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1. Ontology for Spatio-temporal Databases

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1.1 Introduction

Ontology and the related term 'semantics' have recently found increased attention in database discussions. Early discussions of ontology issues important for databases [1.124] [1.76] were lost in a sea of papers on technical, mostly performance issues, despite the fact that textbooks as early as [1.132] discussed briefly the relationship between information system and real world. This is different today: for example, in a recent conference, two of the three invited talks where concerned with semantics. Ceri discussed the expression of semantics in XML and possible extensions [1.37] and Reuter dedicated his whole lecture to the discussion of what semantics a database should contain and of how current database structure is not sufficiently flexible to allow advanced uses. His examples were diverse and ranged from an application providing guidance for tourists moving in the town of Heidelberg to an application from science, where reports about scientific experiments in cellular biology must be organized. Reuter started with the assumption that the ontological categories of Space and Time should be included and proposed History, Topology and Intensions as candidates for the future, a position already advanced by Gadia and Nair in 1993 [1.188, ch2].

Information systems and their implementation as databases rest on ontological commitments. Decisions about the type system used, how identifiers are managed, and so on, are derived from a specific view of the world to which the database relates, in other words from a specific ontology. The ontologies of standard database models make very limited assumptions and therefore the data model is widely applicable. Spatio-temporal databases must make stronger commitments to capture the meaning of space and time. Such an ontology is necessarily more involved and the connection to the application area stronger. The designer of a database application has to reconcile the ontological concepts from the application area with the ontology built into the database. Optimally, a spatio-temporal database involves in its built-in ontology a minimal commitment on how space and time is structured and is thus most open for application specific refinements. Exploring the minimal set of ontological commitment is the goal of this chapter.

The ontology built into a DBMS can be insufficient or it can be too restraining. It is insufficient if the ontological categories necessary for numerous applications are not available and must be reconstructed for each application anew; the resulting incompatibilities will be very costly to correct later [1.79]. It is too restraining if the ontology commits those who apply it to assumptions which do not hold for novel applications. Spatio-temporal databases are typically constructed to integrate the knowledge of many agents and face the problem of heterogeneous environments, a point already raised by Wiederhold et al. [1.188, ch.22]. Current databases do not allow us to model joint beliefs of groups of agents which do not correspond to similar beliefs of other groups of agents; for example, Reuter works with groups of scientists, who manage terabytes of reports of results from experiments in cellular biology, where the validity of the results and their interpretation are debated among the groups. Current ontological investigations related to databases and information systems have been extended into the spatial domain [1.34, 1.35, 1.60, 1.61, 1.63, 1.158, 1.186], but their extension into the spatio-temporal domain [1.42, 1.95, 1.96, 1.118, 1.137] has proved more difficult than expected [1.84] [1.180]. An overview of Time Ontology for computer science was published by [1.168]; Montanari and Pernici discuss the different proposals for temporal reasoning [1.188, ch.21].

I will investigate the questions which arise when information systems are built for purposes involving the representation of real space and time. Examples from the domain of Geographic Information Systems demonstrate the issues. Geographic Information Systems are especially suited for our purposes because they model real-world situations including their spatial and temporal aspects. Their application area is very broad and extends from the administrative and legal rules governing land ownership and registration [1.52] to systems built for environmental purposes [1.109] and for research into global change [1.143]. The situation is not substantially different for other spatio-temporal systems, like systems for motor traffic monitoring or tracking airplanes. Spatio-temporal databases are often built from data from many different sources, which is notoriously difficult [1.101, 1.197]. Data to be integrated differ in their semantics and representation, and a meaningful combination requires bridging the gap created by ontological assumptions as well as translations between the representations once their meaning is in the same context. But even for databases where all data are from the same source, the gap between the ontology of the data collectors and the ontological assumptions of the designer of the GIS software and later the users must be bridged.

I propose a multi-tier ontology, where different rules apply to each tier (table 1.1). The approach used here is empirical and starts with the observation of physical properties for specific locations and instants. Objects are formed as areas of uniform properties which endure through time as identical. Cultural conventions link names to objects and construct objects of 'social reality' [1.10, 1.170], which are meaningful within a set of culture-dependent rules. For example, the legal system of a country gives a meaning to concepts like 'parcel' and 'ownership'. But the corresponding objects do not have physical existence; they are social artifacts. Agents – human beings or organizations which behave like persons with respect to the aspects considered here – make all observations. Agents derive decisions about actions from the knowledge they have acquired. An agent's knowledge evolves over time and spatio-temporal databases must therefore document the temporal evolu-

Ontological Tier 0: Physical Reality:
- the existence of a single physical reality,
- determined properties for every point in time and space,
- space and time as fundamental dimensions of this reality.

Ontological Tier 1: Observable Reality:
- properties are observable now at a point in space,
- real observations are incomplete, imprecise and approximate.

Ontological Tier 2: Object World:
- objects are defined by uniform properties for regions in space and time,
- objects continue in time.

Ontological Tier 3: Social Reality:
- social processes construct external names,
- social rules create facts and relationships between them,
- social facts are valid within the social context only.

Ontological Tier 4: Cognitive Agents:
- agents use their knowledge to derive other facts and make decisions,
- knowledge is acquired gradually and lags behind reality,
- reconstruction of previous states of the knowledgebase is required in legal and administrative processes.

Table 1.1. The five tiers of ontology

tion of an agent's knowledge. The historical state of an agent's knowledge must be considered to make a fair assessment of an agent's actions.

The proposed tiers are ordered from data for which data collections from multiple sources are more likely to agree to data for which disagreement is more likely; they help with the integration of data from different sources to understand the processes which result in agreement or disagreement between data. Debates on the length of a year are limited to scientific discussions on the 12th decimal, the measured height of mountain tops may differ between countries by a few meters; but debates about the location of boundary lines occur occasionally, the limits of areas with economic problems are debated in parliaments and the judgment on desirable areas for vacations is mostly a question of personal preference. This leads to separation of physical reality, object reality and socially constructed reality in different tiers of an ontology.

A multi-tier ontology allows to integrate different philosophical stances, from an extreme realist or positivist view to the current post-modern positions. The multiple tiers recognize that various approaches contribute to our understanding of certain aspects of the world around us and take the philosophically unusual position that none is universal [1.162].

The goal of this chapter is to investigate what the minimal ontological commitments for spatio-temporal databases are. To this end, the concept of ontology in the context of database design is clarified first and then an 'observation-based', empirically justified minimal ontology is designed. The ontology is designed to facilitate a computational model. The approach owes much to the efforts in formal ontology by

Guarino [1.105, 1.173, 1.176, 1.181] and related researchers [1.69, 1.68, 1.199]. It connects, however, their findings with the concept of ’social reality’ introduced by Searle [1.170], which gives a foundation to most of the semantics of administrative data processing. Multi-agent theory [1.73, 1.201] provides a framework to justify the two-time perspectives used in temporal databases [1.185].

1.1.1 Ontology to Drive Information System Design

Guarino [1.107] and Egenhofer [1.74] promote the term ’ontology driven information system design’ and experiments abound to formalize ontology description languages – even an XML-based version is reported [1.48, 1.183]. This is the continuation of the observation that application programs incorporate various properties of the objects handled, properties which are coded many times in the application code – and not always consistently. Database schemata, originally used only for the structuring of storage of data, were soon discovered to be useful for the generation of reports (e.g. the report generation language of CODASYL [1.41]) and later also for the automatic generation of data. These application-independent properties of the object represented in a program can be described as ontology. If such ontological properties of the objects are concentrated in one place and if they can be used by various programs, simplification of the software development process can be achieved and applications may even gain in usability as more consistency in the operations is achieved [1.79]. There is today substantial – even commercial – interest in shareable ontologies (ESPRIT Project [1.70], Protégé Project [1.157]), and there are companies which construct and sell ontologies (CYC [1.51] or Ontek [1.149]). Several international standardization bodies, from ISO (ISO/TC211) [1.120] to OMG [1.148] and OGC [1.147], standardize spatial and temporal aspects of ontology.

1.1.2 Ontological Problems of Geographic Information Systems and other Spatio-Temporal Information Systems

Geographic Information Systems have to reflect truthfully the state of the world; information systems which do not provide reliable and correct information are useless. This correspondence between reality and information system will be used throughout this chapter to define ontology and to explain its role in the design of information systems. The high cost of collecting and maintaining spatial data has led to more demand for data sharing: data should be collected and maintained once and used by many [1.101, 1.197]. This forces differences in the ontological commitments into the open:

- the continuous nature of reality compared to the discrete approximation of space and time in a database [1.92] (chapter 4 in this volume);
- the fact that the world changes continuously and the database lags behind;
- differentiation between ’valid time’ and ’transaction time’ in temporal databases is an ontological differentiation [1.184];

- the closed world assumption [1.160], which is conveniently assumed in databases, is not valid for spatio-temporal databases [1.79, 1.178];
- the interoperability problem, which is the inability of comparable systems to co-operate [1.24];
- the internal hierarchical structures for space, time and categories [1.93], and the consequent stratification in the ontological categories [1.23];
- the difficulty to combine solutions developed for different applications (composability in linguistic terminology [1.121]);
- the difficulty of describing data and the quality of data: the so-called metadata discussion [1.36, 1.142, 1.165];
- the differences in classification found across cultural boundaries [1.30, 1.111, 1.141].

1.1.3 Structure of the Chapter

The chapter discusses the meaning of the notion of ontology in section 1.2. The following section 1.3 introduces typical application domains for spatio-temporal databases, which are used as examples in later sections. Section 1.4 discusses the fundamental aspects of information systems and shows how they relate to ontology. The next section 1.5 gives an overview of the five tiers of ontology. Section 1.6 discusses the languages which could be used to describe an ontology. The major part of the chapter is formed by sections 1.7 to 1.11, which treat tier in detail. A summary section 1.12 lists the ontological commitments encountered. Conclusions and future work are discussed in the final section 1.13.

1.2 The Notion of Ontology

Ontology describes what is; it is ”the metaphysical study of the nature of being and existence” [1.72]. In a naïve view, there should be only one ontology, as there is only one world. In practice, we observe different conceptualizations of the world by different people. Ontology, especially if the term is used in its plural form, describes a conceptualization of the world and is closely related to software engineering activities like conceptual analysis, domain modeling, etc. [1.106].

1.2.1 Classical View

The notion of ontology is borrowed in Computer Science from philosophy. The Greek philosophers, especially Aristotle in his Metaphysics, inquired what the properties of the world and the objects in it are and how we perceive them [1.177, 1.181]. Philosophy uses the term ontology to describe that which is (ontos, Greek, to be; ontology, therefore: the science of what is) and in this sense, it is used as a synonym for ’metaphysics’. Ontology is often used in contradistinction to epistemology, which is ”the field of philosophy, which deals with the nature and source of knowledge”

[1.146]. Quoted after [1.105] epistemology in brief is a ’theory of knowledge’. It is difficult for us living in the world to separate the description of the world from our knowledge of the world and how it is expressed in language. Strictly speaking, if there is only one reality, there must also be only one ontology, and the human views or conceptualizations of this world are not ontologies in the strict sense. We need another term for the ”theory what people believe the world is like”; one could call it ’projected ontologies’ or ’epistemological ontologies’ [1.153].

Ontologies are modeled after scientific theories (or the naïve counterparts thereof), especially physics [1.114] and geography [1.64], and they generalize the rules found there. Recently, philosophical ontologists have begun to study practical problems from law, engineering and commerce [1.177] and they have started to identify the limits of ontologies based on empirical observations of physical objects.

Augustine introduced the related notion ’universe of discourse’. As far as a rational discussion is concerned, the notions of ontology or universe of discourse are related to the concept of a closed system and its boundary. In this sense computer science has borrowed the term ontology to list what is considered within a discussion or an information system [1.114]; database specialists talk about database schema, often with the same meaning. Davis [1.53] separates three levels in the analysis of a microworld: a level of definition of a domain model, a level of formalization with types and axioms, and an implementation level (Figure 1.1). In this chapter, this approach is extended for spatio-temporal databases which must support multiple applications and therefore multiple domain models which fit in a single generic model.

