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Spatial Information Theory

A Theoretical Basis for GIS

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Proceedings

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Foreword

This volume collects the papers presented at the European Conference on Spatial Information Theory (COSIT'93), held in Marciana Marina on the island of Elba (Italy) in September 1993. Spatial Information Theory collects disciplinary topics and interdisciplinary issues that deal with the conceptualization and formalization of large-scale (geographic) space. It contributes towards a consistent theoretical basis for Geographic Information Systems (GIS).

Advances in computer technology and information science and also geography are applied to the practical problem of collecting, managing and presenting spatial data and have produced Geographic Information Systems. GISs are widely used in administration, planning, and science in many different countries, and for a wide variety of application areas. The unifying concept for the GIS is the relation of all information to space, which is realized differently in different applications and cultures. Spatial Information Theory attempts to discover the universally valid principles and to understand the differences of the particular solution. Research results are relevant for GIS, but are distributed in many disciplines and contacts between researchers are therefore hindered. At the same time, development of GIS is limited by the lack of a sound theoretical base.

COSIT'93 follows the international conference "GIS: From Space to Territory. Theories and Methods of Spatio-Temporal Reasoning" that took place in Pisa in September 1992*. That conference brought together experts from different disciplines, most notably computer science, geography, cognitive science and linguistics and was focused on spatial and temporal reasoning about geographic space. This event has established an interdisciplinary dialog within the international scientific community which has continued since and has led to the organization of COSIT'93.

The call for papers, mostly distributed by electronic mail, resulted in over 60 full papers submitted. They were of very high quality and covered a broad field of different disciplines. Each paper was distributed for review to four members of the program committee or other experts in the field. The program chairs then selected the 32 best papers based on the reviewers' assessment to be presented at COSIT'93 and to be included in the proceedings. Comments from the reviewers were sent back to the authors to help them in producing the final copy. We are grateful for the collaborative efforts of the authors and reviewers that allowed us to get this volume ready for the conference.

We thank all people who helped in organizing the conference. In particular the members of the program committee and the additional reviewers contributed generously. Sincere thanks also to Nahid Nayyeri from the ARA Congressi for the organizational and administrative support.

July 1993

Andrew U. Frank
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A Cognitive Model for the Process of Multimodal, Incremental Route Descriptions

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Abstract. In normal life we often give *route descriptions* to inform someone about a specific route. They can be divided into the classes of *complete* and *incremental* route descriptions. We propose that the multimodal, incremental route description process consists of a wayfinding, a waypresentation and a control process and is based on a *segmentation hierarchy*. The presentation of a route description is characterized by the use of different presentation modi like speech, gesture and graphics. We propose a computational model for the multimodal, incremental route description process.

1 Introduction

Route Decriptions are common actions in normal life. They can be divided into two classes: *complete* and *incremental route descriptions (IRD)*. Normally, we use complete route descriptions to give the entire route all at once. The problem for the questioner is that he has to remember a lot of details all at the same time. On his way to his destination point he normally cannot ask the same person for more details. What we usual want are *incremental* route descriptions like those given by a codriver, who ideally gives timley route informations.

Psychology experiments have been conducted concerning the human ability to process and represent information about spatial environment ([Tolman 48; Piaget et al. 60; Siegel & White 75; Haury et al. 92]). The abstract representation format is called *cognitive map* ([Hartl 90]). In this work we are not concerned with the mental model problem. However we want to present a model of the *multimodal, incremental route description process*[1]. Furthermore we give some remarks about the possiblity to remember experiences made by route descriptions received in the past. We explore how to arrive from a spatial representation of a route [2] at a *multimodal incremental route description* (MIRD).

