Modeling the Semantics of Geographic Categories through Conceptual Integration

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Abstract. We apply the notion of conceptual integration from cognitive science to model the semantics of geographic categories. The paper shows the basic ideas, using the classical integration example of houseboats and boathouses. It extends the notion with image-schematic and affordance-based structure. A formalization in the functional language Haskell tests this approach and demonstrates how it generalizes to a powerful paradigm for building ontologies.

1. Introduction

Modeling the semantics of geographic information has been recognized as a key challenge to geographic information science, as evidenced by the research priorities of UCGIS, at http://www.ucgis.org, or AGILE, at http://www.agile-online.org. In the context of semantic interoperability (Bishr 1997), where there is usually no possibility for human interpretation and intervention within a service chain, formalizing the semantics of geographic information has become indispensable.

The overall goal of our work is to improve the usability of geographic information in information infrastructures through a formalization of its semantics. We have sought formal models of semantics for a broad spectrum of problems (Kuhn 1995), ranging from geographic categories (Kuhn 1999) through service interfaces (Frank and Kuhn 1995) to user interfaces (Kuhn 1993). This paper addresses the question how the semantics of categories in geographic information can be modeled by ontologies that use the notion of *conceptual integration* (Turner and Fauconnier 2001).

Recent advances in mark-up languages have spurred approaches to describe the meaning of categories by marking up information resources. While the possibility to mark up and share semantic information is a great step toward semantic interoperability, it is no answer to the question how semantics should be modeled in the first place: How can the meaning of a term be formally *explained*, before it is *exposed* through a mark-up language. We address this issue here and leave the question of how to expose and transfer semantics aside. Our formalization supports eventual exposure, but the exposing mechanism is not permitted to limit the modeling capabilities.

Any theory of semantics must provide explanations for the semantics of elementary concepts (whatever it considers as such) and a mechanism to describe their combination. We have taken an algebraic view of modeling category semantics, informally in (Riedemann and Kuhn 1999) and with formal algebraic specifications in (Kuhn 1999). The work presented here addresses the issue of how to *combine* elementary semantic theories in the same formal framework. A more abstract and generic outline of combining algebraic theories has been given in (Frank 1999). Our intention is to develop the approach toward a practically useful modeling method, starting with specific case studies of the semantics of terms occurring in geographic information.

The results presented here are intended to demonstrate the theoretical background and practical workings of the approach. We use a simple, but rich example of semantic differences between two natural language categories with spatial content (both in the entities and their relationships): the notions of a houseboat and a boathouse. This example has been used in the cognitive linguistics and algebraic semiotics literature (Goguen 1999) to demonstrate the notion of conceptual integration, sometimes also referred to as conceptual blendings (http://www.wam.umd.edu/~mturn/WWW/blending.html).

Blendings have previously been formalized algebraically, using the OBJ specification language (Goguen 2001). In our work, we are less interested in a formal notation for the phenomenon of blendings as such, but in a generalizable mechanism to describe semantic mappings as constituents for the semantics of geographic information. Our approach is closely related to Goguen's, but differs from it by

- starting from an existing (semi-formal) ontology (that of WordNet);
- emphasizing the semantic role of function (affordances provided by an instance of the category) in mappings among conceptual spaces;
- attempting to achieve total (rather than partial) semantic mappings by introducing finer-grained conceptual spaces;
- identifying spatial structures (image schemata) as conceptual spaces for higher level abstractions;
- using the functional programming language Haskell (Peterson, Hammond et al. 1997) as a more general formalization device.

After introducing the idea of conceptual integration in section 2, we present our case study in section 3 and its formalization in section 4. The conclusions, in section 5, discuss what conceptual integration theory can contribute to formalized semantics of geographic categories.

2. Semantics as a Result of Conceptual Integration

Current cognitive linguistics regards *semantic mappings between conceptual spaces* as a key component of any theory of semantics (Fauconnier 1997). Metaphors have been the most intensely studied kind of such mappings (Lakoff and Johnson 1980). A metaphor is a semantic mapping from a source to a target space. We have previously given formal algebraic treatments of metaphors in the context of user interfaces

(Kuhn and Frank 1991) and recent work has extended this approach to an axiomatization method for metaphors (Hochmair 2002).

Authors like Turner and Fauconnier have recognized metaphors as a special case of more general semantic mappings, where multiple sources are combined and projected to complex targets (Turner and Fauconnier 2001). The theory of conceptual integration studies the many varieties of semantic mappings in language and other conceptual systems. It treats the conceptual spaces of the source domains as small theories of concepts that get combined into more complex theories ("blends") by projection.