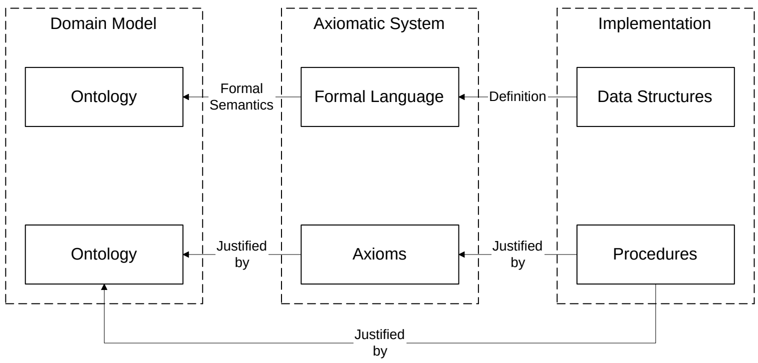

Fig. 1.1. The modeling of a single application after [1.53, p.7]

1.2.2 Social Reality

Ontology describes what is independent of an observer, what exists for every observer. The ontology describes the common reality. The discussion in the past has concentrated on physical reality: on physical objects in the real world. The applicability of this ontology for most of the information systems in administration is doubtful. Much of what is collected in databases are facts not about physical reality (e.g., the position of a building in coordinate space), but rather about human agreements (contracts), about classification according to some culturally fixed rules (e.g., who is an adult) and about social arrangements (ownership rights). These are not physical but nevertheless very 'real'. Many important aspects of our daily life fall in this category: neither money nor marriage or companies are physically existing and can be touched. They are related to physical objects and specific relations between them but they exists themselves not physical in nature.

The physical ontology can only describe the physical part of reality; things like money, ownership, social status, etc., are not real in the same way as is light, physical objects, etc. Multiple observers may see the same objects (e.g., pieces of paper) but may not agree on their value, because for some observers and contexts some of the pieces of paper represent money but not for other observers in other contexts. Sociologists have pointed out that part of what seems real to us is constructed by society [1.10], and Searle [1.170] has provided a succinct analysis of the kind of reality behind money, property of land, marriages, etc., which is extremely helpful to avoid some of the confusing tangles of ontological discussion.

Agents create social reality; they can be single individuals (persons) or aggregations of persons in agencies or organizations. Some agents – in general, the agencies of the state – have the power to make other agents observe the same rules regarding the objects they create. The standard example is money, which physically is nothing else than printed paper; given that all members of a group treat money in the same way, it functions to facilitate commerce, despite the fact that the fiction that one can exchange paper money into gold has been dropped a long time ago.

Social reality, like language symbols, is meaningful only in a context. The law of a country creates a (local) context in which institutional reality as a part of social reality is defined. We will find it helpful to use here the example of the land-registration process to demonstrate how social reality is created, because it demonstrates spatial and temporal aspects [1.1, 1.14, 1.77, 1.144]. Ownership of land requires spatial delimitation, i.e., boundaries, and is, in some countries, created by registration in some sort of information system (cadastre, land registry).

Much of social interaction is based on understanding and speculating what other agents think. Social rules of fairness dictate that agents are not responsible for not knowing facts which they had no possibility to learn. To judge the effects of actions, one must therefore be able to reconstruct what the agents have known at a specific time. In other circumstances posting some facts publicly is crucial to their being established socially. For example, ownership of land must usually be registered in a public register to be enforceable against others; many western movies describe the race between two gold diggers in order to register their claims first.

1.3 Application Domains

Ontologies are influenced by the examples the designer uses. Classical ontology studies, from Aristotle onwards, are based on material objects, preferably solid bodies, the human body or animals, as well as the actions and events in which such objects are engaged. Hayes has studied the ontology of liquids and found it to be very complicated [1.113]. Different domains have different ontological foundations.

Three quite different application domains are used as examples here to assure that the ontological base for spatio-temporal databases does not include commitments which will exclude the application to other domains:

– a table-top situation, with solid and liquid material objects, as they are customarily found on a dinner table; these objects are moved around by humans;
– a city environment, where persons or cars move between buildings and along streets (similar to examples found later, for example, in chapter 4.
– a geographic situation, with plots of rural land, forest, roads and rivers, where people and animals can move unrestricted across the land (somewhat related to the ski resort example (chapter 5 in this book).

The different examples should demonstrate the breadth of the realm of applications requiring spatio-temporal databases and the differences in their conceptualization of reality. I have recommended that particular ontologies be developed for specific application areas [1.79]. For example, an ontology for farming is highly desirable to connect the rules for data collection, calculation of agricultural subsidies in the European Union and the integration of the resulting database for policy [1.80]. Bernasconi has documented an ontology for the sewer systems of a commune [1.11]. Further we urgently need concrete ontologies for land registration to build the base software usable in several countries with different legislation [1.14, 1.144]. Last but not least, an ontology of traffic, private and public, would be very useful in the exchange of data between different traffic guidance systems, transportation schedule services and car navigation aids. The foundation ontology incorporated in the spatio-temporal database must be open to allow each of these ontologies, indeed it must be possible to integrate more than one of them.

1.3.1 Table-top Situation

A well-researched abstraction of the situation on a dinner table was one of the first examples of a computer science ontology: the blocks world [1.8]. It consists of solid blocks, which can be stacked on top of each other. This has served as a fruitful example to discuss the meaning of ontologies [1.104] and to discuss the formal definition of the semantics of spatial relations [1.90, 1.118]. More complex is an environment which includes liquids in bottles or cups [1.113]. Liquids do not have a fixed form, but fill the holes in other objects (only specific kinds of holes can be used to contain liquids [1.34]). Liquids can be poured and mixed, but it is generally impossible to separate two pieces of a liquid once they are merged [1.137, 1.138].

Fig. 1.2. Table-top situation with solid objects and liquids

The objects on a table are under control of a person manipulating them (Figure 1.2). Possession of an object by a person may signal legal ownership and we see here a close connection between physical possession and ownership.

One can see that objects are conceived in such a way that important invariants are maintained. The regular laws of conservation of matter apply and material properties, for example, color, specific weight, remain invariant under a large number of operations. Solid objects on a table maintain their size, volume and form. More complex ontologies apply for cooking, where less invariants are maintained: neither form, color, or volume, nor weight is preserved.

1.3.2 Cityscape

A city contains buildings and streets (Figure 1.3). We can understand the buildings as containers which are further subdivided into rooms. Persons can be in these rooms. Doors between the rooms allow people to move between the rooms or leave the buildings. Streets are formed by the empty space available for movement. Streets and plazas can, again, be seen as containers, but for navigation in a city, a linear conception of a street as a path between doors is a more effective conceptualization. For most purposes, the details of the movement of a person in a street is irrelevant, important is only that the person follows the street from intersection to intersection.

But not only a container and a linear model of space are applicable, we find also an areal one: Considering the rainfall on buildings, the amount of rain running off a roof is proportional to the area. The runoff then follows the streets and in modern cities disappears in the sewer network (again a linear, graph like, structure) [1.29].

Buildings, streets, plants, etc., do not move from their location and the processes of creation take much time. Persons, cars and other vehicles move among them rapidly; their movement is restricted to certain pathways.

Fig. 1.3. City situation with buildings, streets and people

This example shows how different tasks lead to different conceptualizations of space: the same cityscape is seen in terms of volumes, areas and lines. But even within a single type of geometry, for example, the linear network structure of a street network, different levels of detail are used, depending on the specific task: planning a trip uses a less detailed representation of the street network than the description of a path to take, where every intersection must be mentioned. Finally driving in lanes and changing between lanes is yet a third level of detail in a street graph [1.192]. A hierarchy of containers is also useful to navigate in a city environment and to produce maps at different levels of cartographic generalization for this purpose [1.191].

Physical possession is not sufficient to indicate ownership of land. Legal institutions, often called land tenure, are necessary to transfer and publicize ownership and other rights in land. The registry of deeds or a registry of title are maintaining public knowledge about these rights.

1.3.3 Geographic Landscape

The first object of the geographic world is the surface of the world and its form (Figure 1.4). The landscape is seen as an undulated surface (a two-dimensional geometrical object) embedded in three-dimensional space. The geological processes create this surface, most importantly through erosion caused by water flow. The general importance of water and water flow for our lives leads to the concept of height measured as potential with respect to a reference potential assumed as 'sea level'.

Water flows under the force of gravity over surfaces and forms rivers at the bottom of valleys. Streams form a linear network and watersheds form a functionally defined subdivision of space – for every point along a street network there exists a

Fig. 1.4. Landscape with hills and valleys

corresponding watershed (namely all the area from which water flows to this point) [1.88, 1.150, 1.151].

Couclelis has pointed out the contradiction between objects and fields: ”people manipulate objects but cultivate fields” [1.46]. The surface of the earth is divided into parcels, which are manipulated like objects, bought and sold like books or shoes. Fences divide the fields and streets link fields to populated places.

Remote sensing allows observation of large areas and permits the classification of actual land use. Areas of uniform use, for example, forest area, do not automatically correspond to the areas of land ownership. The maps in planning offices show the intended use of some area, but this does not automatically correspond to actual use.

All objects in the geographic world change and move, but some move much faster than others. Most geographic processes are so much slower than the majority of human activities that geography seems to be the ’stable’ backdrop against which other processes are played out. Mountains and rivers do not move, people move between them. Considering a geological scale, mountains rise and are eroded, rivers change their courses; changes in land use are relatively rapid and woods can appear or disappear within a few decades. Movements of geographic objects are qualitatively different from the movement of persons along a street or across a field [1.89], like the airplanes in chapter 4 of this volume.

Man-made objects in the landscape are sharply delimited, but most natural objects do not have sharp boundaries. Various methods have been discussed – from fuzzy logic to qualitative reasoning – to deal with objects with undetermined boundaries, from forests to geographic regions like ’the North Sea’ [1.26, 1.25].

1.4 Model of Information Systems

Information systems are advanced forms of symbol manipulation, but this point of view is not sufficient to understand the relation between reality and the information the system provides. Information systems are used to make mental experiments when real experiments are undesirable, too expensive, etc. They are useful and valuable only if the information they represent corresponds to the state of the real world. This correspondence between reality and information system is used to define formally the meaning of ontology in a model.

1.4.1 Information Systems as Vehicles of Exchange between Multiple Agents

The simplest situation in which ontological issues become important requires at least two cognitive subjects, both of which consider reality possibly in different ways, and both of which communicate about this reality. The cognitive subjects here will be called 'agents' to stress that we include single persons as well as multi-person organizations, for example, state agencies, companies, etc. A practical example is the collection of street information by one agent, which is then provided to another agent to help him find his way; this is done, for example, by national mapping agencies, which collect topographic information and distribute this information to the public in the form of maps; but it is also encountered when somebody informs a friend how to find his way home [1.83].

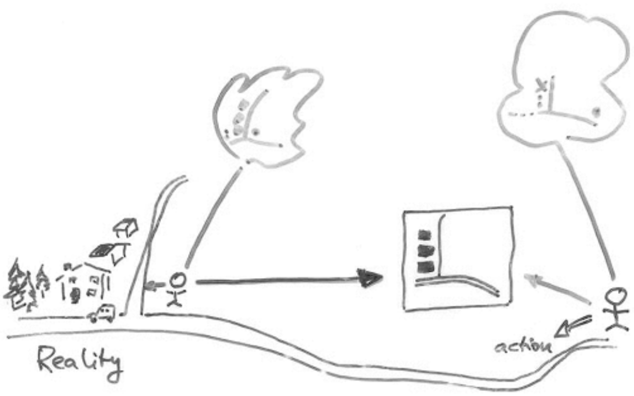

Fig. 1.5. An agent producing a map and another agent using a map for navigation [1.83]

The basic situation is sketched in Figure 1.5: a person observes the world and builds a database of his observation ('beliefs' in the terminology of [1.53]). He gives this description of the world, which is a small database, to another person, who uses it to find his way to a goal. The data in the database are only useful to this other person if his planned path is effective and brings him to the desired location. For this it is necessary that the information gained from querying the database is the same information as that the agent would gain if he would inspect the world directly. For example the length between the two street intersections must be predictable from the database with sufficient precision to select the shortest path.