Route knowledge and its connections to other human abilities has been investigated in psychology by different views ([Blades 91a; Garling 89; Hayes-Roth & Hayes-Roth 79]). Piaget differentiated between landmark and route knowledge ([Piaget et al. 60]), whereas Siegel and White propose that landmarks are the preliminary stage of learning routes ([Siegel & White 75], for a good review see [Blades 91a]). Complete route descriptions are well examined for psychological ([Streeter et al. 85; Thorndyke & Goldin 83]) and linguistic reasons ([Klein 79; Wunderlich & Reinelt 82]), but there is little known about incremental route descriptions.

The main process is usually divided into two subprocesses. The first subprocess is the wayfinding process, that modells the human ability to learn and remember a route through the environment ([Blades 91b]). The second subprocess is called the waypresentation process. In general, both processes depend on the knowledge about the environment, on the questioner, and some external parameters like weather and time[3]. Approaches that integrate knowledge about the questioner and external influences to construct an adequate and adaptive model of the cognitive process of incremental route descriptions do not exist.

In general, route descriptions can be clearly defined to enable a questioner to find his path from a starting point to a destination point following some constraints. In this case many linguistic examinations about the structure of complete route descriptions are available ([Wunderlich & Reinelt 82; Klein 79; Meier et al. 88; Habel 87]). Wunderlich and Klein have divided the presentation into four phases: introdution, mainpart, verification and final phase. The sentence structures in complete route descriptions are very restricted and sometimes schematic. There are a number of computational models for the generation of textual route descriptions. Habel proposes a three-phase model that is a special case of the architecture presented in [Hoeppner et al. 90].

In contrast to complete route descriptions, temporal aspects are very central for MIRD. If one wants to present spatial informations one has to fix the temporal structure of the whole process. Therfore one has to decide on the start

[1] As the spatial basis for incremental route descriptions we use a 3-dimensional map representation.

[2] Multimodality means the presentation of information in different modes, like natural language, gestures, and graphics.

[3] From now on, these external parameters and the knowledge about the questioner will be called constraints.

of information retrieval and the beginning of the presentation of an information unit. A general constraint for a MIRD is that the information is presented timely.

A description like the following example combines various description levels:

> You must follow the Goethestraße until you reach a red house on the right side, where you turn right into the Schillerstraße.

In this description one level is used that is defined by paths (e.g. Goethestraße, Schillerstraße) and one level that is defined by landmarks (e.g. red house). Usually, we change the level of description to give the questioner a unique orientation in his actual spatio-temporal environment. As the example shows, descriptions are not only at a very basic level (*... red house on the right side, where you turn right ...*), but sometimes we give some more abstract information (*... follow the Goethestraße*) to give the questioner a global orientation. Beside the topological and topographical information that is relevant for the route descriptions, we often use explanations *why* we have choosen a specific route segment, but not an alternative one (*Now, we drive down the Schillerstreet, because the Mozartstreet is a one-way street in the other direction*). For explanations we have to appeal to information that are relevant for the wayfinding process before.

2 A Cognitive Model for the Multimodal, Incremental Route Description Process

We use the term *cognitive model* in the sense of Pylyshyn:

> In order that a computer program be viewed as a literal model of cognition, the program must correspond to the process people actually perform at a sufficiently fine and theoretically motivated level of resolution. ([Pylyshyn 84] p. xv)

In this sense we want to present a model for the MIRD-process. First we give a general question of the whole process in order to delimit our model from others. Then the representation structure is introduced, followed by the subprocesses and their interactions.

Klein and v. Stutterheim propose that a text is used to answer an explicit or implicit question, which they call *quaestio* of a text ([Klein & v.Stutterheim 87]). The more precise the quaestio can be formulated the better is the structure of the text. So route descriptions are very interesting because of their precise quaestio:

What is the way from X to Y?