A familiar example for conceptual integration, in the context of information systems, is the good old desktop metaphor (Kuhn and Frank 1991; Turner and Fauconnier 2001). A computer desktop inherits semantic structure from multiple conceptual spaces: physical desktops, office documents, folders, clip boards etc. How the features from source domains are picked out and blended together is the key question that conceptual integration theory tries to answer.

With multiple source domains comes the possibility to combine the same sources in different ways to achieve distinct complex semantics. This suggests that the mental spaces blended into a complex concept can take on different roles. For example, in the case study introduced below, the role of a boat to carry passengers is mapped unchanged to the boats in boathouses, but takes the special form of carrying inhabitants in houseboats.

3. A Case Study

A classical example of conceptual integration is the combination of the mental spaces house and boat in two different ways, to arrive at *houseboat* and *boathouse* (Goguen 1999). In each case, some aspects of the two source domains are carried over to the target, while others are not. For instance, houseboats and boathouses both retain the sheltering function of a house; but while the houseboat affords shelter to humans, the boathouse transfers that affordance to boats. Conversely, the conveying function of boats is retained by a houseboat, but not by a boathouse. This section of the paper describes the conceptual integration informally. In order to build on an established informal semantics, we use the two concept hierarchies from WordNet (Fellbaum 1999) as a starting point.

3.1. Boathouses and Houseboats in WordNet

Reducing WordNet's synsets (sets of synonymous terms) to single concepts and eliminating irrelevant parts of the glosses, leads to the following hypernym hierarchies for boathouse and houseboat:

boathouse -- (at edge of river or lake; used to store boats)
=> **house** -- (a building in which something is sheltered or located)
=> building -- (a structure that has a roof and walls and stands more or less permanently in one place)

=> structure -- (a thing constructed; a complex construction or entity)
=> artifact -- (a man-made object)
=> object -- (a physical (tangible and visible) entity)
=> entity -- (anything having existence (living or nonliving)).

houseboat -- (a barge that is designed and equipped for use as a dwelling)
=> barge -- (a boat with a flat bottom for carrying heavy loads (especially on canals))
=> **boat** -- (a small vessel for travel on water)
=> vessel -- (a craft designed for water transportation)
=> craft -- (a vehicle designed for navigation in or on water or air or through outer space)
=> vehicle -- (a conveyance that transports people or objects)
=> conveyance -- (something that serves as a means of transportation)
=> instrumentality -- (an artifact that is instrumental in accomplishing some end)
=> artifact -- (a man-made object)
=> object -- (a physical (tangible and visible) entity)
=> entity -- (anything having existence (living or nonliving))

3.2. Observations

Some observations about these two conceptual hierarchies will motivate their subsequent refinement and formalization:

1. The concept hierarchies are both unique, i.e., there is only one sense each for boathouse and houseboat. Given the specificity of the concepts, this is not surprising;
2. Within this single sense, they are both strict hierarchies, as is the case for all WordNet noun hierarchies (each noun is only allowed to have one hypernym);
3. They both contain one of the two blended concepts early in the hierarchy (house and boat, respectively, delivering the basic affordances of shelter and river transportation).
4. The other blended concept, describing the afforded entity, is contained explicitly (boats) or implicitly (dwelling) in the glosses;
5. Glosses at lower levels tend to use functional descriptions ("used to store boats", "for travel on water"), while those higher up in the hierarchies are not only more abstract, but also formulated independently of function;
6. There appears to be a "change of gears" in the abstraction at a certain point in both hierarchies: when going from building to structure and from conveyance to instrumentality, the kinds of concepts and their definitions become significantly more abstract;
7. Above level 5 of the boathouse hierarchy and level 9 of houseboat (artifact), the two hierarchies are identical;
8. There is a case of a spatial relation being used as a defining property (boathouses are "at edge of river or lake").

3.3. Limitations

Most existing ontologies (i.e., theories of category semantics) are based on generalization hierarchies like the one of WordNet. An advantage of such an approach is that semantic similarity can be measured based on the distance between two concepts in terms of the number of steps separating them from a common node in a hierarchy (Rodriguez, Egenhofer et al. 1999). Thus, the concept of boathouse would be twelve steps away from that of houseboat, passing up and down in the common hierarchy through the least common node of artifact (ignoring the need for normalization).