Abstracting from the particulars of Figure 1.5 we arrive at Figure 1.6, which shows reality and the model of reality in the information system and the operations which enable persons to interact with the information system and reality: R stands for the reality, D for the realm of the data representation, f for the mapping between the data and reality. An operation g_0 carried out on the data must have the same effect as the corresponding operation g_n carried out in reality; mathematically a homomorphism must exist between real world and data [1.99, 1.104, 1.116]:

$$f(g_0(d_i)) = g_n(f(d_i)) \tag{1.1}$$

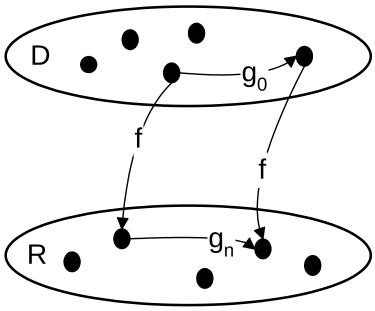

Fig. 1.6. Homomorphism [1.76, p.18]

1.4.2 Correctness of Information System Related to Observations

The correctness of an information system is expressed as a homomorphism between the information system and some portion of reality. The mapping between data representation and reality is based on observations. A generic observe operation links reality to a data value. Observation provides a homomorphism for all operations defined in the information system: the programmed method which returns the shortest path between two nodes in a navigation system and the shortest path traveled in the city must correspond (otherwise the information system does not properly inform about the portion of reality it pretends to model).
For all objects in r in R and all op in R and op' in D

$$observe\ op(r) = op'(observe\ r) \tag{1.2}$$

The approach suggested here is related to the correspondence theory of truth introduced by Aristotle and reformulated by Tarski [1.189]. It goes, however, beyond the regular correspondence between concepts and reality, but links all concepts to observations of reality and operations to actions applied to the objects in reality (Figure 1.7). The objects 1 and 2 are observed, operation d applied to objects 1 and 2 results in object 3 – for example, the shortest path between two locations 1 and 2 requires turn 3 at location 1. Carrying out the action 'turn 3' completes the loop from the observation of the world to acting on the world and observing the results of the action:

$$\begin{aligned} & act(op'(observe(r_1), observe(r_2))) \\ = & act(op'(d_1, d_2)) \\ = & op(act(d_1), act(d_2)) \\ = & op(r_1, r_2) \end{aligned} \tag{1.3}$$

with $act = observe^{-1}$ and $act(op'(r)) = op(act\, r)$ (corresponding to equation 1.2).

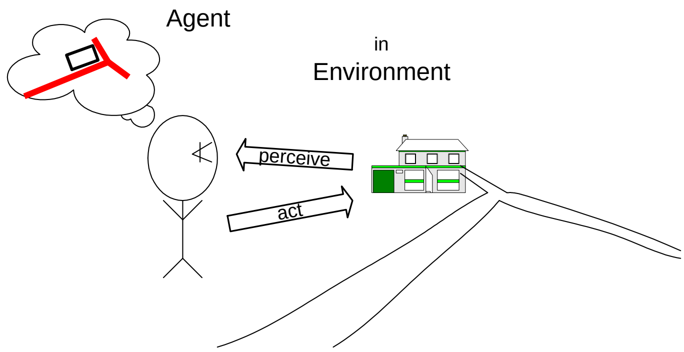

Fig. 1.7. Observation and action form a closed loop

Observations link reality to data and actions link data to reality. In this closed loop, the connection between the observation operation and the ontology applied by the observing agent can be compared to the action and the ontology it implies.

1.4.3 Semantics for Terms in Information Systems

The meaning of the symbols in an information system are linked by conventions with the objects in reality at the level of individual instances or tokens; Saussure already has pointed out that words are only meaningful in the context of a language [1.166]. Individuals in reality correspond to entities in the database. Database books as early as 1978 [1.132] described perception and codification conventions, which connect the real world in which humans live to the information system. The database schema lists the types of objects, usually describing them with common nouns. Software engineering tools equally rely on natural language and a common understanding of words [1.21, 1.45].

It is, however, well known that natural language terms have multiple meanings, and even common terms, like 'road width', may have multiple, slightly differing interpretations in different contexts [1.38]. Defining the natural language terms using other natural language terms leads to infinite recursion. Some linguists try to identify a small number of base words from which all others can be defined; it is claimed that a list of about 100 base words occurring in all natural languages is sufficient for this [1.202]. Easily accessible is the Wordnet project, which defines words by sets of synonyms and covers currently over 150'000 English words [1.72].

The specification of semantics is a deep problem, which makes it difficult or impossible to link different databases [1.101, 1.197] to produce comprehensive databases covering a large area. It has proven very difficult to construct databases covering the European Union, due to differences in the interpretation of terms. Take the simple concept of dividing a population in minors and adults; European countries use different age thresholds for adulthood and therefore to establish the number of European adults is a questionable project. However, to make statistics covering each age group, defined by numerical age, is much less error prone, as these concepts are more likely used uniformly. The customary approach for database integration is based on the comparison of some static properties of the database schemata, but the important decisions are left to the team of database designers to establish links where possible [1.55].

1.4.4 Grounding of Semantics in Physical Operations

Cognitive linguists, in particular Lakoff and Johnson, suggest that the meaning of words is related to the bodily experience of humans with the world [1.122, 1.128]. The possible base interactions of humans in the world are simple and limited, and their meaning is captured in so-called 'image schemata'. An incomplete list is given in (Table 1.2) and the close connection to the list prepared by Wierzbicka [1.202] is striking, despite the completely different approaches followed.

Container	Balance	Full-Empty	Iteration	Compulsion
Blockage	Counterforce	Process	Surface	Restraint Removal
Enablement	Attraction	Matching	Part-Whole	Mass-Count
Path	Link	Collection	Contact	Center-Periphery
Cycle	Splitting	Merging	Object	Scale
Near-Far	Superimposition			

Table 1.2. image schemata (after [1.122])

The specifications of the image schemata relate to operations humans can perform and their results. The semantics of closely related terms are described in a cluster. For example, the container image schema is described by operations of put-in, take-out, the effects of which can be observed by testing whether something is in the container or not (table 1.3). The definition of the meaning of symbols in the information system must be such that an isomorphism between information system and reality obtains [1.90]. This overcomes most of the classical problems with the definition of words, at least for the meaning of words used to describe the physical, spatial and temporal world. The complex, abstract concepts humans are capable of are combined from these base concepts by transformation (Lakoff calls them metaphorical mapping in [1.130, 1.128], Fauconnier and Turner use the term 'blend' [1.71, 1.195]). Goguen has shown how to formalize such blends [1.99].

Operations:

$$\begin{aligned} empty &:: s\,a \\ isEmpty &:: s\,a \to Bool \\ size &:: s\,a \to Int \\ put &:: a \to s\,a \to s\,a \\ isIn &:: a \to s\,a \to Bool \end{aligned}$$

Axioms:

$$\begin{aligned} isEmpty(empty) &= True \\ isEmpty(put(a,s)) &= False \\ size(empty) &= 0 \\ size(put(a,s)) &= 1 + size(s) \\ isIn(a, empty) &= False \\ isIn(a, put(b,s)) &= \text{ if } a = b \text{ then } True \text{ else } isIn(a,s) \end{aligned}$$

Table 1.3. Algebra Container $s\ a$ with Eq for a

1.5 The Five Tiers of the Ontology

1.5.1 Physical Reality Seen as an Ontology of a Four-Dimensional Field

The physical laws which describe the behavior of the macroscopic world can be expressed as differential equations, which describe the interaction of a number of properties in space – seen as forming a continuum. For each point in space and time a number of properties can be observed: color, the forces acting at that point, the material and its properties, like mass, melting temperature at that point, etc. Movement of objects can be described as changes in these properties; even the movement of solid objects can be described as the result of the cohesive forces in the body maintaining its shape. The description of reality by differential equations (e.g., the description of forces on a plate under a load p) is widely used in mechanical and civil engineering, geology, etc. Models of mechanisms or building structures are described and their reaction under various applied forces is analyzed. This view is also quite natural for most studies under the heading of 'global systems' [1.143].

A field model can be observed at every point in space and time for different properties:

$$f(x, y, z, t) = a \tag{1.4}$$

Abstracting from the temporal effects, a snapshot of the world can be described by the formula which Goodchild called ’geographic reality’ [1.100].

$$f(x, y, z) = a \tag{1.5}$$

The processes occurring in this physical reality have spatial and temporal extensions: some are purely local and happen very fast; others are very slow and affect very large regions. The processes of objects moving on the tabletop are fast (m/sec) and the spatial extent is small (m); movement of persons in cities is again fast (m/sec) and the movements of the buildings very slow (mm/annum); geological processes are very slow (mm/annum) and affect large areas (1000 km^2). One can thus associate different processes with different frequencies in space and time [1.93]. Each science is concerned with processes in a specific spectrum of space and time, which interact strongly; other processes, not included in this science, appear then to be either so slow or so fast that they can be considered constant. Space and time together form a four-dimensional space in which other properties are organized. Giving space and time a special treatment results in simpler formulations of the physical laws that are of particular interest to humans. For example, the mechanics of solid bodies, e.g., the movement of objects on a tabletop, is explainable by Newtonian mechanical laws, which relate phenomena which are easily observable for humans in a simple form ($s = vt$, etc.). Other sciences, e.g., astrophysics, prefer other coordinate systems in which mass is included.

However, the assumption that the formula $a = f(x, y, z, t)$ describes a regular function which yields only a single value, is equivalent to the assumption that there is only one single space-time world and excludes ’parallel universes’ as parts of reality.

1.5.2 Observation of Physical Reality

Agents can – with their senses or with technical instruments – observe the physical reality at the current time, the ’now’. Results of observations are measurement values on some measurement scale [1.187], which may be quantitative or qualitative. Such observations are assumed in later chapters of this book to describe, for example, the movement of airplanes. Observation with a technical measurement system comes very close to an objective, human- independent observation of reality. A subset of the phenomena in reality is objectively observed. Many technical systems allow the synchronous observations of an extent of space at the same time, for example, remote sensing of geographic space from satellite (figure 1.8). Typically a regular grid is used and the properties observed are energy reflected in some bands of wavelength (the visible spectrum plus some part of infrared).

The same kind of observation as sampling in a regular grid can be used in any other situation, the blocks world on my table as well as the city, including moving objects. They can be sampled and described as a raster. Such observations are mainly used for robots, where TV cameras which sample the field in a regular grid are used

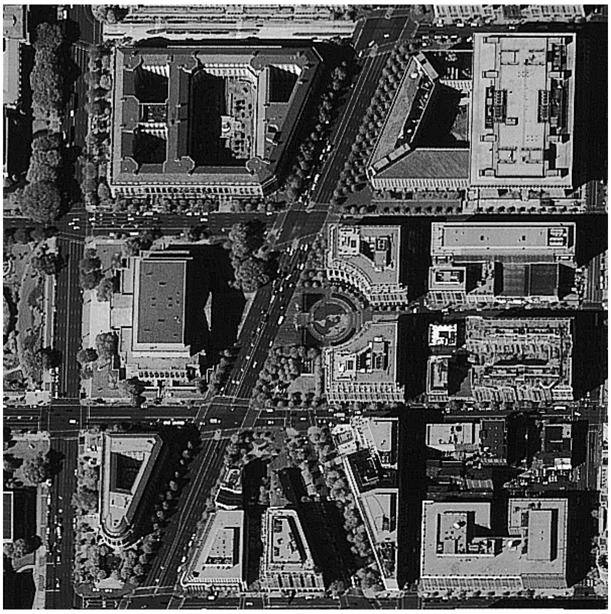

Fig. 1.8. Remote sensing image

to construct 'vision' systems to guide the robot's in manipulating objects on a table or moving through buildings [1.127].

1.5.3 Operations and Ontology of Individuals

Our cognitive system is so effective because, from the array of sensed values, it forms individuals, which are usually called objects, and reasons with them. Thinking of tables and books and people is much more effective than seeing the world as consisting of data values for sets of regularly subdivided cells (i.e., three-dimensional cells, often called voxels). It is economical to store properties of objects and not deal with individual raster cells. As John McCarthy and Patrick Hayes have pointed out:

> ...suppose a pair of Martians observe the situation in a room. One Martian analyzes it as a collection of interacting people as we do, but the second Martian groups all the heads together into one subautomaton and all the bodies into another. ...How is the first Martian to convince the second that his representation is to be preferred? ...he would argue that the interaction between the head and the body of the same person is closer than the interaction between the different heads. ... when the meeting is over, the heads will stop interacting with each other but will continue to interact with their respective bodies. [1.135, p.33]

Our experience in interacting with the world has taught us that the appropriate subdivision of continuous reality is that into specific types of individuals. Instead of reasoning with arrays of connected cells (as is done, for example, in computer simulations of strain analysis or oil spill movements), we select the shorter and more direct reasoning with individuals: The elements on the tabletop are divided into objects at the boundaries where cohesion between cells is low; a spoon consists of all the material which moves with the object when I pick it up and move it to a different location. This is obviously more effective than individual efforts to reason about the content of each cell. Animals and most plants form individuals in a natural way.

The cognitive system is very fast in identifying objects with respect to typical interactions. We see things as chairs or cups if they are presented in situations where sitting or drinking are of potential interest (under other circumstances, the same physical objects may be seen as a box or a vase). The detection of 'affordances' of objects is immediate and not conscious. The identification of affordances implies a breakup of the world into objects: the objects are what we can interact with [1.98]. Cognitive science has demonstrated that even infants at the early age of three months have a tendency to group what they observe in terms of objects and to reason in terms of objects. It has been shown that animals do the same. Most of the efforts of our cognitive system to structure the world into objects are unconscious and so it is not possible for us to scrutinize them. There are a number of well-known effects where a raster image is interpreted in one or the other way; for example, Figure 1.9 can be seen as cube or a corner, but not both at once. In Figure 1.10 the decision what is foreground and what is background is arbitrary, but we can alternatively see the two faces or the vase, not both at the same time.