One of the main criterions is the *adequacy* of route descriptions. Adequacy, in the sense that the description is similar to those given by humans ([Habel 87]) is intentionaly not very clearly defined. It reflects what Pylyshyn means with that *the eventual successes of cognitive science, if they come at all, will have to explain a varity of empirical phenomena* ([Pylyshyn 84] p.272). So the main task is to give a model that incorporates all known processes which seem to be relevant for the MIRD-process and associated representation structures. In general the route description process consists of the *wayfinding* and the *route presentation process*. What both processes have to achieve is relativly clear but the connection between them is almost undefined. For this reason we presume another process that is called the *control process*. The main task of this process is the coordination of process interactions. In *complete route description* there exist two competing strategies: planning in advance and stepwise planning ([Klein 79] p.7). In cause of the incrementality, the MIRD-process can be characterized as a stepwise planning process. At the startingpoint there is only a *rough path* to the destination point and only some segments of the whole route are consciously present. We assume that a path from the starting point to the destination point can be splitted into segments. Furthermore we presume that in MIRD in every moment of the description only the actual and the next segment are used ([Meier et al. 88] p.19).

Our general architecture of a route description process consists of a wayfinding and a presentation process with abilities to switch and interact between both processes, which is done by the control process. The central knowledge structure could be seen as a hierachical extension of the *primary plan*[4] introduced by Klein ([Klein 79]).

2.1 Segmentation Hierarchy

One of the first hierarchical models for a cognitive map is the approach suggested by Pailhous, ([Pailhous 70]), who organized the spatial knowledge into a *basic network* and a *secondary network*. It seems to be widely accepted that for different uses of cognitive maps we need different views or layers. One possible approach is the idea of overlaying many thematic maps of the same space ([Gluck 91] p.126).

In our model we propose a *segmentation hierarchy* that is similar to Kuipers differentiation into the hierarchy of regions. A *segment* is a vertical part of the hierarchy, that consists of two spatio-temporal entities, e.g landmarks, and their connection by a finite spatio-temporal unit (paths). The union of all segments of a specific route description is called the *segmentation hierarchy*. Segments are defined concerning a specific level that depends on various parameters[5].

A segment is the basis for all processes that are relevant for the MIRD-process. We will present an example to clearify what is meant by the segmentation hierarchy. The problem lies in presenting a route from the *starting point*

[4] The primary plan is part of a cognitive map that contains the starting and the destination point.

[5] If we go by feet important landmarks are the segment-constituing spatio-temporal entities which define the segementation level. If we go by car we use the level of turning point landmarks.

S to the destination point Z (see fig. 1). On the choosen route there are three turning point landmarks (A, B, C). Between S and A is one landmark, a gate on the right side, and between A and B are two landmarks, namely a house on the right side and a tower on the left side of the street. First we predict that the rough path[6] from S to Z is known by experience[7]. It is also known that the questioner is familiar with the segments SA, BC, and CZ but he does not know the segment AB.

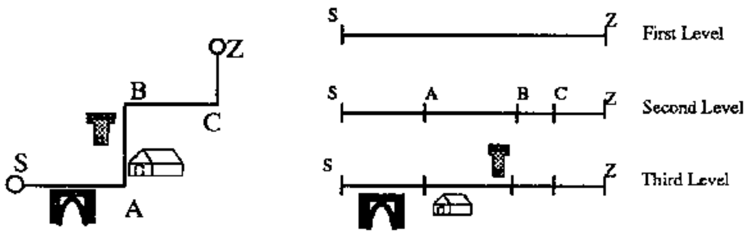

Fig. 1. Complete Segmentation Hierarchy

The second level of the hierarchy represents the differentiation between the starting point S, the landmarks A, B, C, and the destination Z. In this example, the landmarks A, B, C, are turning points where we have to turn right or left. It is widely accepted that turning-point landmarks are very important for temporal-spatial instructions, so they are used in nearly every model of route descriptions ([Klein 79; Wunderlich & Reinelt 82; Habel 87; Meier et al. 88; Hoeppner et al. 90]). It can be deduced that turning-point landmarks are very high up the segmentation hierarchy.

