Sandbox Geography – To learn from children the form of spatial concepts

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Abstract

The *theory theory* claims that children's acquisition of knowledge is based on forming and revising theories, similar to what scientists do (Gopnik and Meltzoff 2002). Recent findings in developmental psychology provide evidence for this hypothesis.

Children have concepts about space that differ from those of adults. During development these concepts undergo revisions.

This paper proposes the formalization of children's theories of space in order to reach a better understanding on how to structure spatial knowledge. Formal models can help to make the structure of spatial knowledge more comprehensible and may give insights in how to build GIS. Selected examples for object appearances are modeled using an algebra. An *Algebra Based Agent* is presented and coded in a functional programming language as a simple computational model.

1 Introduction

Watch children playing in a sandbox! Although they have not collected much experience about their surroundings, they follow rules about objects in space. They observe solid objects and liquids, they also manipulate them, and they can explain spatial behavior of objects albeit their judgments are sometimes in error (Piaget and Inhelder 1999). Infants individuate objects; they seem to form categories and can make predictions about object occurrences. Like geographers they explore their environment and make experiments and derive descriptions. Geographers omit large scale influences like geomorphologic movements, so do children. Lately social interactions are considered in spatial models. These can be also found in the sandbox. The playing toddlers have contact with other kids and from time to time they check if their caring parents are still in the vicinity. Children also form theories about people (Gopnik, Meltzoff et al. 2001).

This paper proposes to exploit recent findings of psychologists in order to build formal models for GIS. Different approaches are taken to explain how adults manage spatial knowledge. Newcombe and Huttenlocher (2003) review three approaches that influenced spatial development in the research during the last fifty years Piagetianism, Nativism and Vygotskyanism. Followers of Piaget assume that children start out with no knowledge about space. In a four-stage process child knowledge develops to adult knowledge.

A follower of the nativist view is Elizabeth S. Spelke, who has identified in very young children components of cognitive systems that adults still make use of. It is called *core knowledge* (Spelke 2000). New knowledge can be built by the composition of these core modules. The modules itself are encapsulated and once they are triggered they do not change (Fodor 1987).

Vygotskyanists believe that children are guided and tutored by elders, cognitive efforts are adapted to particular situations, and that the human has a well developed ability in dealing with symbolic material (Newcombe and Huttenlocher 2003).

The present work concentrates on a view called the *theory theory* explored by A. Gopnik and A. N. Meltzoff. From the moment of birth the acquired knowledge undergoes permanent change whenever beliefs do not fit together with observed reality (Gopnik, Meltzoff et al. 2001; Gopnik and Meltzoff 2002). The presented paper starts with a formalization of this model using Algebra as a mathematical tool for abstracting and prototyping.

Finding very simple and basic concepts about the physical world is not new. Patrick Hayes proposes in a manifesto a Naïve Physics (Hayes 1978; Hayes 1985). A Naïve Theory of Motion has been investigated (McCloskey 1983). The geographic aspects have been considered in a Naïve Geography that forms a "body of knowledge that people have about the surrounding geographic world" (Egenhofer and Mark 1995). This knowledge develops through space and time. It starts at very coarse core concepts and develops to a fully fledged theory. An initiative for common sense geography has been setup to identify core elements (Mark and Egenhofer 1996). The demand for folk theories has been stated by several authors in Artificial Intelligence science to achieve a more usable intuitive interface. Recent results by the psychology research community can influence GIS by forming new and sound models. In extension to the naïve geography new insights about how to structure space can be won by the investigation of children's mind.

Recent research in developmental psychology is discussed in section two of the paper. Section three connects these findings to current GIS research. The use of Algebra in GIS is introduced in section four. An *Algebra Based Agent* is proposed in section five, using simple examples for object appearances on static and moving objects. Section six introduces the prototypic modeling done so far. In the concluding seventh section the results and future research topics are discussed.

2 Children and Space

In a multi-tiered approach for GIS (Frank 2001) the human plays a central role – a cognitive agent is modeled as its own tier. For the last fifty years children were ignored in geo-sciences. Children for a long time were not investigated as an object of psychological research. Aristotle and the English philosopher John Locke considered them *tabulae rasae,* not knowing anything in advance. Nowadays a whole research enterprise has developed which investigates children's mental models. It started with Piaget in the early fifties (Piaget, Inhelder et al. 1975; Piaget and Inhelder 1999). Although he was wrong in some of his assumptions his ideas have been studied in detail.