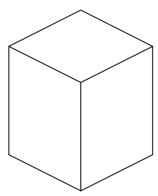

Fig. 1.9. A cube or a corner?

Efforts to explain the categorization of phenomena in terms of common nouns based on a fixed set of properties, as initiated by Aristotle, occasionally lead to contradictions. Dogs are often defined as 'barking', 'having four legs, etc.'; but from such a set of attributes it does not follow that my neighbor's dog, which lost a leg in an accident, is no longer a dog. Modern linguistics assumes generally that prototype effects make some exemplars better examples for a class than others. A robin is a better example for a bird than a penguin or an ostrich [1.163, 1.164]. Linguistic analysis suggests that the ways objects are structured are closely related to operations one can perform with them, and empirical data support this [1.72, 1.121].

Humans have a limited set of interactions with the environment – the senses to perceive it and some operations like walking, picking up, etc. – and these operations are common to all humans. Therefore the object structure, at least at the level of di-

Fig. 1.10. Two faces or a vase?

rect interaction, is common to all humans, and it provides the foundation on which to build the semantics of common terms [1.129]. In general, the way individual objects and object types are formed varies with the context, but is not arbitrarily. Different from the viewpoint of physics, humans experience space and time not just as different dimensions of a continuum. Time is experienced by all biological systems as a vector and processes are not reversible – energy is used and dissipated, and entropy increases by the laws of thermodynamics [1.47]. All observation of the world is limited to the observation at the time 'now'. 'Now' is not only a difficult philosophical problem [1.75] but also a tricky problem for temporal query languages.

Human experience of time contrasts with space, which is isotropic: it has the same properties in all directions. Humans experience the direction of gravity as most salient 'up-down' axis, which leaves the plane orthogonal to gravity as space which is experienced isotropically – what is in front of me is behind me if I turn around [1.196]. Objects can move, nearly without effort, in this plane and these movements are reversible. The geometry of the object – especially the distance between two points on the object or angles – remains the same, independent of movement.

Points in space seem natural, despite the fact that they are abstractions, which cannot be materialized. Similarly, time-points, called instants, are important to mark boundaries between intervals [1.95]. Spatial objects have boundaries, which are lines and surfaces which bound volumes. The objects of the tabletop are modeled as solid volumes, most of them with fixed form (except for liquids and similar). Their surfaces can touch, but the volumes cannot overlap. Euler has described the rules for the manipulation of polyhedrons, so-called Euler operators, for merging and splitting of solid objects and these rules were used to construct an ontology for Computer Aided Design systems [1.56]. The movement of solid objects can be represented as a translation of the center of gravity and a rotation around this point.

An agent – and its database – may abstract space in one of several ways, for example, a regular raster of observations or an object concept, or may use them in combination. The linkage between these views poses difficult theoretical problems, which are addressed in the spatial reasoning community. The question "what is special about spatial?" has been asked by several authors, but no generally satisfactory answer has been given [1.57, 1.139].

1.5.4 Social Ontology

Human beings are social animals; language allows us to communicate and to achieve high levels of social organization and division of labor. These social institutions are stable, evolve slowly and are not strongly observer dependent. Conventionally fixed names for objects, but also much more complex arrangements which are partially modeled according to biological properties, for example, the kin system, or property rights derived from physical possession, can be refined and elaborated to the complex legal system of today's society.

Names. The common names in language are clearly the result of a social process: words as names for individuals. This gives identifiers for objects, which are different from predicates to select an individual based on some unique set of properties. Nevertheless, socially agreed identifiers seem to be part of the individual, because they exist outside of the observing agent. Pointing out that 'chien', 'Hund' and 'cane' are equally good words to describe what in English is called a dog should make it clear that none of these names is more natural than any other. Examples for proper names and similar identifiers reach from names for persons and cities to license plates for cars; there are also short-lived names created, like 'my fork', during a dinner.

Institutions. Social systems construct rules for their internal organization [1.10], for example, laws, rules of conduct and manners, ethics, etc. Such rules are not only procedural ("thou shalt not kill"), but often create new conceptual objects (e.g., marriage in contradistinction to cohabitation without social status, adult person as a legal definition and not a biological criterion, etc.). Institutions are extremely important in our daily life and appear to us as real (who would deny the reality of companies, for example, Microsoft Corporation).

Much of what administration and therefore administrative databases deal with are facts of law - the classification of reality in terms of the categories of the law. The ontology of these objects is defined by the legal system and is only loosely related to the ontology of physical objects; for example, legal parcels behave in some ways similar to liquids: one can merge them but it is not possible to recreate the exact same parcels again (without the agreement of the mortgage holders) [1.137, 1.138].

1.5.5 Ontology of Cognitive Agents

Cognitive agents – persons and organizations – have incomplete and partial knowledge of reality, but they use this knowledge to deduce other facts and make decisions based on such deductions. Agents are aware of the limitations of the knowledge of other agents; social games, social interaction and business are to a very large degree based on the reciprocal limitations of knowledge. Game theory explores rules for behavior under conditions of incomplete knowledge [1.6, 1.54, 1.145]. The knowledge of a person or an organization increases over time, but the knowledge necessarily lags behind the changes in reality. Decisions are made based on this 'not quite' up-to-date knowledge. Social fairness dictates that the actions of agents are judged not with respect to perfect knowledge available later, but with respect to the incomplete knowledge the agent had or should have had if he had shown due diligence. Sometimes the law protects persons who have no knowledge of certain facts. The popular saying is 'Hindsight is 20/20' or 'afterwards, everybody is wiser'. A fundamental aspect of modern administration is the concept of an audit: administrative acts must be open to inspection to be able to assess whether they were performed according to the rules and regulations or not. Audits must be based on the knowledge available to the agent, not on the facts discovered later. For audits it must therefore be possible to reconstruct the knowledge which an agent, for example, in a public administration, had at a certain time.

1.6 The Language to Describe the Ontology

Some formal language is necessary for the description of an ontology. Database schema, for example, are described in the Data Description Language [1.3]. The description of ontologies using logic or the use of data description languages resting on the relational data model to describe the schema of a database is (barely) sufficient to capture the meaning of the terms for a snapshot, an a-temporal database. Numerous practical experiences show that describing spatial data types with these means is very difficult [1.85, 1.92, 1.167], and the problems encountered when integrating data from different sources are so far not resolved [1.55]. The description of ontologies for spatial-temporal databases is even more demanding. In this section we propose to use algebras, which are not restricted to static relations, but permit to describe objects and operations in the same context and thus better capture temporal aspects. Practical proposals for the description of conceptual models for spatio-temporal applications follow later in this book (chapter 3).
The language used to describe an ontology should have the following properties:

- formal, independent of subjective interpretation, i.e., it must be described as an algebra with (abstract) types, operations and axioms fixing the behavior up to isomorphism [1.65];
- declarative and independent of implementation;
- typed, to avoid the difficult logical tangles of untyped languages: Russell's antinomy with sets containing themselves and Goedel's undecidability problem are not existing in a typed universe;
- automated methods to check the consistency of ontologies must exist [1.86]; it is not humanly possible, to write substantive formal systems without error [1.50], quoted after [1.82, 1.154].
- executable, at least as a prototype: it is very difficult to assess if a given formal description captures the correct intuition about the world; however, human beings are very good in judging if a model is a correct description of their experience if one can execute it [1.86].

Many are tempted to invent a new language to describe ontological models [1.131], but this is not necessary. Ontologies are traditionally investigated using logic, primarily first-order predicate calculus, where the variables range over the individuals (instances or tuples in the database jargon) [1.33]. This approach is very useful to construct rules to capture the foundation classes for reusable ontologies [1.107]. The differentiation between an extensional and intensional interpretation is important, i.e., possible world semantics [1.125] must be considered. Ontologies for spatio-temporal systems can be formulated in temporal logics, or in situation calculus introduced by McCarthy, and extended to a useful formalization for actions by Reiter [1.161]. Mereology [1.171] and mereotopology [1.175] extend ontological studies to the spatial domain. The formalism of simple logic formulae is easy to understand, but when the numerous technical restrictions are added to deal with time and space, the resulting discussions are very difficult to follow. Further, the use of logic is very often leading to formalizations which are not constructive and thus not directly translatable into implementations. For example, the widely referenced RCC calculus uses non-constructive axioms [1.159] and is therefore ”not suitable for direct implementation in a reasoning system” [1.22, p.2].

An alternative with equally good mathematical pedigree is algebra. Here technically, by ’algebra’ we understand universal algebras (specifically heterogeneous or multi-sorted algebra) as introduced by Birkhoff [1.12, 1.13, 1.134]. An algebra is a triple, namely a set of carriers, a set of operations with signatures and a set of axioms which define the operations [1.134]. An algebra describes some abstract behavior of a set of objects, called the carrier, which is not further specified. Heterogeneous algebras allow multiple carriers for their objects, which correspond roughly to the notion of type in computer science [1.32]. There may exist several realizations for an algebra, often called models or implementations (for example, in chapter 4 of this book), which cannot be separated with the methods included in the algebra. One says that an algebra defines objects and their behavior up to an isomorphism; all models of the algebra are isomorphic, they show the same behavior with respect to the observations possible within the algebra. Technically, the world and the information system are then models for the abstract behavior described algebraically. The definition of structure up to isomorphism is exactly what is desirable for an ontology used for the design of information systems: the ontology should describe the behavior of reality and information system equally. The rules observed in reality and the rules used in the information system must be structurally the same (they cannot be the same rules, as the former apply to physical objects and the latter to the data objects representing these in the database). As an example, we use here the familiar natural numbers N (equations 1.6-1.11). The axioms for natural numbers are as given by Peano [1.136]:

$$1 \in N \tag{1.6}$$

$$\forall m \in N\, \exists m'(m' \in N), m' \text{ is called the successor of m.)} \tag{1.7}$$

$$\forall m \in N\, m' \neq 1 (\text{1 has no predecessor).} \tag{1.8}$$

$$m, n \in N, m' = n' \rightarrow m = n \tag{1.9}$$

$K \subseteq N \rightarrow K = N$ provided that the following conditions hold:

$1 \in K$

$$k \in K, \rightarrow k' \in K. \quad (1.10)$$

Addition:

$$m, k \in N,\ m + 1 \stackrel{df}{=} m', \exists(m + k) \rightarrow m + k' = (m + k)' \quad (1.11)$$

For natural numbers there are many different realizations – as Arabic numbers, Roman numerals, apples, sheeps in a flock or binary numbers (figure 1.11). In all cases, the rules for addition hold the same way. $VII + II = IX$ is the same as $7 + 2 = 9$.

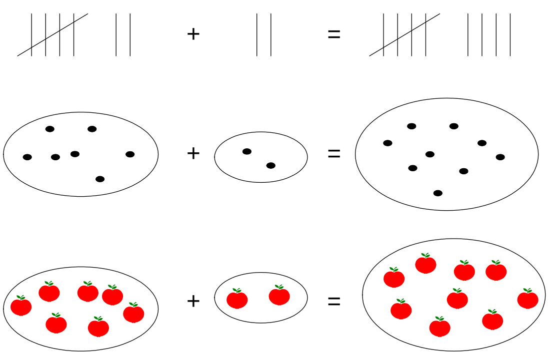

Fig. 1.11. Different realizations of the natural numbers

The essence of an algebra, completely abstracting from the representation, is captured in category theory [1.5, 1.9, 1.155]. This can be applied to query languages [1.115] or to algebraic specifications [1.66, 1.133].

1.6.1 Tools to Implement Ontologies

The algebraic approach for the definition of ontologies for spatio-temporal databases can use modern functional programming languages as tools for formalization and to build executable models. Universal algebra and the development of functional programming languages rest on the same mathematical foundations: category theory. In category theory properties of operations are discussed in complete abstraction from the application of the operation on objects [1.5].

Functional programming languages can be implemented today close to mathematical concepts and serve as tools to apply the corresponding theories to practical problems. Haskell is the result of a decade of experimentation and is the unification of different proposals. It is a standardized and widely used language [1.152, 1.154, 1.190]. It is a non-strict (lazy) purely functional language with classes. In Haskell algebras are described as classes (abstract data types) and simple models constructed for testing. In order to create executable models, care must be taken to include only constructive axioms; other axioms can be included as tests for the model and exclude non-intended interpretations. The following code gives the example of Peano's algebra in Haskell with the executed example t5 = 2 + 3 = 5.

```
class PeanoNum n where
    suc :: n -> n
    eq :: n -> n -> Bool
    plus :: n -> n -> n

data Nat = One | Suc Nat

instance PeanoNum Nat where
    suc = Suc
    eq One One = True
    eq (Suc m) (Suc n) = eq m n
    eq _ _ = False
    plus m One = Suc m
    plus m (Suc n) = Suc (plus m n)

t5 = plus (Suc (One)) (Suc ( Suc (One)))
result:         Suc (Suc (Suc (Suc One)))
```

In a functional language, everything is a function which yields a value. Haskell is a second-order language, which allows variables which are functions. Most current programming languages are first-order languages and permit variables only to range over constant values, e.g., natural numbers, floating point numbers, etc.; in a second-order language, a variable can also be a function, e.g., cos or $absoluteValue$. Research in database formalization has previously identified a need for second-order languages [1.110].

