to human activities, services, emotions and so forth. Searching for places rather than traditional space-based search represents significant challenges. The most prevalent method of addressing place-related queries is based on placenames but has limited potential due to the vagueness of natural language and its tendency to lead to ambiguous interpretations. In previous work we proposed a system-oriented formalization of place that goes beyond placenames by introducing composition patterns of place. In this study, we introduce flexibility into these patterns in terms of what is necessarily or possibly included when describing the spatial composition of a place and propose a novel automated process of extracting these patterns relying on both theoretical and empirical knowledge. The proposed methodology is exemplified through the use case of locating all the shopping areas within London, UK.

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1 Introduction and Related Work

People live and act on space but deal and interact with places. Place is a human invention to describe space [2] and spatial experience. Several disciplines formalize the notion of place to enable a human friendly way of searching space, henceforth place *search*. Indicative approaches treat place as a reference (placename) to the geographical space either in its primitive form, or augmented with semantics, or even as a full-fledged model. An emerging question is to determine the extent to which the existing place search techniques can encapsulate the nature of place, reflecting the meaning infused within. For instance, "is it possible to locate a shopping area if it is not denoted as a shopping mall?" This work contributes to the formalization of place and development of place search methodology that is not limited to placenames or semantic infusion of spatial entities; instead, it treats places as entities that conform to specific spatial patterns. The objective of this methodology is twofold: (1) to provide an enhanced representation of place that relies on both statistical and narrative information and (2) to identify locations and extents of places that possess a set of desired features, in order to yield results that cannot be captured simply through search based on placenames or place properties.

The most prevalent method of place search relies on digital gazetteers [4], which are spatially-referenced catalogs of placenames. The major limitation of this approach is the lack of information, which is narrowed down to placenames, spatial footprints and simple properties such as place types. The use of ontologies [5] overcome these limitations. CIDOC CRM [3] is an upper level ontology that provides a detailed knowledge representation about places facilitating sophisticated search; however, most of the ontologies provide relative, limited or devoid absolute spatial representation. Ontological gazetteers [6], on the other hand, combine the aforementioned methods by enriching the traditional structure of placenames and spatial footprints with additional semantics. Nevertheless, according to [11], the meaning of place is something more than a collection of semantics.

Following a meta-modeling approach, [9] establishes places from narratives by taking into account the relations between semantics instead of lists of properties, combined with spatial information. However, the high dependency on natural language makes this approach context-dependent, as well as, it raises many technical difficulties. On the other side of the spectrum, [10] follows a bottom-up approach. Particularly, it gives emphasis on the extraction of semantic signatures of places, in the form of co-occurrence patterns of points of interest, using LDA topic modeling and statistical analysis. These patterns are then used to discover similar regions that comply to the aforementioned signatures. The unsupervised nature of this method imply certain limitations with respect to describing the plausible meaning of places.

In previous work, we proposed the model of functional space [7]. This emphasizes on a fraction of the meaning of place that is functionality. Particularly, according to this model a place is a system that satisfies people's purposes by offering certain functions. These functions are regarded as "services" enabled or disabled by the spatial organization that governs a place, known as composition. Under this model, places are formalized based on composition patterns[8], which are defined as sets of components and rules, denoted as $Comps$ and $Rules$, respectively. The former refers to the physical entities that constitute a place, whereas the latter is a set of implications between functions and first-order logic formulas that form the composition rules. These rules stand for relations between physical entities and external variables. The overall formalization is visualized in Figure 1 and the set of all the available composition rules, denoted as C_R is shown in Figure 2. Composition patterns are created through text analysis. Specifically, narratives, such as dictionaries, Wikipedia pages, design guidelines and so on, are analyzed to extract information about the functions and the composition of a place. This knowledge is then organized as a composition pattern, essentially offering a commonly accepted blueprint for the place under consideration.

The composition patterns enable function-based search of space [7], that is, locating places that support certain functions. However, the rigid rules that describe the composition patterns can be more restrictive than necessary in some use cases. In particular, since the composition rules are expressed in first-order logic, every associated function is either

Element	Description
Functions	Functions the place offers
Comp	Components that form the place
C_R	Composition rules
F_R	$F_* \rightarrow f(C_*)$, $F_* \in$ Functions, $C_* \in$ Comp, f logical formula

Figure 1 Composition pattern.