Piaget had the opinion that children start out into the world without any innate knowledge. All the knowledge a person has at a certain point of time had to be acquired before. Today researchers suppose that there is some innate knowledge available that is either triggered in some way and reused or developed in form of adaption. According to the *theory theory* the learning process is driven by three components (Gopnik and Meltzoff 2002):

Innate knowledge – core knowledge: Evidence shows that babies are born with certain abilities. Object representations consist of 3 dimensional solid objects that preserve identity and persist over occlusion and time (Spelke and Van de Walle 1993). Gopnik, Meltzoff and Kuhl show that there is also an innate understanding of distance. The same authors also detected evidence that there are links between information picked up from different sensor modalities (Gopnik, Meltzoff et al. 2001).

Powerful learning abilities: Equipped with those innate structures babies start a learning process. Language acquisition especially shows how powerful this mechanism must be (Pinker 1995). In the first six years a child learns around 14 000 words. Another thing that has to be learned is the notion of object permanence. To understand object permanence means to understand that a hidden object continues to exist. Different approaches seem to be used by children to explain this phenomenon during their learning process. The formation of object categories and the understanding of causal connections are two other aspects that have to be learned by children throughout many years (Gopnik, Meltzoff et al. 2001).

Unconscious tutoring by others: Adults teach children by doing things in certain ways. By repeating words, accentuating properly and speaking slowly they help children unconsciously to acquire the language. Children learn many things by imitation. The absence of others can heavily influence social behavior. As demonstrated by Kaspar Hauser 1828 in Nürnberg, Germany.

These three components innate knowledge, powerful learning and tutoring by others are also the basis for the *theory theory* by A. Gopnik and A. N. Meltzoff (Gopnik, Meltzoff et al. 2001; Gopnik and Meltzoff 2002). Children acquire knowledge by forming and revising theories, similar to what scientists do. The spatial concepts infants live in are obviously different from an adult's concepts. Ontological commitments are made in order to explain events in the world. The theories babies build about the world are revised and transformed. Children form theories about objects, people, and kinds; they learn language and all this is connected to space. The core about the *theory theory* is formulation and testing of hypotheses. It is a theory about how humans acquire knowledge about the world (by forming theories). When children watch a situation, they are driven by an eagerness to learn. They set up a hypothesis about a spatial situation and they try to prove it by trial and error. If the outcome is as expected they become uninterested (bored) and give up testing after some tries. If something new happens they test again and again, even using methodology. When they are puzzled they try new hypothesis and test alternatives. An 18 months old child is not supposed to concentrate for a long time. But an experiment shows that they test hypothesis up to half an hour (Gopnik, Meltzoff et al. 2001).

User requirement analysis is a common way to build ontologies for GIS, using interviews, questionnaires, and desktop research. Infants can not communicate their experiences with space through language, so psychologists make use of passive and active measure studies. Two methods will be shortly described here.

Studies of predictive action like reaching with the hand for an object: Infants are presented with a moving object while their reaching and tracking actions are observed and measured. When doing so children act predictive. They start reaching before the object enters their reaching space, aiming for a position where the object will appear when it will reach their hands.

Similar observations can be made for visual tracking studies and studies that measure predictive motion of the head. There is evidence that infants extrapolate future object positions (von Hofsten, Feng et al. 2000).

Studies of preferential looking for novel or unexpected events: When children are confronted with outcomes different from their predictions they are puzzled. It is like watching magic tricks (Gopnik and Meltzoff 2002). The surprise can be noticed by the children's stare. An independent observer can measure how long children watch a certain situation in an experimental setup. It is evident that children make inferences about object motions behind other objects (Spelke, Breinlinger et al. 1992).

3 Sandbox Geography

A sandbox is a place for experimentation; The laws of physics can be investigated using very simple models. The models are made of sand, so they do not last forever, but they can raise new insights into the little engineers' understanding. The objects treated in a sandbox underlie a mesoscopic partitioning (Smith and Mark 2001) they are on human scale and they belong to categories that geographers form. "Sandbox Geography" is motivated by children's conception of space and can be seen as a contribution to the naïve geography (Egenhofer and Mark 1995). The investigation of very simple spatial situations is necessary to find out more about how space is structured in mental models. *The goal is a formalization of these simple models.* There is no need to connect these models to a new theory of learning nor do the authors intend to build a computational model for a child's understanding of space. Furthermore, the sandbox is also a place to meet, a place of social interaction. The social aspect is considered more and more in building ontologies for GIS. The presented research may contribute new insights for finding structures to define sound GIS interfaces.