Haskell is a strongly typed language [1.31] extending the Hindley-Millner type inference systems further. In a typed language, every value has a type and operations are applicable only to values of the correct type; the type system used here assumes type inference, i.e., the type checker infers types for expressions which are not explicitly typed from the types of inputs and outputs. Haskell has classes and allows parametric polymorphic application of operations defined in classes to all elements for which the class has been instantiated. This covers what is usually called 'multiple inheritance' in a consistent and rigorous framework, in which the algebra, an abstract data type, is parameterized and the instantiations separately describe how an operation is applied to a specific representation (data type). In this framework, operations which apply to an element in a data structure are then polymorphically extended to apply to the data type; this is called 'lifting'. Second-order formalizations are extremely useful to deal with spatio-temporal data types. A data type $movingPoint$ can be seen as a function, sometimes called a 'fluent', which for every point in time (i.e., instant) yields a point in space. In a second-order language, such functions are properly typed (they have a type described as $movingPoint :: Instant \rightarrow Location$). Operations can be applied to such 'function types', for example, two movements can be added; in a polymorphic language like Haskell, the operation '+' can be lifted to extend to this new data type $movingPoint$ and thus it becomes possible to add two movements simply with the operation '+'. The result is defined as vector-addition for each instant.

As an example, we show how from time-varying values 'moving points' are constructed in Haskell. We assume floating-point numbers with the operations '+', '–', '*', square and square root, which are implemented for a data type Float[1].

```
class Number a where
   (+), (-), (*)  :: a -> a -> a
   sqr, sqrt :: a -> a
   sqr a = a * a
```

A type 'Moving a' for any type a is used to represent a family of time variable types; for this parameterized type the operations of the class $Number$ are implemented as synchronous – '+' applied to two moving values produces a moving value, which is for each time point the sum of the values at this time point. This lifting of the operations from values to time-varying values permits to operate with time-varying values as simply as we operate with constant values.

```
type Moving v = Time -> v
instance Number v => Number (Moving v) where
   (+) a b = \t ->  (a t) + (b t)
   (-) a b = \t ->  (a t) - (b t)
   (*) a b = \t ->  (a t) * (b t)
   sqrt a = \t ->  sqrt (a t)
```

Points are defined with operations to combine the two coordinate values and the projection operations x and y and the operator to calculate the distance between two points. We also lift the operations '+' and '-' to apply to points as the regular vector addition and subtraction.

```
class Number s => Points p s where
   x, y :: p s -> s
   xy :: s -> s -> p s
   --
   dist :: p s -> p s -> s
   dist a b = sqrt (sqr ((x a) - (x b)) +
              sqr ((y a) - (y b)))

data Point f  = Point f f

instance Number v => Points Point v where
```

[1] In Haskell, classes define abstract algebras and instances give the implementation for a specific datatype. Implementation can be parametrized and the parameters restricted to instances of certain classes – here used for the operations on Points. Function application is written without parameters, i.e. f (x) is written as f x. The lambda construction is written as $\backslash x \rightarrow ax$, defining a function f (x) = a (x).

```
   x (Point x1 y1) = x1
   y (Point x1 y1) = y1
   xy x1 y1 = Point x1 y1
instance Number v =>  (Point v) where
   (+) a b = xy (x a + x b) (y a + y b)
   (-) a b = xy (x a - x b) (y a - y b)
```

Moving points are created as points with moving values as coordinates and for such moving points, the code necessary to calculate distances between points is derived automatically. We can define two points $np1$,$np2$ and calculate the distance between these two moving points as a moving value; $movingDist\_1\_2$ is the distance as a function (which could be passed as an argument to a function to find its minimum or maximum value) and $dist\_at\_1$ is the value of the distance function for time 1.0 – this is all the code necessary to execute!

```
np1, np2 :: Point (Moving Float)
np1 = xy (\t -> 4.0 + 0.5 * t) (\t -> 4.0 - 0.5 * t)
np2 = xy (\t -> 0.0 + 1.0 * t) (\t -> 0.0 - 1.0 * t)
movingDist_1_2 = dist np1 np2
dist_at_1 =  movingDist_1_2 1.0
```

1.6.2 Multi-Agent Systems and Formalization of Database Ontologies

The framework in which spatio-temporal databases must be discussed, shown in Figure 1.5, is quite similar to the logical framework used for the discussion of multi-agent systems [1.73, 1.201]. Indeed, the multi-agent system provides the theoretical framework, in which ontological discussions can be grounded following the idea expressed in Figure 1.10 (and an attempt to create such a view is already present in [1.107]).

A database represents beliefs (in the terminology of [1.53]) some agent has collected about the world. Agents can, by definition, have only a partial and approximate knowledge of the world (the observations of tier 2). The knowledge stored in the database is likely incomplete, incorrect and approximate.

An agent in a multi-agent framework can be a single activity [1.140], a single living entity with some cognitive abilities (an animal or a human being) or a larger organizational unit, for example, an agency, a ministry or a company. For building ontologies, single persons and organizations (from small companies or research groups to whole nations) are considered as agents.

In a multi-agent system, a formal discussion of the correspondence between the simulated reality and the simulated database content is possible. In most discussions of ontology the non-formalized reality is contrasted with the formalized model in an informal discussion. Here, we posit a formally constructed figment of reality, which is then connected with the model. This allows us to construct formal models of an ontology in which the theoretical issues can be discussed and the necessary theories constructed. Such systems are not directly useful as information systems, but useful to design ontologies and to demonstrate how different domain ontologies can be

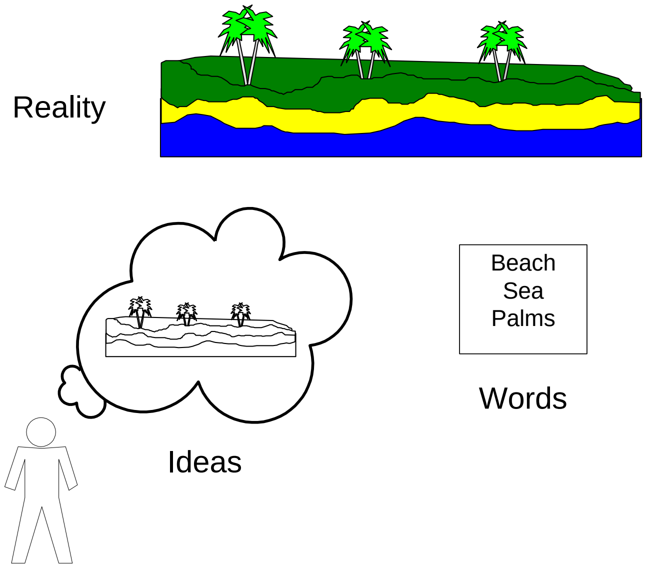

Fig. 1.12. Agents in the world

integrated. For example, the situation described in subsection 1.4.1 and Figure 1.5 has been translated to an executable model [1.83].

1.7 Ontological Tier 0: Ontology of the Physical Reality

Ontology, in a naïve view, should describe what is. In this section, the necessary minimal assumptions about physical reality are described. We assume that

- physical reality exists,
- it has determined properties at any point in space and time,
- different types of properties exist.

This gives a minimal ontology of points in space and time. Property values at each point in space and time are quantitative or qualitative values.

This section is necessarily very brief because there is little we know objectively about the physical reality. Even from millions of empirical observations no deductive knowledge about the world ever follows. It is often overlooked that all we know about the world is based on observation; a database represents the beliefs of some agents about the world, never the physical world directly. This section talks about the assumption necessary that the inductions in the following sections, which have led to the theoretical sciences, are possible.

1.7.1 Properties

Properties of the world combine a point in time and space with a value expressed on a continuous scale, represented by real numbers. Some properties can be observed and the property values are transformed by the observation process in measurement values.

There are different properties at every point of reality. The properties at a point in time and space are determined, i.e., multiple observations will always start with the same property value (but may yield different results, due to imperfections in the observation process, see subsection 1.8.1). The same properties have at different points in time and space different values. Typing rules avoids nonsensical operations (Figure 1.13).

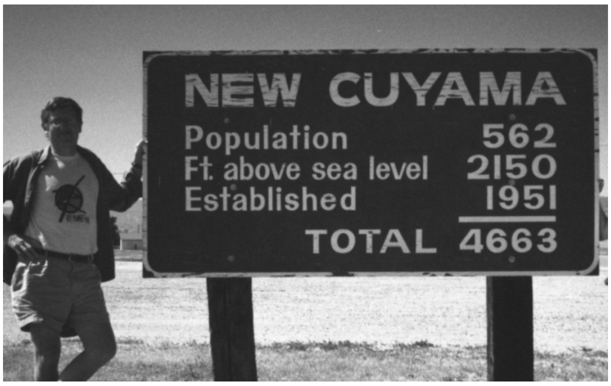

Fig. 1.13. Billboard found in New Cuyama, California

1.7.2 Physical Space-Time Field

For the abstract (non-constructive) level of ontology, points in space and time are described with coordinate values of real numbers to establish continuous time and space. This is the classical model of space and time of physics, where both real-world space and time is mapped to an n-cube with real number axes. This physical abstract field model is described with a function. An observation at a given point in space and time yields a single value. The temporal and spatial coordinates are formally equivalent. There is no special treatment of natural constants – they are understood as varying in time and space, and most of the 'natural constants' are indeed varying in time or space (see subsection 1.5.2). The world is implemented as a function.

This formal model of reality as a function (1.12) expresses the ontological assumption of a single reality as observable by a (single-valued) function reality (comparable to $f(x, y, z, t) = a$); if we had allowed multi-valued functions here, then we would permit ’parallel’ universes, as made famous by Asimov in Living Space [1.4]. With such a single-valued function the situations shown in Figure 1.2, Figure 1.3, and Figure 1.4 can be represented.

$$reality :: world \to property \to spacePoint \to \\ timePoint \to value \tag{1.12}$$

1.8 Ontological Tier 1: Our Limited Knowledge of the World through Observations of Reality

Observations of reality are necessarily limited: we can only know a (very small) subset of reality, with very limited precision. We can only observe at specific locations and at specific times, and human observers are restricted to observations of the properties for the moment ’now’. Continuous observations are actually rapid samples at discrete points. Measurements are observed with unavoidable error and are expressed with limited resolution; sometimes this is all subsumed under the notion ’discretization’ [1.100]. These limitations are modeled in tier 1.

1.8.1 Observations

Observations translate the value of a property at a specific point in time and space into a measurement value. Observations are realized as physical processes which translate the intensity of some property into an observation value, expressed on some measurement scale; observations are always made at the present time (’now’):

$$observation :: world \to observationTypes \to \\ location \to value \tag{1.13}$$

The domain of this function is composed of:

- the world observed;
- the types of observation agents (humans, with or without technical means) are capable of different methods to observe the same quantity are not necessarily equivalent;
- the location on the earth; it is finite space, but unbounded, empty space is isotropic.

The range of the function are values on some measurement scale.

Measurement values. Measurement values describe the result of the observation process. Values are formal, i.e., mathematical objects, introduced here to capture the outcome of the observation. Values are defined as algebras, and are typically described as derived algebras using some base (given) fundamental algebra. For example, integers are used to construct values of type Money. The algebras for values must connect the values to the outside world. All values have operations to translate from and to a human readable form.

For example, the natural numbers are defined by the axiom system given by Peano (see equations 1.6-1.11). From natural numbers rational and real numbers and other number systems can be defined similarly; for example, rational numbers can be defined as pairs of integers.

Stevens, in a landmark article [1.187], has shown the fundamental properties of the measurement scales. He listed four measurement scales, namely the

- Nominal scale: only the equality between values can be tested (example: names of persons);
- Ordinal scale: values are ordered (example: grades in school, rank in a race);
- Interval scale: differences between values are meaningful (example: temperature in degree Celsius, height above sea level);
- Ratio scale: ratios between values can be computed and an absolute zero exists (example: temperature in degree Kelvin, population counts, money in a bank account).