Composition rule	Description
Occurrence (A, N)	Component A appears N times. N ∈ ⊂ Z^+
Property (A, <name, value>)	Component C has property <name, value>
PartOf(A, B)	Component A is a part of component B
Correlation (A, B, N)	Proportion of occurrence of components A and B is N. N ⊂ R^+
Topology (A, B, T)	Component A and B have topology T (DE-9IM)
Distribution (A, MI)	The Moran's Index of component A is MI ∈ **[-1, 1]** ⊂ **R**
Proximity (A, B, Dist)	Average distance of A and B is Dst ⊂ R^+
Organization (SO, A)	Component A has SO distribution. SO ∈ **[linear, centralized, radial]**

Figure 2 Composition rules.

permitted or forbidden. This hinders the effectiveness of place search, especially when dealing with inconsistent data or in cases of increased vagueness that marks a function to be optional. Furthermore, the extraction of composition patterns highly depends on narratives, which often reflect the ideal or the most general definition of a place, abstracting away the diversity that characterizes the real world.

This study proposes an improved version of the composition patterns of place, described above, that addresses the aforementioned limitations. Specifically, the composition patterns are extended to support flexibility in terms of what is necessarily or possibly included in the composition of a place. In addition, the extraction process of composition patterns is enhanced with empirical knowledge, which revise and complements the knowledge extracted by narratives.

The remainder of this paper is organized as follows. Section 2 proposes the improved composition pattern of place and introduces an empirical methodology for extracting patterns of place. Then, Section 3 demonstrates the applicability of the proposed model for the use case of searching shopping areas in London, UK. Finally, Section 4 concludes and points out directions for future work.

2 Methodology

In this section, we first analyze the required extensions that will improve the composition patterns of place with flexibility. Then, we detail how the process of extracting patterns is (1) adjusted to conform to the extended formalization and (2) enhanced in order to allow automations and patterns with finer details based on spatial analysis and statistics.

2.1 Flexible Composition Pattern

The initial model of composition patterns of place is extended by introducing its flexible counterpart, the model of *flexible composition patterns*. This extension is made possible by applying the principles of modal logic [1]. Note that modalities are chosen, instead of quantities, to represent necessity and possibility in a concise and natural manner, and to preserve the model's generality. In the remainder of this document, we refer to these flexible composition patterns simply as patterns.

The newly proposed patterns conform to the fundamental assumption that "place is space with ascribed functions" and are formalized as a collection of three sets $(Comp, C_R, F_R)$. The first two stand for the possible components and composition rules (Figure 2) that frame the composition of a place, respectively. F_R contains logical implications between functions and logical formulas comprised of composition rules. The latter are extended with modal operators that allow the expressions "necessarily" and "possibly" (denoted as $\Box$ and $\Diamond$, respectively) in order to attribute a certainty value for every rule. Considering the above, a particular function is enabled, if the combination of necessary or possible rules holds.

2.2 Enhanced Pattern Extraction

In order to achieve automated creation of more realistic patterns, we propose an extraction process that utilizes both theoretical and empirical knowledge. According to this approach, a pattern of place is no longer a strict reflection of the written word, but a combination of text-based and experiment-based information acquired through the phases of *theoretical design* and *empirical revision*, respectively.

The phase of theoretical design uses text analysis to extract a *theoretical* pattern, which includes the textually derived knowledge about the composition of a place. This pattern is regarded as a collection of "echoes", after Alexander's 15 structural properties [12] and it describes the expected features that would enable the functions of the place under question. Since text-based knowledge is usually designed with generalization in mind, it is safe to assume that the composition rules included in this pattern are marked as possible (and not necessary) in terms of the level of certainty.

The empirical revision focuses on the analysis of regions that are considered as the ideal candidates of the place for which the theoretical pattern was created. More specifically, spatial and semantic data are acquired for a wide range of ideally defined instances of the place under question. Considering the latter as anchors, additional data is collected about adjacent components conforming to requirements listed in the theoretical pattern.