The basis of the present investigation is the *theory theory* as explained in the previous section. An initial geographic model formed under this assumption will underlie changes. The necessity for adaptation can be caused by two reasons. First, the environment may change and the models we made about it may not be applicable anymore. Second, we may acquire new knowledge or be endowed with new technology. Our conceptual models then change and we perceive the environment differently. Consequently we do model the environment differently.

We select one example of several theories in this paper for modeling what is called object permanence in psychology. Where is an object when it is hidden? Adults have a quite sophisticated theory about "hidden objects". Four factors contribute to their knowledge. Adults know about spatial relations between stationary objects, they assume the objects to have properties and they know about some laws that govern the movement and the perception of objects. Equipped with this knowledge they can predict where and when an object will be visible to an observer. They can explain disappearance and reappearance and form alternate hypothesis about where the object might be if the current rules do not hold (Gopnik and Meltzoff 2002).

Children start out with quite a simple theory where an object might be. 2.5 months old infants expect an object to be hidden when behind a closer object, irrespective of their relative sizes. After about a month they will revise this theory and consider the size as well. An object that disappeared is firstly assumed to be at the place where it appeared before. That is habituation – parents tidy up in the world of infant's objects. A later hypothesis is that an object will reappear at the place where it disappeared. The object is individuated only by its location. The properties of the object seem to be ignored.

It is even possible to exchange a hidden object. In a series of experiments an object is presented to the child and then hidden behind a screen. An experimenter exchanges the hidden object e.g. a blue ball by a red cube. Then the screen is removed. A child around the age of six months will not be surprised as long as an object reappears where it disappeared. Surprise appears only if observations and predictions about an object do not fit together. Because the child's prediction does not consider properties of objects, the exchange of the object will not lead to a contradiction between prediction and observation.

The object individuation by location will change in the further development to an object individuation by movement. An object that moves along a trajectory will be individuated as a unique object even when it does change its properties. Additionally, there seems to be a rule that solid 3D objects can not move into each other as long as they are on the same path. The child will even be able to make a prediction about when the object will appear on a certain point in the trajectory. This theory will again change to an object individuation by physical properties like shape, color, and size. As it goes through this process the child will come closer to an adult's theory of objects with every new experience it makes about the objects.

In the following sections we want to present a formalization of the "hidden object" problem. It is the first model in the necessary series of models for the sandbox geography.

4 Algebra

An algebraic specification consists of a set of sorts, operations, and axioms (Loeckx, Ehrich et al. 1996). There are well known algebras, like the algebra for natural numbers, the Boolean algebra or the linear algebra for vector calculations. An algebra groups operations that are applied to the same data type. The Boolean algebra has operations that are all applied to truth values. Axioms describe the behavior of these operations. An example is given below.

```
Algebra Bool b
operations
      not :: b -> b
      and, or, implies :: b -> b -> b
axioms (for all p,q)
      not(not p) = p
      p and q = if p then q else False
      p or q = if p then True else q
      p implies q = (not p) or q
```

A structure preserving mapping from a source domain to a target domain is called morphism. Morphisms are graded by their strength and describe the similarity of objects and operations in source and target domain. Finding or assuming morphisms helps to structure models. They help to link a cognitive model to a model of the real world.

Previous work has successfully used algebra to model geographic problems (Frank 1999; Frank 2000; Raubal 2001). Algebras help to abstract geographic problems and offer the possibility to do this in several ways. An Algebra can be used as a sub algebra within another algebra and thus allows the combination of algebras. Instantiation is another way to reuse algebras (Frank 1999). This research assumes the following hypothesis: *Theories of space can be described by a set of axioms. It is possible to revise such a theory by adding, deleting, or exchanging axioms.* Therefore algebra seems to be the right option for modeling the problem. Algebras for different spatial situations can be built and quickly tested with an executable functional programming language.

5 Agents and Algebra

To model the "hidden objects" an agent based approach has been chosen. An agent can be defined as "Anything that can be viewed as perceiving its environment through sensors and acting upon the environment through effectors" (Russell and Norvig 1995). Several definitions can be found in the literature (Ferber 1998; Weiss 1999).

Modeling an *Algebra based Agent* is motivated by using the tiered belief computational ontology model proposed by (Frank 2000). A two tiered reality beliefs model allows to model errors in a person's perception by separating facts from beliefs. This distinction is vital for modeling situations where agents are puzzled. This happens always when a belief about the "real world" does not fit together with the actual facts. Several reactions are possible in this situation.

1. The agent retests the current belief against the reality.
2. The agent makes use of an alternative hypothesis and tests it.
3. If no rule explains the model of reality the agent has to form a new ad-hoc rule that fits.
4. If all rules fail and ad-hoc rules also do not work the agent has to exchange its complete theory. This is not the case under the hypothesis taken that theories can be revised by adding, deleting, or exchanging axioms.