These measurement scales correspond to algebras; we often find the roughly corresponding algebras of equality ($=, \neq$), order ($<,>,\geq, \leq$), integral ($+, -$) and fractional ($+,-, *, /$). Other measurement scales exist but are not as prominent or well researched [1.39, 1.77]. The nominal and the ordinal scale are often called qualitative, especially when the number of different values is small. For example, the size of a garment can be expressed on an ordinal, qualitative scale with the values 'small', 'medium', 'large', 'extra large'.

Observation Error. All observations are imperfect realizations and imply error. This is in the limit a fundamental consequence of Heisenberg's uncertainty principle, but most practical observations are far removed in precision from the fundamental limits. Measurements better than 1 part in a million are generally difficult (i.e., distance measurements with an error of 1 mm per kilometer are very demanding, few centimeters per kilometer are standard performance of surveyors today) and the best observations are for time intervals, where 10^{15} is achieved, but the theoretical limit would be 10^{23}. Parts of the error of real observations are the result of random effects and can be modeled statistically. Surveyors report measured coordinates often with the associated standard deviation, which represents – with some reasonable assumption – an interval with approximately 60% chance to contain the true value. Error propagates through the computation. The Gaussian law of error propagation approximates the propagation of random and non-correlated error; it says that the error propagates with the first derivation of the function of interest. Given a value $a = f(b, c)$ and random errors for b and c estimated as e_b and e_c (standard deviations), then, following Gauss, the error on a is:

$$e_a = \sqrt{\frac{df}{db}e_b^2 + \frac{df}{dc}e_c^2} \tag{1.14}$$

A number system can be extended in such a way that every value is associated with an error estimation. Numeric operations on values are lifted to calculate not only the result but also the estimated error in the result using Gauss's formula [1.81].

```
data Efloat = EF Float Float
instance Num Efloat where
    (EF v’ s’) + (EF v2 s2) =
       EF (v’ + v2) (sqrt (sqr s’ + sqr s2))
```

Resolution and Finite Approximation. The results of observations are expressed as finite approximation to real numbers (often called floating point numbers). Geographers often use the term ’resolution’ to describe the smallest discernible difference between two intensities, not necessarily one unit of the last decimal. For example, distance measurements are often read out to mm, but the error (one standard deviation) is much larger: 1 cm + 1mm /km.

Constructing software for geometrical calculation using the finite approximations available in computers is difficult [1.92]. Some solutions have been developed recently [1.103, 1.117, 1.167].

1.8.2 Measurement Units

Measurements describe the quantity or intensity of some properties at a given point in comparison with the intensity at some other, standard, point or standard situation. Well known is the former meter standard, defined as the distance between two marks on a physical object manufactured from precious metal and kept in Paris (it is superseded today by a new definition, which links to a physical process that can be reproduced at any location). The temperature of melting ice is used as the reference point for the °Cscale [1.67].

length:	meter	m
mass:	kilogram	kg
time:	second	s
electric current:	ampere	A
thermodynamic temperature:	kelvin	K
amount of substance:	mole	mol
luminous intensity:	candela	cd

Table 1.4. SI units

Observation systems are calibrated by comparing their results with the standard. They are expressed as a quantity times a unit, 3 m, 517 days or 21°C. The Systeme International d’Unites (SI) is founded on seven SI base units for seven base quantities assumed to be mutually independent (Table 1.8.2). Before, people used the cgs-system (centimeter-kilogram-second). For example, the unit of gravity in the cgs-system was Gal, named after Galilei (1 Gal = 1 $\frac{cm}{s^2}$), but newer books refer to the SI standard ($\frac{m}{s^2}$).

For the same kind of observation different units are used, most important the metric units and the Anglo-Saxon units (which come in imperial and U.S. variants). The fundamental physical dimensions (length, mass, etc.) are easily converted, but practically errors occur often. Most spectacular was the recent loss of a probe to land on Mars due to a lack of conversion between metric and Anglo-Saxon measurement units of length. Practically, conversions are a problem, not for the different measurement units, but for the differences in the observation methods, which result in somewhat different properties observed, even when expressed on the same physical scale (for example, noise level measured in dB). Conversion can be achieved, as the two observation methods can be applied at the same location and time, and the results can be compared. From sufficiently well comparable observations a conversion formula can be deduced.

1.8.3 Classification of Values

In daily life and in most applications, the results of observations are expressed on qualitative scales, i.e., scales with only a few values. People are classified in small, medium, tall and very tall; days are hot or cold; etc. These classifications capture sufficient information for the task at hand [1.94]. For example, to meet a person at an airport, a description using adjectives like 'gray, tall, bespectacled, 50ish male' is usually sufficient to identify the person.

Classification translates observations from a larger set of values to a smaller set of values (discretization can be seen as a special case of classification). The age of a person is mapped to the set child, adult with the rule

```
classify :: valueType_1 -> valueType_2
classify age = if age > 20 then adult else child
```

Roads for maps are classified from the width (measured in m with two decimals) to road classes first order, second order, and third order:

```
classify roadwidth = if width > 5.50 then firstOrder else
   if width > 4.0 then secondOrder
   else thirdOrder
```

These two examples clearly demonstrate the difficulties involved in classification and the use of classified data. Seldom do the classifications for two different tasks correspond: How to compute the number of adults in Europe? There exists no uniform concept of adulthood, as age limits vary. A road map which shows a road changing in classification at the border (Figure 1.14) allows two interpretations: either the road changes its width at the border or the classification scheme for roads is different in the two countries.

1.8.4 Special Observations: Points in Space and Time

Descartes discovered that calculation with coordinate values can simulate geometric constructions. Surveyors and engineers make extensive use of analytical geometry. The algebra of vector space, constructed from the field of real numbers with operations for scalar multiplication, vector addition and multiplication, is extremely

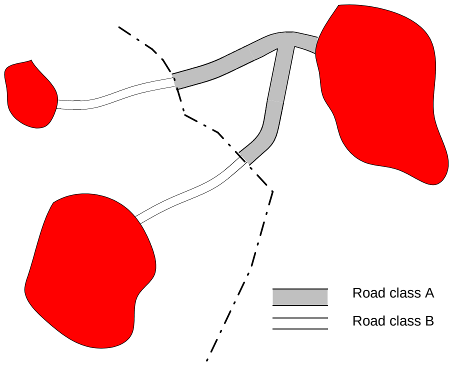

Fig. 1.14. Apparent changes of road classification across border

convenient. Orthogonality of vectors, etc., can be tested and areas of figures calculated with simple arithmetic operations.

These computations with length measurements and the positions of points are expressed as distances from a conveniently selected point of origin. No physical process can measure absolute time or points in space; only relative measurements are possible. Distance measures (in space or time) are always relative to other points and no direct coordinate measurements are possible. Relative measures are tacitly converted into coordinates assuming a conventional origin. These computations make statistical descriptions of errors in the coordinate values difficult.

Buyong describes a method to represent locations by relative measurements and uses coordinates only for computation [1.27, 1.28]. A database would contain as original determination of location the relative measurements and new measurements can be added freely. Coordinates are calculated from measurements using adjustment calculation [1.126], either when needed and immediately discarded, or stored and recalculated after each addition of new measurements. In the traditional coordinate-based system, location information deteriorates over time with the integration of new point locations and occasionally a complete new survey of all locations must be made (typically every 30 to 50 years). In a measurement-based system, the quality of the determination of location improves with the addition of new measurements.

Continuous time: instants and time measurement values. We measure time with respect to a time scale with a conventionally selected origin. The customary Gregorian calendar has the origin related to the birth of Jesus Christ (and other religions select origins related to the history of their religion). The conventional time measurement scale has some interesting particularities; for example, there is no year 0, after year 1 BC follows 1 AD; the way the duration is commercially calculated between two dates depends if you borrow or lend, etc. [1.78].

Continuous space: points and coordinates. Every country has selected a prominent point as an origin for the national grid of coordinate values. Two global systems are used: the well known system of geographic longitude and latitude, where distances are measured by angles and the origin is the intersection of the meridian of the astronomical observatory in Greenwich (exactly the optical center of the old passage instrument) with the equator (figure 1.15); whereas the modern system uses three orthogonal axis, situated in the center of the earth mass.

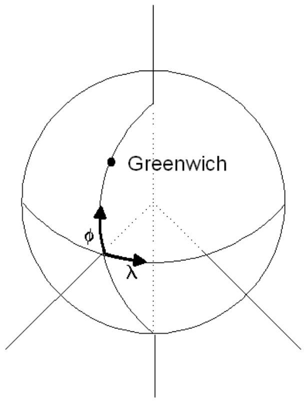

Fig. 1.15. Geographic coordinate systems

For each coordinate system, origin point and direction of the axes must be fixed. In practice, the origin of the coordinate system is of no relevance as the coordinate system is realized by the totality of all points for which coordinate values are determined, and which can be used to measure distances and directions to new points.

Most surveying systems separate the position in the plane from the height and introduce a separate zero point for the height measurement. The conventional origin at sea level has no precise definition and leads to confusing differences between the heights of points expressed in different national systems; well known is the apparent height difference of several meters between Germany and Belgium. Height can be measured as the potential from an assumed zero potential surface or can be measured as a distance from this same surface (figure 1.16); precise height measurement systems are not a completely resolved topic in geodesy.

1.8.5 Approximate Location

Points (in time and space) are mathematically without extension. Real observations identify small extents which are all mapped to the same value. The dissertation of Bittner [1.15] showed how operations with such approximations are possible (the recent paper by Smith and Brogaard exploits some similar ideas [1.179]).

Bittner and Stell describe the location of spatial objects within sets of regions of space (cells) that form regional partitions (figure 1.17 and 1.18). The location of spatial objects is characterized by sets of relationships to partition cells. The figure

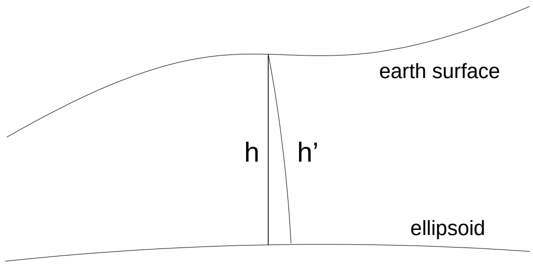

Fig. 1.16. Differences in height measurements

(1.17) shows the approximation of a non-regular shaped region, r, with respect to a raster-shaped regional partition. The raster-shaped partition simplifies the example; in general arbitrary partitions of 2-D space are possible. Bittner and Stell distinguish three relations between the region, r, and a partition cell, $g \in G$: (1) Full-overlap, i.e., r contains or is equal to g (Cell K in Figure 1.17). (2) Partial-overlap, i.e., r and g share parts, but do not fully overlap. (All partition cells except K,A,I, and M). (3) Non-overlap, i.e., r and g do not even overlap partially. (Cells A, I, and M). There are coarser and finer distinctions possible (see [1.17] for details). Formally, the approximate location of the region r within the partition G as a mapping of signature $(\alpha_r) : G \rightarrow \Omega$. The mapping (α_r) returns for every partition element $g \in G$ the relation between r and g, i.e., fo for full-overlap, po for partial-overlap, or no for non-overlap.

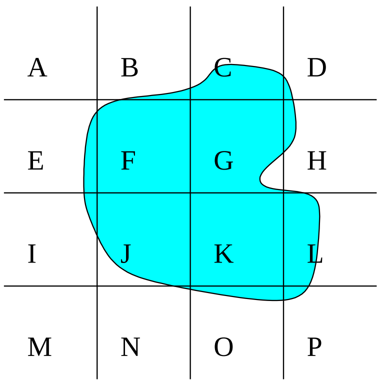

Fig. 1.17. A region approximated by a regular partition

Approximations represent sets of regions, i.e., all those regions that are represented by the same approximation mapping. Bittner and Stell [1.17] defined union and intersection operations on approximation mappings, such that their outcome constrains the possible outcome of union and intersections operations between the approximated regions. Moreover, they derived sets of possible relations between spatial regions, given their approximations [1.18]. Bittner [1.16] showed how approximate spatial reasoning can be applied to the temporal domain.

Consider, for example, the approximations of a water reservoir and a pollution area with respect to an underlying soil-classification-partition. Assume both approximations are based on independent observations in different moments of time. Bittner and Stell [1.17] derive which relations can hold between the water reservoir and the area of pollution from the knowledge about their approximate location. This can be used, for example, to determine if it is possible that both objects overlap or it is certain that they do (or do not) overlap.