While such hierarchical theories may approximate human similarity judgments, they cannot capture other semantic relationships. For example, while boathouses and houseboats are not very “similar” (by most notions of similarity), they are certainly related, even semantically close, in other ways. We need to develop ontologies that can account for these additional relations.

In particular, the *functional* relations of concepts should become part of formal semantic theories (Barsalou, Sloman et al. 2001). WordNet captures functions (such as the sheltering function of a house) prominently in its glosses, i.e., in the dictionary-style explanations of concepts. However, they are treated outside the formal apparatus of hypernymy and hyponymy relations. Our formalization will treat functions as the primary structuring elements.

Another characteristic of most ontologies, including WordNet’s, is their limitation to *strict hierarchies*, with single inheritance. In an algebraic framework like ours, where functions are the units of inheritance, this restriction can be relaxed, allowing for a concept to inherit from multiple parents.

3.4. Refinements

How does the notion of conceptual integration help to enrich ontologies and overcome these limitations? Primarily by its close ties with an *algebraic view* of information processing and sign systems (Goguen 1999). In algebra, a rational number, for example, is categorized as such because it admits division. Similarly, in an algebraic view of semantics, a vessel belongs to that category because it supports water transportation.

An algebraic view underlies the *formalization* approaches of Goguen (Goguen 2001) and ourselves (Kuhn and Frank 1991; Frank and Kuhn 1999; Kuhn 1999). It allows for treating semantic mappings as *morphisms* (structure-preserving mappings) among theories of conceptual spaces. For example, the function of a boathouse to shelter boats, or of a houseboat to shelter humans, can be described as the result of different morphisms from the theories of houses and boats to those of boathouses or houseboats.

Taking WordNet’s two conceptual hierarchies, we will produce informal semantic theories for boathouses and houseboats. They elaborate WordNet’s concepts into conceptual spaces and describe mappings between them. The theories depart from WordNet in several ways:

- they explain the meaning of each conceptual space by the functions (affordances) its instances provide;
- they map the entire set of affordances from a super-concept to a sub-concept (total mappings);
- they use a special kind of conceptual spaces (image schemata) at the higher levels of hierarchies;

As observed above, the glosses in WordNet tend to emphasize function. We exploit this feature by giving a purely functional description of each conceptual space. The meaning of a concept, in this view, is determined by the functions that its instances afford to humans. A more comprehensive structuring of WordNet's glosses is given in (Harabagiu and Moldovan 1998).

We have previously proposed to apply a loose interpretation of Gibson's notion of *affordances* (Gibson 1986) to semantic theories (Kuhn 1996). The work presented here proceeds further along these lines, without discussing the affordances notion in detail (but see (Frank and Raubal 1999)). Many discussions of conceptual integration, such as (Goguen 1999), implicitly use the notion of affordances in their selection of mapped features. Recent work in cognitive psychology further supports the adoption of a functional view in the construction of ontologies (Barsalou, Sloman et al. 2001).

Each synset of WordNet potentially constitutes a conceptual space. Its structure is composed of components specific to itself and components inherited from other conceptual spaces. The decision on how finely grained the conceptual spaces should be seems arbitrary. WordNet needs to introduce a synset for each lexicalized concept. Semantic mappings between synsets could be partial or total, as it is likely that lexicalization is not necessarily producing total mappings. Goguen uses a minimum of conceptual spaces: house, boat, houseboat, boathouse, and a generic object. His semantic mappings (which he calls semiotic morphisms) need to be partial, because the conceptual spaces are rich in structure and not all of their structure is passed on in all mappings.

Given the freedom of choice for conceptual spaces, we attempt to choose them such that all *semantic mappings become total*. This is a strategy that has proven valuable in algebraic specifications, as it reduces the number of special cases and exceptions. Thus, we only retain those synsets from WordNet that play a role in distinguishing boathouses from houseboats and allow for total mappings.

Another departure from the WordNet conceptual hierarchy is the introduction of *image schemata* at higher levels. Image schemata are basic conceptual structures, rooted in the human perceptual system, to capture ideas like containment, support, contact, or motion (Johnson 1987). The observed "change of gears" in abstraction at a certain level in WordNet hierarchies is taken as a motivation to introduce the cognitively more plausible and semantically richer abstractions of image schemata for those higher-level abstractions.

In particular, the *container* schema is invoked as a source of house semantics (sheltering being interpreted simply as containment). Similarly, the *surface* schema is chosen to capture the affordance of boats to carry loads, and the *path* schema to capture their motion. Finally, the *contact* image schema offers the spatial relation stated for boathouses ("located at the edge of a river or a lake"): the boathouse needs to be adjacent to a water body for the boats to reach it.