The agent generates a reaction of surprise when beliefs do not fit together with facts about the world. An environment with a cognizant agent has to be built as a computational model.

6 Computational Model

The computational model consists of a simple world with named solid objects. The objects can be placed in the world. Their locations are described by vectors. It is also possible to remove objects. An agent has been modeled that can observe his own position and orientation in the world.

```
Algebra World(world of obj, obj, id, value)
Operations
        putObj
        removeObj
        getObj
```

```
Algebra Positioned(obj, vec) Uses VecSpace
Operations
    putAt
    isAt

Algebra VecSpace(Vector,length)
Operations
    dotProd
    orthogonal
    distance
    direction
    ...

Algebra Object(obj)
Operations
    maxHeight
    maxWidth
    color
    ...
```

The computational model motivated by the *theory theory* makes use of three basic properties. The prototypic agent has to be endowed with innate knowledge. Jerry Hobby claims that there is a certain minimum of "core knowledge" that any reasonably sophisticated intelligent agent must have to make its way in the world (Hobbs and Moore 1985). The agent is able to observe the distance and direction between him and an object. The objects are given names in order to identify them. The agent can give an egocentric description about the objects in the environment. A *learning mechanism* shall enable the agent to revise his knowledge and have new experiences with his environment. The agent shall apply a mechanism of theory testing by making hypotheses and testing and verifying them.

To determine the location of an object the agent is equipped with an object-location memory. Each object is situated on a vector valued location in the world. The agent stores locations with a timestamp in order to distinguish when objects have been perceived at a certain location. For the first version of the computational model agents do not move. The agent generates a reaction of surprise when beliefs do not fit together with facts about the world.

```
Algebra Agent
Operations
```

```
        position :: agent -> pos
        direction :: agent -> dir
        observe :: t -> world -> [obj]
        predict :: t -> [[obj]] -> Maybe
        egocentric :: t -> [obj]
    Axiom
        isSurprise = If observe(t1,world) <> predict(t1,[[obj]]) then TRUE
```

By the exchange of one axiom three different behaviors and thus three spatial conceptualizations can be achieved. In the first model a disappearance of an object will be explained by the following hypothesis. *The object will be behind the occluding object where it disappeared.* The *predict* function will return a list of objects at time t_i, being behind an occluding object.

Axiom: *predict* (t,[[obj]]) = [obj(t_i)]

Observing contradiction with prediction, an axiom is replaced. This gives new prediction. The second model formalized will consider that *the object will be where it appeared before*. The *predict* function will return a list of objects being perceived at an initial observation time t_0.

Axiom: *predict* (t,[[obj]]) = [obj(t_0)]

The final model will assume that *an object will be where it disappeared.* The *predict* function will deliver a list of objects visible at the observation time t_v.

Axiom: *predict* (t,[[obj]]) = [obj(t_v)]

For the realization of this computational model an executable functional language has been chosen. Haskell is widely accepted for rapid prototyping in the scientific community (Bird 1998).

7 Conclusion and Outlook

Naïve Geography theories can benefit from the presented investigations. We have shown that it is possible to formalize the conceptual models children have about space. Further research in developmental psychology will be beneficial for this work, but the already existing body of research will be sufficient for my Ph.D. Future research will certainly concentrate on moving objects and extend the presented approach. The formalization has to be enhanced and different spatial situations have to be modeled using algebra. We will not undertake human-subject testing, but concentrate on formalizing operations reported in the literature.

The model of our current agent can be extended by the inclusion of perspective taking, delivering intrinsic and absolute allocentric descriptions of the world. If an agent is tutored by other agents it requires rules about when and how knowledge is acquired. Last considerations are at that time omitted in our research. However we want to keep it as an interesting topic for the future.

It is important to identify the structures in the spatial models and find mappings between them. To form a sound GIS theory we need to find simple commonsense concepts. Children's understanding of space can be exploited to find these concepts. This paper wants to contribute towards a better understanding of the formal structure of spatial models – the Sandbox Geography.

Acknowledgements

This work has been funded by the E-Content project GEORAMA EDC-11099 Y2C2DMAL1. I especially like to thank to Prof. Andrew Frank for guiding me through the process of finding a Ph.D. topic, for his discussions and all the help with this paper. Gratefully we would like to mention Christian Gruber and Stella Frank for correcting the text and checking my English. Last but not least many thanks to all colleagues especially Claudia Achatschitz from the Institute for Geoinformation for their valuable hints.

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