The next level is more detailed than the second level. In the third level, all objects that we know by normal perception, like houses, trees, human beings, animals etc., are integrated. The difference between the second and the third level is that we switch from *large scale space* to *small scale space*. In large scale space we look at a spatial environment where we cannot see the destination point from the starting point. In small scale space the destination point is visible from the starting point. It is not necessary to percept the landmark C from the starting point. But if we say that on the right side is a tree when we pass by it, it is necessary that we then see the tree.

On this level we want to show how the experience of the questioner can be integrated. As we assume for our example the questioner knows the segments SA, BC, and CZ. But he is not so familiar with the spatial environment that he

[6] It seems that the relative position of the starting to the destination point, and the distance between both are mainly responsible for the determination of the rough path.

[7] If the route is not known the waysearching process will be started.

knows the complete route, especially the connections between these segments. So information from the second level has to be used in describing the segments SA, BS, and CZ and from the third level for segment AB. For the description of segment AB, we integrate the house at the right side of the road and the tower at the left side, but the gate in segment SA is not mentioned.

Now we have the whole segmentation hierarchy for the complete route SZ. The hierarchy is incrementally generated (see example 1) and determined by two general phases. In the first phase a rough spatial path is examined. It reflects the common strategy that if we want to find a path on a map in an unkown area we will look at a general map where the starting point and the destination point are integrated. There we determine a rough path (usually using our finger) between both points. Generally it does not matter if the roads we determine in that way are not obviously connected. In this case we use the general assumption that in the western world all roads are somehow connected[8]. A model for this rough path is the first level of the segmentation hierarchy.

In the second phase, we refine the first level so that we find the segment SA and AB where we follow Klein ([Klein 79]) who has mentioned that in normal route descriptions we only use the actual and the next segment at one time[9].

Every time when we change the actual segment we have to determine the next. For example, if we turn left at A, we leave SA and reach AB that becomes the actual segment. Now, we have to determine the segment BC to be able to give the transition from segment AB to BC.

The whole segmentation hierarchy is incrementally generated on the way from the starting point to the destination point. This reflects the assumption that the whole description is in detail not known in the beginning. Description elements like a tree or a house are integrated as they are perceived. Another assumption is that humans can easily choose a new path if they have followed the wrong way. In the proposed model a new rough path, the new actual and the new next segment have to be determined to proceed with the description.

2.2 Wayfinding Process

Klein divides the planning of the primary plan for complete route descriptions into two techniques: advanced and stepwise planning. These techniques can be used in combination. Advanced planning, means that the route description process is mostly sequential. In contrast, stepwise route planning, implies that there is an interaction between the wayfinding and the route presentation process. It is therefore meaningful to assume a combination of both techniques ([Klein 79]).

Klein does not say a lot on how to find a way. He only reports of a person who shows a behaviour that can be outlined as a trial and error technique. Habel distinguishes between *route finding* and *route knowing* which we denote with *way search* and *experience-based wayselection* ([Habel 87]). Gluck remarks, that

[8] Here we do not take into account that mountains, vallies and seas are important restrictions (see the barrier effect ([Kosslyn et al. 74]).

[9] At that time segments BC, and CZ are still not computed.

the potential optimizing functions that are relevant for the wayfinding process, are not restricted to minimal distance or even minimal effort. He also mentions, however, that there is no model that accounts for them ([Gluck 91]). The wayfinding process modelled in the TOUR model is a simple and slow approach to find a way ([Kuipers 77]). In the TRAVELLER model an incomplete wayfinding process is used, that can not find partial ways in the cognitive map ([Leiser & Zilbershatz 89]).

To also give adequate descriptions, the wayfinding process has to integrate the spatial representation, information about the questioner and external constraints. The spatial representation, is in the map-based approach a topographical representation of the spatial environment. The adequacy of a description, is mainly based on the information about the questioner and some external parameters. There is a wide difference between an 8 and an 80 years old person, as much as between a tourist and a stockbroker. Also the weather (e.g. rainy, dry) and the time (e.g. rush hour, night) are important.