3.5. An Informal Theory of Boathouses and Houseboats

The above refinements of WordNet's ontologies produce the following shorter, but semantically richer list of conceptual spaces. Our informal descriptions first repeat WordNet's glosses and then express them by affordances inherited from other concepts and image schemata.

A **boathouse** is a house used to store boats, located at the edge of a river or a lake.
It inherits the *sheltering* affordance from **house** (applying it to boats) and the **contact schema** attaching it to a **water body** (which in turn is used as a generalization of rivers and lakes).

A **house** is a building in which something is sheltered or located.
It inherits the *containment* affordance from the **container schema**. We eliminate the **building** concept, as it only serves to specialize the kind of container ("a structure that has a roof and walls") and to state the absence of a mobility affordance ("stands more or less permanently in one place").

A **houseboat** is a barge that is designed and equipped for use as a dwelling.
It inherits the affordances to *travel on water* and to *carry heavy loads* from **barge**. It further inherits the *sheltering* (serving as a dwelling) affordance from **house**, applying it to humans. (WordNet defines a dwelling as "a physical structure (e.g., a house) that someone is living in".)

A **barge** is a boat with a flat bottom for carrying heavy loads (especially on canals).
It inherits the *water travel* affordance from **boat**. We ignore the property of flat bottoms (being a design feature to permit the affordance), as well as the prototypicality for canals.

A **boat** is a small vessel for travel on water.
It inherits the *water transportation* affordance from **vessel**, applying it to humans (which turns transportation into travel). We ignore the qualification "small".

A **vessel** is a craft designed for water transportation.
It inherits the *transportation* affordance from **vehicle**, applying it to water as a medium. We drop the craft concept, as it only introduces alternative media (such as air).

A **vehicle** is a conveyance that transports people or objects.
It inherits the *motion* affordance from the **path schema** and the *support* affordance from the **surface schema**. We drop the conveyance concept, as it does not provide any further generalization (transportation can only be for people or objects anyway).

This completes our informal ontology of boathouses and houseboats. Its major advantages over previous theories, both in WordNet and in (Goguen 1999) are to

- offer richer explanations of the conceptual spaces and their relationships;
- constrain the choice of source concepts through the condition of total mappings;
- introduce image schemata as meaningful higher-level abstractions.

We will now proceed to an algebraic formalization of this ontology.

4. Formalization

A formalization of ontologies for geographic categories serves at least two purposes: it creates the basis for implementing and using geographic information services, and it allows for assessing the completeness and consistency of the ontologies themselves. We use the functional language Haskell to provide a formalization that is testable. Details on the formalization method and reasons to use it can be found, for example, in (Frank and Kuhn 1999).

We limit the presentation to type classes, representing categories as the set of types sharing some behavior, i.e., offering common affordances. Details of the types themselves are omitted from the presentation. The semantics of basic concepts like houses and boats have been modeled as sparsely as possible.

The simplifications made in the informal theory and in its formalization do not affect the generality of the approach. Our emphasis lies on the kinds of ingredients of ontologies and the mechanism for their combination, which are both independent of the details about each ingredient. Note also that, as in any taxonomy, the features and relations indicated for a concept do not need to be complete, just sufficient to distinguish among the concepts that are considered different.

We begin our formalization with the four image schemata that were called for by the informal model: container, surface, contact, and path. For the sake of simplicity, we do not structurally distinguish the container from the surface schema. Each image schema is specified as a class of (so called constructor) types with one or two parameters. For example, `Containers a b` stands for all container types `a` holding things of type `b`. The operations afforded by the types in the class are described through their signatures. For example, the `insert` operation puts a thing of type `b` into a `container a b` and returns the `container a b` holding the thing. Query functions return lists `[b]` of the things contained, supported, or attached.

```
class Containers a b where
          insert :: b -> a b -> a b
          remove :: b -> a b -> a b
          whatsIn :: a b -> [b]

class Surfaces a b where
          put :: b -> a b -> a b
          takeOff :: b -> a b -> a b
          whatsOn :: a b -> [b]

class Contacts a b where
          attach :: b -> a b -> a b
          detach :: b -> a b -> a b
          whatsAt :: a b -> [b]

class Paths a b c where
          move :: c -> a b c -> a b c
          origin, destination :: a b c -> b
          whereIs :: a b c -> c -> b
```

These image schemata will take care of the spatial relations in the theories of boathouses and houseboats: Houses shelter people or, as boathouses, boats (container), boats move on water bodies (surface and path), and boathouses are located at water bodies (contact). These constraints will be used in the derivations of these classes below.