The next step aims to extract and describe the most significant components that characterize the ideal places under question. This is achieved by classifying the aggregated data into context-specific categories by conducting statistical and spatial analysis. Statistical analysis includes extraction of the population count and the average frequency of occurrences per category. Spatial analysis, on the other hand, focuses on the mean distance between components and the centroids of the ideal candidates of place. By the end of the analysis, an *empirical* pattern is constructed that includes the required and optional information that describes the composition of the place under question. A context-specific significance threshold is employed in order to classify which rules are considered as necessary or optional. The aforementioned threshold is chosen empirically and is calculated based on the statistical importance. Particularly, we assume the following convention: aggregated data that exceed this threshold introduce necessary composition rules, while the rest imply possible rules.

It is worth noting that there are cases where necessity or possibility rules depend on the possible or necessary existence of some components, respectively. These scenarios imply to possible necessity and conditional possibility and so forth. Figure 3 illustrates all the possible cases of interrelation between necessity rules and conditional existence of components along with the corresponding descriptions.

3 Experiment

This section demonstrates the proposed methodology using the example of shopping malls in London, UK. The objective of the described experiment is to create a pattern which can enable a place search system to locate all places that offer functions similar to a shopping mall, even if they are not explicitly defined as one. By convention, we refer to these places as shopping areas, for which the ideal representatives are the standard shopping malls.

Before proceeding, we list some basic assumptions that underline our experiment. We consider a simple version of shopping areas that support the functions of shopping experience,

Dependency Condition	Explanation
Let C be a component and R a composition rule	
□ C AND □ R	C exists and R must hold
□ C AND ◊ R	C exists and R can hold
◊ C AND □ R	if C exists then R must hold
◊ C AND ◊ R	if C exists then R can hold

Figure 3 Dependency between necessity rules and existence of components.

Components				
Shop	Amenity	Road Junction	Road	Bus station

Functions	
Shopping experience (F_S)	Existence of Shops
Leisure (F_L)	Existence of Amenities
Walkability (F_W)	Shops and Amenities are within a walkable distance.
Accessible to drivers (F_{AD})	Existence of Road junctions and Roads within min. driving distance.
Accessible to non drivers (F_{AN})	Existence of bus stations within walkable distance.

Figure 4 Functions and components of a shopping area.

leisure, walkability, accessibility to drivers and accessibility to non-drivers (Figure 4). In addition, we assume that the maximum walkable distance is 500m and the minimum driving distance is no more than 5000m. We use a subset of the composition rules in Figure 2 that includes *Occurrence, Correlation* and *Proximity*.

Considering the assumptions above, textual analysis is performed on the following sources: Wikipedia reference, dictionary definition and architectural guidelines of shopping malls. This results in the theoretical pattern depicted in Figure 5.

Empirical revision is then conducted using data acquired from OpenStreetMap. We collected a set of 63 polygons, outlining shopping malls in London. Using the centroids of the latter we aggregate: (1) point geometries of shops, amenities and public transport stops within a 500m radius, and (2) junction points along with line geometries of primary and secondary highways within a 5000m radius. Figure 7 illustrates indicative results of the spatial and statistical analysis applied on the acquired components for all the ideal instances of shopping areas.

For the construction of the empirical pattern, we assume that a variable is significant and hence it implies a necessary composition rule if the coefficient of variation for the corresponding mean value is no more than 25%. Values more than this level result to insignificant variables and, hence, refer to possible rules. The empirical pattern is shown in Figure 6.

Our method is evaluated by conducting and comparing two function-based search processes for shopping areas: one relying on the theoretical pattern, and one on the empirical one. Pattern matching is realized by converting each pattern to a sequence of spatial queries and procedures, implemented using PostGIS and QGIS. Particularly, every function, included in the pattern, is expressed as a query that reflects the implied composition rules. Afterwards, the generated queries are issued on the database. The theoretical pattern is evaluated by aggregating the results of each query in a conjunctive manner. The empirical pattern, on the other hand, is evaluated in two steps. Initially, queries based on the necessity rules suggest candidate regions of the place under question; then the possibility rules are checked

Function	Formula
(F_s)	Occurrence(Shop, [2,))
(F_t)	Occurrence(Amenity, [1,)) AND Correlation(Shop, Amenity, [2,))
(F_W)	Proximity(Shop, Amenity, [, 500m]) AND Proximity(Shop, Shop, [, 500m]) AND Proximity(Amenity, Amenity, [, 500m])
(F_{AD})	Proximity(Shop, Road Junction, [,500m])
(F_{AN})	Proximity(Shop, Bus station, [,500m])

Figure 5 Theoretical pattern.