We have to distinguish between the selection of a path that is known by experience (experience-based wayselection) and the search for a path by using a map ([Elliott & Lesk 82]). Kuipers ([Kuipers 77; Kuipers 78]) in his TOUR model and Leiser/Zilbershatz ([Leiser & Zilbershatz 89]) in their TRAVELLER model mainly use an experience-based approach. Both models are based on a graph network which represents a mental model of the spatial environment and concentrate on how to integrate new knowledge about the *external* world into it. Leiser and Zilbershatz divide route knowledge into a basic network for the main routes and a secondary network for the other routes. This division is based on experiments done by Pailhous ([Pailhous 69]) and Chase ([Chase 82]).

The waysearching process does not seem to be as well understood as the experience-based wayselection process[10]. In most of the relevant works, the route that has to be presented is almost known or generated with some straightforward algorithm[11]. But the waysearch process has also to observe various kinds of constraints. If the person goes by car, the search process has to consider roads for cars. It is also relevant to consider the weather, e.g. if it rains you will prefer to show someone a covered path. There is much evidence that the cognitive ability of wayfinding combines the experience-based wayselection process and the waysearch processes. This is meaningful because it is not usual that we know a large scale space route without searching for some path segments. It seems that a combination of both processes is what we do if we are looking for a route.

If there is no experience that could be used, the path for this segment has to be searched. In figure 1 the segments SA, BC, and CZ are known by experience on the second level. A familiar segment is relevant for the wayfinding process if it connects two spatio-temporal entities on the prospected path under

[10] It seems to be very unlikely that heuristic search algorithm, like A*, are similiar to human search ability in maps.

[11] The algorithm are mainly based on recursive procedures or some kind of standard search algorithm like A* [Habel 87; Carstensen 91].

consideration of external constraints.

The output of the wayfinding process is a *segmentation hierarchy fragment* (SHF). The rough path is in some kind completly determined because you always have an unspecific idea of the way[12]. At any position the actual segment and all following familiar segments are considered until there is a segment in which the path has to be searched for. The complete hierarchy instantiates the *segmentation hierarchy*.

2.3 Control Process

The SHF is an abstract semantic representation of the objects for the path from one spatio-temporal entity to the next. There is no information attached that assigns items of the SHF to a presentation mode, because we suppose that the wayfinding and the presentation processes are independent[13] from each other. This assumption is based on neurological results that show that presentation processes, for example the speaking process, are principally independent ([Springer & Deutsch 88] p.3) from each other. The coordination of the presentation processes is done by a central process which we call the *control process*[14].

The assignment of items of the SHF to a presentation mode can be divided into two main techniques. First, there are schematic descriptions of route segments. For example, if you want to tell someone that he has to go up a street until he reaches a crossing, you use some kind of presentation like:

> You have to go up the street [point with a gesture along the street][15] until you reach a crossing.

On the other side, we have to consider unusual descriptions, that are mostly unusual in cause of the spatio-temporal environment. For example, if you want to describe someone how to hillclimb to the next position.

> You have to put your right food on that ledge [point to the ledge] and than grep with your right hand the crack one meter right above the ledge [point to the crack] .

It seems to be clear that the usage of schemas depends on how common we are with the spatio-temporal environment. If you are a good hillclimber you will

---

[12] This depends on the distance and the way you move. E.g. when you go by car and you want to go from Berlin to Saarbrücken, then you first look for the longest Autobahn segments between both cities. An important assumption is that there always exist an acceptable path from every point in Berlin to that Autobahn segment and from that to Saarbrücken.

[13] Presenation modes are any independent information mode, like *natural language, gestures, graphics etc.*

[14] Such a central control process is also supported by neurological results. E.g. the Thalamus seems to coordinate some aspects of speech and motorical skills ([Springer & Deutsch 88] p.109).