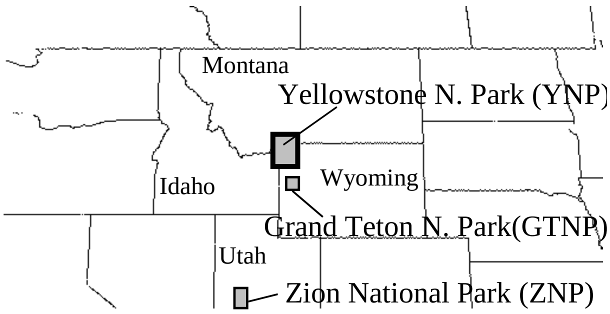

Fig. 1.18. The position of National Parks with respect to some western states of the USA

1.8.6 Discretization and Sampling

An observation yields different values, depending where and when we observe reality. Some processes change rapidly (in time or in space), others vary very slowly: Observing the height of a mountaintop is (nearly) independent of the time as the value changes only very slowly. Observing the position of a car is highly dependent on the length of time we observe the car. Measuring gravity gives very similar results, independent of time or location.

The limitation of the representation enforces some careful optimization when building models of parts of reality – the model is necessarily limited and an approximation. Information systems concentrate on some processes in reality, e.g., the movement of cars on highways, development of cities or the weather. Each of these processes (or complex of processes) has a certain 'scale'. Space and time can be treated equally: some properties change quickly if we move in space (e.g., elevation) and others change very slowly (e.g. geology). One can speak of a temporal and spatial frequency of events [1.93]. For example, geological processes typically have a resolution of 10 to 100 meter in space and thousand to millions of years in time. Movement of cars on highways has a spatial resolution of several m in space and seconds to minutes in time.

If we observe a process, then our observations must have a minimum density to avoid misleading 'aliasing'. A process can be described with a frequency of change (in space and time). The sampling theorem states that observations must be made with at least twice the frequency of the highest frequency in the process of interest. To avoid erroneous observations, so-called aliasing, frequencies higher than half the sampling frequency must be filtered out before the signal is sampled (Figure 1.19).

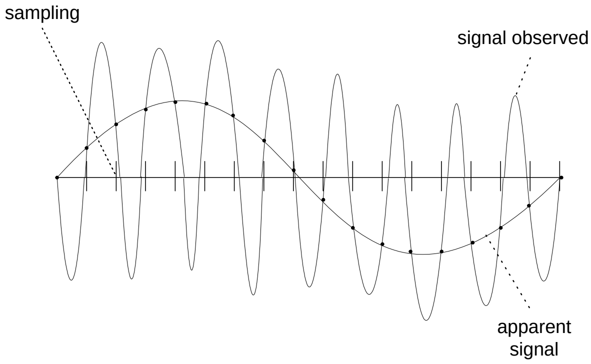

Fig. 1.19. A low frequency signal emerges from a high frequency signal not correctly sampled

The practically very important method of data collection by remote sensing (Figure 1.8) takes the average value over the area of the pixel and thus applies at the same time a filter which eliminates too high (spatial) frequencies. If point sampling is employed, then the high frequencies present in the signal can lead to significant errors in area estimates; this is particularly dangerous in areas with regular structures, e.g., the road network in the U.S. Midwest.

1.8.7 Virtual Datasets: Validity of Values

It is convenient to organize large numbers of observations in such a way that a comprehensive model of reality emerges. It is possible to link datasets available on different computers internally and to provide an interface which gives the same functionality as the real observation of the world (equation 1.12):

$$ObsValue :: dataStore \rightarrow location \rightarrow \\ time \rightarrow observationType \rightarrow value \quad (1.15)$$

Vckovski has labeled such datasets as 'virtual' and discussed their properties [1.198]. Unlike the observation function of reality in subsection 1.8.1, the observations of virtual datasets are partial - not for every combination of input values a result is available; often the value is unknown. Values resulting from simulated observations from a dataset and not direct observation of the world must be qualified:

- Bounded knowledge in time and space: the data collected always covers only some limited time span and some area. For positions and times outside this area, the result is unknown.
- Values for points other than those observed must be interpolated. The selection of appropriate interpolation methods is a difficult problem [1.49].
- Values were measured with limited precision. The user must be made aware of the error resulting from measurement and the error resulting from interpolation. The effects of classification or different observation methods must be tracked and values converted as far as possible.

Observation operations to the information system are partial: requests for values for points in time or space, before the first or after the last value available (or outside of the spatial limit), must not return a regular value. Computation with total functions is simpler. Wrapping the result value in a data type $Maybe$ allows us to transform the partial to a total function and lift operations to this data type ($Maybe$ is a monad [1.200], but this is not important here).

```
data Maybe a = Just a | Nothing
obsValue :: dataStore -> location -> time ->
     observationType -> Maybe value
class Number a => Number (Maybe a) where
    (Just a) + (Just b) = Just (a + b)
    _ + _ = Nothing
```

For virtual data sets, time series, coverages [1.39] or raster images, the regular operations can be applied ('lifted'). It is possible to add two time series, to apply mathematical formulae to values of corresponding cells, etc. Tomlin has shown how this 'map algebra' can be extended with operations useful for planning [1.194, 1.193].

1.9 Ontological Tier 2: Representation – World of Individual Objects

Humans have the ability to see objects – and they use very different criteria in the way they carve reality into objects: objects are formed according to the current needs, i.e., the task a human agent tries to complete at a given instance. An ordinary tree stomp can be seen as a table, a seat or platform to stand on. The human interactions with the environment, especially with solid bodies as included in the table-top environment, are ubiquitous and probably prototypical for our understanding of objects. But there is also the large class of geographic objects, which are typically unmovable and not physical themselves, but made up from other physical objects (a road or a forest is an area of space, not a physical object). Humans 'see' objects with respect to their interaction with them. Gibson called these potentials for interaction 'affordance' [1.98].

Physical objects are extremely real for the human cognition. But instead of following the philosophical tradition, which assumes a preexisting understanding of objects, a very pragmatic approach is followed: objects are defined by uniform properties. The properties which must be uniform for an object are related to the possible ways of interaction with an object. Depending on the property, which is uniform, very different types of objects are formed and these objects then follow different ontological rules (which we call lifestyles, see subsection 1.9.5). The properties, which are fixed to determine uniformity, can be used to define a topological, morphological or functional unity [1.107].

Objects preserve invariants in time and are therefore a method of human cognition to reduce the complexity of the world, by grouping areas of uniform properties with respect to potential interactions. The most salient example are solid bodies, which preserve form, volume, material, weight, color, etc. There are transformations from point observations to observations of objects, typically integrating specific properties (e.g., specific weight) over the volume of the object. Representations for objects are best selected to respect the invariants; the geometric form of an object is best expressed in a coordinate system fixed with the object and a vector which indicates the location of the object and an angle of rotation; from this coordinates in an exterior system can be deduced.

The approach selected here – namely to define objects simply as areas of uniform observable properties – avoids the difficulties philosophers have found in the foundation classes of ontologies, where the most fundamental classes of entity, object, etc., are defined. Guarino and his colleagues have compared several ontologies and have found conflicts and hidden assumptions, which made comparison between the ontologies and transfer of knowledge integrated in one ontology to another ontology difficult [1.108].

The object concept used here is restricted to ’physical objects’ (which contains as a subset the ’material objects’ but is much larger), i.e. things which exist in the physical world and can be observed by observation methods. This is not the most general concept of an object, as it is often used in philosophy or software engineering; specifically, constructions like abstract ideas, social constructions, etc., are not included and will be discussed in the next sections.

1.9.1 Objects are Defined by Uniform Properties

Objects are defined as spatio-temporal regions of some uniform property. The uniformity can be in the material type, in what moves jointly, etc. Table-top objects are typically delimited by what forms a solid body, but other properties are often used, for example, color, texture, etc., is typically used to identify objects on photographs, including remote sensing images. More complex properties, like ’same DNA’ for a living animal body, are also possible.

Examples for objects on the tabletop are the cup, knife, piece of bread, etc. In the cityscape, objects are buildings, persons or cars. In the landscape, forests, lakes, mountains and roads are all objects with boundaries of varying degrees of sharpness [1.26]. In order for things to have uniform properties, the properties must be classified and small variations in reality, or by the errors in the observation process, eliminated. The classifications can be applied to values which are the result of some computations, combining multiple values; for example, to detect areas which are connected, one can observe direction and speed of movement (the same result can be achieved with a static analysis of the resistance to stress and strain, which indicates where a collection of material bodies will separate). Ultimately, the classification results in a binary result – a point in space or time is part of or is not part of an object.

1.9.2 Geometry of Objects

The geometry of objects results from a classification of some property values. Delimiting areas of uniform value have some desirable geometric properties: They form a partition, i.e., they are jointly exhaustive and pairwise disjoint (see figure 1.20).

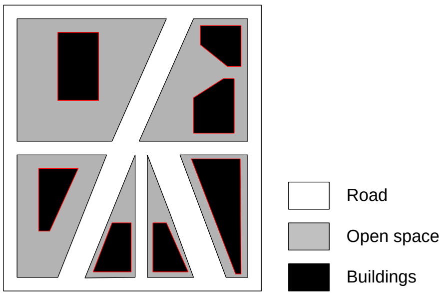

Fig. 1.20. Classification of a part of the remote sensing image from Figure 1.8

Spatial objects have a geometry. Spatial objects have boundaries. In many cases, specific observation systems are organized to find the boundary positions directly in the terrain and not from the point-wise observation of the environment. Surveyors go out and measure the boundary of the forest by detailed observation in the field and then measure the location of the boundary.

If the classification is applied to a collection of raster values, then the discretization effects of the observation step shows. The smallest object which is certainly detectable must have an area of at least four times the cell size (follows from the sampling theorem, see subsection 1.8.6.

Geometric objects relate to other objects. For spatial objects, the location of the centroid and the boundary of the objects can be deduced:

```
getObjBoundary :: env -> spatobj -> boundary
centroid :: env -> spatobj -> point
```

Both the boundary returned and the centroid point are objects and have properties. For example, the position of a point can be asked, the length of the boundary or the area delimited can be found, and a complementary set of geometric operations for point, line and area are provided in most Geographic Information Systems. The Open GIS Consortium works towards standardization in conjunction with the ISO standard for extension of the query language SQL.

```
position :: point -> env -> coordinate
area:: boundary -> env -> areaValue
length :: boundary -> env -> lengthValue
```

Boundaries can be approximated by a sequence of straight lines and the corners of a boundary are a set of points:

```
corners:: boundary -> env -> [points]
```

The object-object relations are necessary to document that the boundary of parcel A is as well the boundary for the parcel B (Figure 1.21). An inverse function to $getObjBoundary$ retrieves for a boundary line the two areas which are bounded by this line:

```
getBoundedArea :: boundary -> env -> [object]
```

The object-object relations are also necessary to model containment of objects with different granularity. One object may be part of a larger object and the larger object may contain a number of smaller objects.

```
contains :: obj -> env -> [objs]
contained:: obj -> env -> obj
```

Containment relations may form hierarchies, for example, for the political subdivision of a continent in countries, regions, provinces, communes, etc. (for example, the European NUTS subdivision forms a hierarchy of partitions, where each higher level forms a refinement of the previous one). Timpf has investigated how such containment hierarchies are formed, how they relate to other hierarchies (for example, functional), and how they are used for cartographic generalization [1.191].

Objects resulting from classification form topological complexes. The boundaries of a set of objects coming from a single classification form a complex [1.97]; each boundary bounds an areal object on each side. All the objects form a partition, i.e., they jointly exhaust the space and are mutually disjoint (often described as JEPD, jointly exhaustive, pairwise disjoint). In the extreme of a binary rule forming a single object, the object formed and the background together are JEPD.

Given a classification to determine what is a ’uniform’ object one can ask for a list of all objects within an area.

For geometric objects in a complex, operations can can the boundariy of the object or the co-boundary. For a cell or simplicial complex (figure 1.21), these operations form algebras with well-defined properties. The boundary of an area are the lines, the boundary of a line are the two bounding points. The co-boundary is the converse operation; the co-boundary of the line are the two areas bounded by this line, and the co-boundary of a point are the set of lines starting or ending in this point.

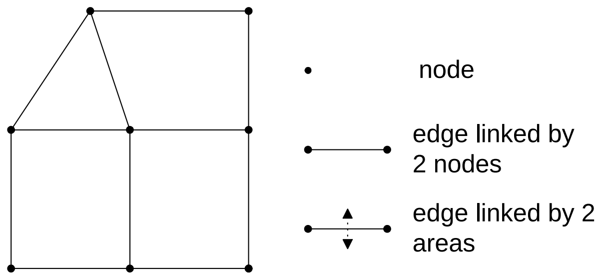

Fig. 1.21. Simplicial complex of nodes, edges and areas with boundary and co-boundary relations

A spatial database for which objects have these or comparable operations is often called a topological GIS or a topological data structure. These properties were identified very early in the history of GIS and used for checking for errors in data freshly input [1.44].

The topological relations between objects are usually described by the set of topological relations, which were proposed by Egenhofer in his dissertation [1.62]. They are a generalization of Allen's relations for temporal intervals for two (and higher) dimensional regions. They are similar (but differently defined) to the relations the RCC calculus proposes [1.43].