Next, we introduce the three auxiliary concepts required in addition to the WordNet hierarchies: people (as house inhabitants and boat passengers), heavy weights (as defining capacity of barges), and navigable water bodies (as transportation media). All three are treated as constants, since their internal structure is irrelevant for the explanation of boathouses and houseboats. Water bodies are derived from surfaces by a so-called class constraint or context in Haskell (=>). It says that all `WaterBodies` need to be `Surfaces`.

```
class People p

class HeavyLoads l

class Surfaces w o => WaterBodies w o
```

Now, we supply the formal definitions for all conceptual spaces above the target concepts in the two modified WordNet hierarchies. While the first hierarchy (above boathouse) is completed by the simple derivation of houses from containers,

```
class Containers h o => Houses h o
```

the second hierarchy involves a longer inheritance chain. Vehicles are first derived from surfaces (affording to ride on the vehicle) and paths (affording motion). They end up with parameters for the type `o` of the transported object, the type `a` of the path, and the type `b` of the origin and destination places. Note that the letters used for the parameters have only mnemonic significance; all that counts for the model is the class constraints imposed on the parameters:

```
class (Surfaces v o, Paths a b (v o)) => Vehicles v o a b
```

Then, vessels are defined as vehicles for water transportation, inheriting a slot for the type `w` of water body:

```
class (Vehicles v o a b, WaterBodies w (v o))
          => Vessels v o a b w
```

Boats are vessels for travel, constraining the type of transported objects `o` to people `p`:

```
class (Vessels v p a b w, People p) => Boats v p a b w
```

Finally, barges get the additional constraints that their loads are heavy:

```
class (Boats v p a b w, HeavyLoads p) => Barges v p a b w
```

Now, the two target concepts can be derived from their immediate super-classes. Boathouses are houses used to store boats; thus, the type `o` of the sheltered object is constrained to a boat `v` (as defined above). Furthermore, they are located at the edge of a water body, namely the one (`w`) on which the boats can move; thus, a constraint for contact, attaching the boathouse to the water body, is introduced:

```
class (Houses h (v p), Boats v p a b w, Contacts w (h (v p)))
          => BoatHouses h v p a b w
```

Houseboats are barges used as dwellings, i.e., as houses for people. The barges thus inherit the behavior of houses, and the objects sheltered must be people:

```
class (Barges v p a b w, Houses v p, People p)
          => HouseBoats v p a b w
```

The Haskell code given so far is complete and type checked, explaining the entire refined concept hierarchies. With instantiations for types of boathouses and houseboats, values can be declared and axioms stated and evaluated to demonstrate semantic properties and differences. For example, it can be shown that a passenger on a boat in a boathouse cannot be said to be an inhabitant, while a passenger on a houseboat can.

5. Conclusions

The goal of this paper was to point to conceptual integration theory as a fruitful idea in cognitive science and to demonstrate its applicability to modeling the semantics of categories in geographic information. The informal description of the category hierarchies derived from WordNet and the formalization in Haskell show that the theory of conceptual integration provides indeed a powerful paradigm for semantic modeling. They further demonstrate the ease of integration with existing ontologies (like WordNet) and the suitability of an algebraic formalization.

Key characteristics of conceptual integration theory are its reliance on multiple inheritance and (implicitly) on functions to capture the meaning of conceptual spaces. We have taken the notion two steps further by requiring total mappings (which impose constraints on the granularity of the integrated concepts) and positing affordances as core semantic properties.

We do not need the assumption (made in the cognitive science literature) that blends somehow magically produce their own intrinsic semantics. Avoiding this assumption can be seen as another insistence on totality of mappings: the mappings should be *right* total, in the sense of explaining all semantic structure in the target that one wants to explain.

Future work will need to demonstrate that the given formalization for semantic mappings is powerful and general enough to deal with a relevant subset of the semantic problems in geographic information science. We are currently exploring a case study on roads – a concept taking on different meanings depending on its use context.

Acknowledgments

Current support for our work on semantic modeling and mappings is provided in part by the European Commission's BRIDGE-IT and ACE-GIS projects. Discussions with

many colleagues (among them Andrew Frank, David Mark, Barry Smith, and Martin Raubal) have shaped the ideas presented here.

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