[15] The brackets denote gesture actions.

not think about the hillclimbing description. On the other side, if you live in the forest you may have some problems to give the first description. Beside the user and environment dependencies, external parameters, like the actual time, are important for MIRD. For example a landmark may be relevant in the night because it is illuminated, but not during the day.

It seems that we have no problems to switch between the presentation modes if we want to inform the questioner about, for example, a red house on the right side of a street. We can do this with a verbal expression, with a pointing gesture or a line drawing. So it seems to be evident that there is a central representation structure. When the control process assigns items of the SHF to presentation modes, it has to consider some problems with the classification of the items, like the *cross-referentiality problem*. This means that an item can be parallely presented in different modes like the crack in the second example. To solve this problem the control process assigns the crack item to the verbal and the gesture mode and sends this item to both presentation processes.

2.4 Presentation Processes

The control process distributes the route information to be presented according to the individual strength of each presentation mode. For presentation processes we use approaches presented in ([Herzog et al. 93; Maaß et al. 93]). The presentation processes are mainly the verbal, the gesture and little more less the graphical process. The control process passes a semantic representation structures of the intended information to the processes. For explanation of the main points, we use the following simple example:

```
MOVE( MODE    (verbal)
      TYPE    (by-feed)
      ACTUAL  (type(street),   time(t1),     name(Goethestraße))
      RIGHT   (type(house),    time(t2),     attr(red))
      LEFT    (type(tower),    time(t3),     attr(big))
      UNTIL   (type(crossing), time(t1, t4))
      NEXT    (type(street),   time(t4),     name(Schillerstrasse)))
```

The semantic structure provides global information, like the presentation mode and the way the questioner moves. It also contains information about the actual spatial segment, ACTUAL(type(street), time(t1), name(Goethestraße)), and the following segment, NEXT(type(street), time(t1), name(Schillerstrasse)). If it is necessary to give more detailed descriptions, the details are integrated in this structure, like RIGHT(type(house), time(t2), attr(red)) and LEFT(type(tower), time(t3), attr(big)). Another important item of the structure is the next spatio-temporal entity, UNTIL(type(crossing), time(t1, t4)), that defines the connection to the next segment. The timemarker t_i fixes the moment when the items are presented. Items with the same timemarker are presented at the same time in one coherent expression.

With this semantic structure the text process generates a verbal expression like:

t1: Go down the Goethestraße, until you reach a crossing.
t2: Pass the red house on the right side
t3: Pass the big tower on the left side
t4: At the crossing, turn right into the Schillerstrasse.

3 Conclusion

The research in route descriptions leads to the conclusion that we have to assume three subprocesses: a wayfinding, a presentation process, and a control process. Central for our approach is the segmentation hierachy, that is incrementally generated, and the integration of various external constraints, which influence all subprocesses.

We presented a global framework, that has to be refined, perhaps modified, and compared with results of psychological examinations in the future. Especially the interaction between the subprocesses and the representation structure has to be examined in more detail. We have finished a 3-dimensional domain model and the realization of new display techniques (2-dimensional projections, perspective views, animation). Our current work is concerned with the seamless coordination of the presentation modes.

4 Example

Here is the complete example used in the paper.

1. t1: Go along the street until you reach landmark A.
   [point with a gesture along the street]
   t2: Turn left into the Goethestraße. [Point left]
   (First SHF)
2. t3: Go down the Goethestraße, until you reach a crossing.
   [point straight ahead]
   t4: Pass the red house on the right side.
   t5: Pass the big tower on the left side.
   t6: At the crossing, turn right into the Schillerstraße. [point right]
   (Second SHF)
3. t7: Follow the Schillerstrasse. [point straight ahead]
   t8: Turn left behind landmark C. [point right]
   (Third SHF)
4. t9: Go down this street until you reach your destination point.
   [point straight ahead]
   t10: Here you see your destination point.
   (Final SHF)