Function	Formula
(F_s)	□Occurrence(Shop, [4,))
(F_t)	◊ Occurrence(Amenity, [1,)) AND ◊ Correlation(Shop, Amenity, [7,))
(F_W)	□Proximity(Shop, Amenity, [, 63m]) AND □Proximity(Shop, Shop, [,63m]) AND □Proximity(Amenity, Amenity, [,63m])
(F_{AD})	□Proximity(Shop, Road Junction, [,3496m])
(F_{AN})	◊Proximity(Shop, Bus station, [,291m])

Figure 6 Empirical pattern.

	Count(shop)	Count(amenity)	Proximity(Shop, Amenity)	Proximity(Bus st., Shop)	Count(Bus st)
min	4	0	5.8	47	0
median	64	17	63	261	4
coefficient of variation	19%	49%	22%	47%	6%

necessary (yellow): Count(shop), Proximity(Shop, Amenity), Count(Bus st)
possible (blue): Count(amenity), Proximity(Bus st., Shop)

Figure 7 Indicative results of spatial and statistical analysis.

in order to mark which among the selected candidates better fit the initial functionality. The algorithms used for the function-based search go beyond the scope of this work, and the methods used are not considered optimal but used for demonstration purposes only.

Figure 8 illustrates the results retrieved by the theoretical pattern, with blue cells representing all candidate shopping areas and cross symbols indicating the locations of the shopping malls. It should be clear that all ideal places are included, however there is no indication as to which cells better support the required functions. In contrast, the results shown in Figure 9 indicate that the empirical pattern enables a finer delineation of shopping areas, as well as a clear indication of the level of functions support (illustrated using a heat map where blue represents least support and red represents highest support). Note that due to a much smaller grid size, Figure 9 corresponds only to the rectangle area in Figure 8.

4 Conclusion

This study contributes to formalizing place and place search. In particular, we introduce a more flexible formalization of place capable of capturing what is necessarily or possibly included in the composition of a particular place. Furthermore, we propose a pattern extraction process that combines the theoretical, text-based design of composition patterns of place with empirical revision based on statistical and spatial analysis. The resulting pattern provides a detailed description of place that is closer to reality and can lead to more accurate results in function-based search of space, as evidenced by the conducted experiment of locating shopping areas in London, UK. This work indicates that place can be treated as a functional region and be formalized as a system using both narratives and spatial data, however further development is necessary. The dependency of theoretical patterns on narratives raises important obstacles; indicatively, natural language processing has many technical difficulties and usually the extracted information is context-dependent and highly vague. In addition, a more formal definition of the composition rules is required, which will allow the introduction of new rules or the modification of existing ones. Furthermore, although modal logic seems a convenient solution, when it comes to reasoning, it hinders quantification, which in return limits the model's ability to provide grading on places or functionality rating. Interesting directions of future work include the integration of probabilistic models, which will quantify the possible knowledge about places, and the automation of the pattern extraction process utilizing deep learning techniques.

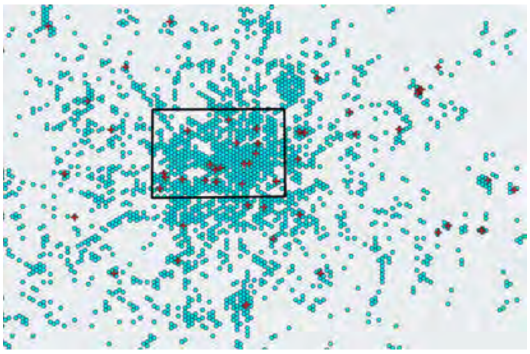

Figure 8 Results using theoretical pattern.

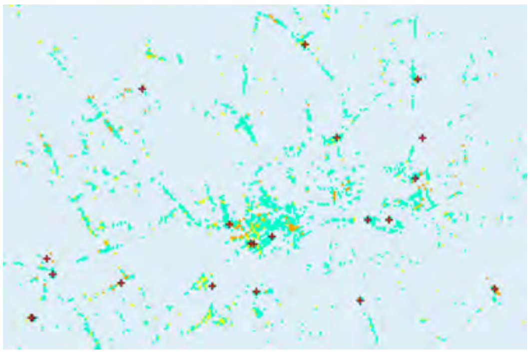

Figure 9 Results using empirical pattern.

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