1.9.3 Properties of Objects

Some properties of the objects are related to the problem of identifying regions of uniform properties. Other properties of objects can be related to the properties of the observable (and sometimes non observable) physical properties of the field ontology [1.59]. For example, the weight of an object is the integral over the weight of its material. The effort necessary to move along a path is related to the accumulated height differences along the path.

Operations to integrate observations for a geometry can be defined as an extension of point observations: integrate along a path, integrate over an area for some property (if the property is time-variant, the movement in time must be provided). From such integrations, properties of objects follow: the length or the area of a geometry by integrating over the constant function 1, but it can also be used to determine the height difference along a path, the annual rainfall over an area, etc.

1.9.4 Geographic Objects are not Solid Bodies

The classical concept of object is a generalization from the physical objects on the tabletop; such material objects are exclusive: where one object is, no other object can be. This is correct only for solid body objects and not the case for other physically observable objects: in most applications, more than one classification is possible [1.179]. In the city environment the classification can be based on a pedestrian viewpoint or a legal-ownership viewpoint: a pedestrian is interested in the areas which are uniformly ’not obstructed’, whereas a bank is interested in seeing what areas have an uniform ownership.

This gives more than one object at a single location. Similar differences in the classification of land for planning purposes can be observed: Classifications based on natural habitat, car traffic, pedestrian traffic, residential constructions, all are examples of objects of different types which overlap and coexist (figure 1.22).

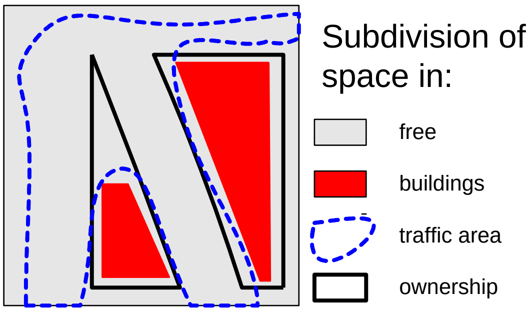

Fig. 1.22. Subdivision of space in building objects and ownership objects which overlap

This is a fundamental problem for any object ontology: the division of the world into objects is not unique and depends on the observer and his intentions. A special case is given if a classification is finer than another [1.91] (Figure 1.23). There, the objects form a lattice [1.136].

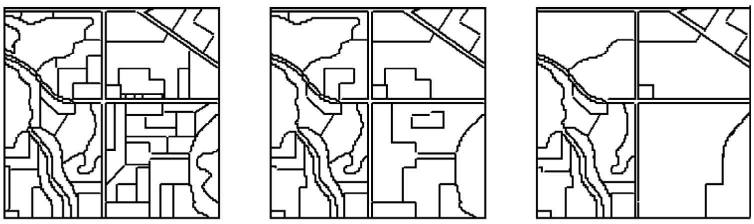

Fig. 1.23. Three different classifications for urban land use (with 4, 7 and 24 classes)

1.9.5 Objects Endure in Time

Objects, especially physical objects, endure in time. Physical objects have individual properties, which differentiate them from other objects which look similar, even if these differences are often not relevant and not noticed by human observers.

Objects in reality maintain their identity from begin to end – even a grain of salt has an identity, which is lost when it is dissolved in the soup. Objects are ”worms in four-dimensional space”. Worboys and Pigot explored the mathematics of such constructions [1.156, 1.203], referring back to classical geographic conceptions of space-time diagrams [1.112].

The concept of physically observable objects is a generalization of material objects, from which we know from experience that they endure in time: the piece of bread on my table now (Figure 1.2) will remain a piece of bread even five seconds later. Many of its properties remain the same; they are invariant with respect to short intervals of time.

The stable identity of objects is modeled in a database with a (stable) identifier, which replaces the combination of numerous properties which make each individual physical object different from all others. Identifiers are nominal values; they support only the operation $equality$ (for performance reasons, it is useful to make internal use of lexigraphical order in the identifiers, but this must not be construed as meaningful).

Objects can be seen as functions from an identifier, an observation type and time to a value (formula 1.16). Objects are formed such that many important properties remain invariant, primarily with respect to advancing time but also with respect to other operations.

$$observation :: id \to time \to obs \to value \tag{1.16}$$

Object Lifestyles. The changes of objects can be continuous or catastrophic: an object can move or it can be destroyed and ceases to exist. Catastrophic changes are affecting the ’existence’ of the object and these changes follow different rules: The solids on the desktop can be glued together such that two objects become one and later this connection can be broken again and the two original objects reemerge. If we pour the water from one glass into the wine in the other glass, the two liquid objects water body and wine body cease to exist and a new ’water-wine-body’ emerges. This operation cannot be undone; the two original liquids cannot be restituted. Considering the life of an object in time, we observe that different objects have different ’life styles’. Solids can be glued together and reemerge, but the liquids mixed cannot be separated again.

Definition of lifestyles. In the real world objects are perceived as having their life – a span of time bounding the existence of objects as separable identifiable entities. In a spatio-temporal database objects are modeled in the same manner, i.e., a span of time bounding the *existence of object identifiers in the database* between the two fundamental events: creation and destruction. The way objects emerge and later change the modus of their existence differs for different categories of objects. For example, a liquid object while flowing into a container and overflowing it, gives rise to two new liquid objects: the first one remains in the container, and the second one spills on the ground [1.113]. This behavior is completely different from the blocks world: solid objects on a table can be piled one upon the other, but their identities are preserved.

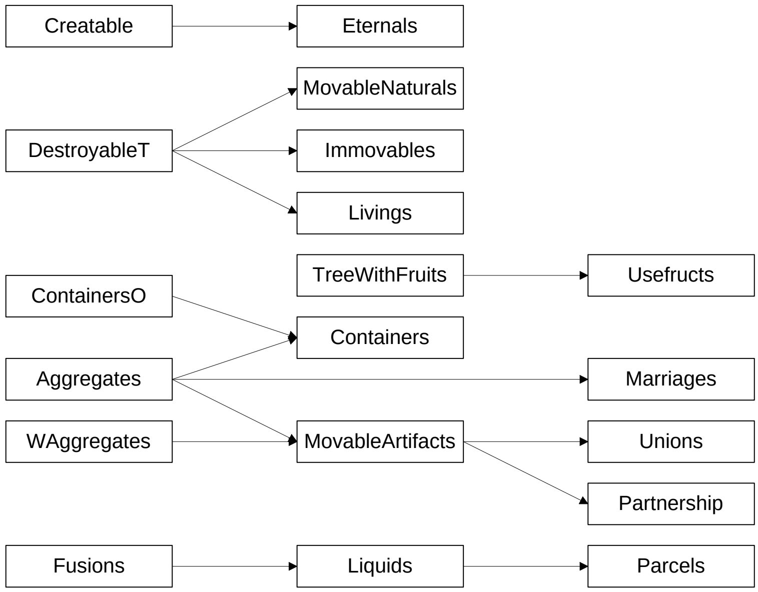

Fig. 1.24. The subsumption-graph of lifestyles

Lifestyles are sets of special, identity changing operations applicable to object identifiers of different kinds of objects (figure 1.24). These special operations form a finite set. Combined together they describe a large number of object categories. Beside the inevitable creation of an object identifier, possible destruction, the concept of temporary loss of identity for an object, has been introduced with operations suspend and resume with the same meaning as kill and reincarnate in [1.40]. An object may change its identifier keeping track of its predecessor through evolution, modeled as a composition of a creation and a deletion. Complex lifestyles are composed from simpler ones. Thus, of aggregation the parts are suspended, whereas the melting of objects is described as fusion (parts are destroyed). The fundamental difference is that the inverse of the former process (segregation) is reversible while the inverse of the latter (fission) is not: the contents of a glass of water and a glass of wine poured into a carafe cannot be restituted. Examples of lifestyles described in [1.137] range from physical reality like simple movable objects (stones, blocks), immovables (man-made buildings and bona fide objects like valleys and mountains), living beings, containers, liquids, to abstract concepts like ownership rights, marriages, and partnerships.

The concept of lifestyles allows the designer of a spatio-temporal database to use the same classes of operations for apparently different kinds of objects. In modeling abstract objects, one can benefit from already achieved models of the simpler physical realm. For example, legal cadastral parcels follow the ’lifestyle’ of liquids: two parcels which are merged are not re-emerging after a split [1.87].

Lifestyles describe the change in object identifiers: an object exists in the database or does not exist (or it is suspended). A possible extension is the change in object types: a liquid object can evaporate changing its appearance. Melting of solid objects into a liquid state is an important transition as well. The change of identity in objects produces many side effects: topological relations, for example, are of the greatest importance in spatial domain. Thus, the investigation relates lifestyles and the change in topology of emerging objects [1.118].

Moving and changing objects. Objects have permanence in time and can move their position or change shape. The observation of movement or change of shape for table-top objects which are under our permanent scrutiny is easy. Solid objects move but maintain their shape, other objects on the table may change form as the result of actions.

The recognition of moving and changing objects in geographic space is more difficult. What can be stated about the sand dunes of (Figure 1.25), where we have observations which are half a year apart? One might conclude that the sand dune X in spring 1999 is the effect of merging the two dunes A and B from fall 1998, but this is not necessarily the correct interpretation. The question is generalized to the problem: Given two observations of snapshot spatial objects i_1 at t_1 and i_2 at t_2; construct a time varying object o, such that o at t_1 is i_1 and o at t_2 is i_2.

$$o(t_1) = i_1 \wedge o(t_2) = i_2 \tag{1.17}$$

In this case, we are justified to label the two observed non-temporal objects with the same identifier and consider them as projections of the single object. The detailed rules depend on the particulars of the application.

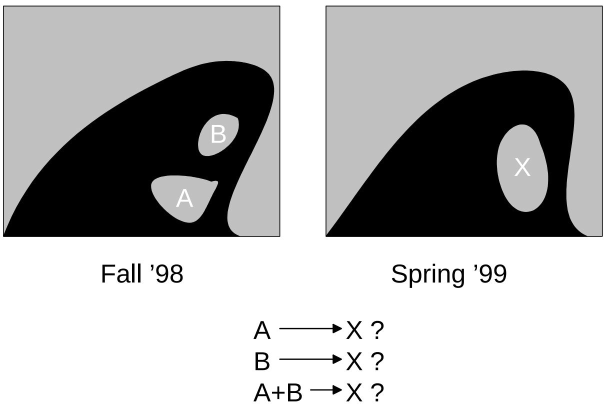

Fig. 1.25. Wandering sand dunes

Time-varying geometry. If we allow for time-varying values as the result of determination of object property, then the geometric operations can all be applied to moving objects. For moving objects, they return a time-varying value for the location of the centroid, for the length of the boundary, etc. The operation applicable to fixed values can be lifted to apply to time-varying values (care must be taken for functions like minimum or maximum) (see chapter 4 in this volume). For example, the distance between two moving objects is a changing floating-point value (see subsection 1.6.1).

1.9.6 Temporal, but A-Spatial Objects

The same principles of identification of area with uniform properties which were using a fixed time point can be inversed to identify temporal regions with uniform properties for a fixed location. To form objects as regions from a snapshot (fixed time) is more common, but sequences in time with uniform properties can be considered as 'temporal objects' as well [1.172]. Examples would be my summer vacation period, an employees sickness leave or the presidency of Bill Clinton. Such temporal objects have a start and an end and one can ask for their duration, they are time intervals:

```
ObjStart :: id -> time
ObjEnd :: id -> time
```

Allen defined topological relations between time intervals [1.2].

1.10 Ontological Tier 3: Socially Constructed Reality

In the last section objects were constructed with respect to the human interaction with the world. This physical reality includes a large number of the things we interact regularly with, from fruits and other small objects to land, lakes and weather.

Unfortunately, most of what an administrative spatio-temporal database contains are not the physical properties of the world, but the legal and administrative classification of the world, classified and named within the context of social, especially institutional, rules. In the city, building lots, street names, and building zones are administrative facts; in the landscape, county boundaries, right of way and areas of nature parks are administratively constructed facts. These areas created by administrative rules are further simplifications of the complexity of reality to the restricted view of the law. These administrative constructs are valid only within a legal context.

1.10.1 Social Reality is Real within a Context

A concentration on the ontology of physical things leaves out a very large part of the reality humans perceive. Naming things and using the names to communicate with others is one of the most important cultural achievements. Society consists of a complex web of relationships between people and things, which need to be defined and named. Elements of social reality thus named appear as real as physical reality to us. There is a strange belief – manifest in witchcraft – that an object has a direct and natural link to its name; pointing out that ’Hund’, nor ’chien’ or ’cane’ describes the same species as the English ’dog’, reveals the contextual nature of the naming conventions. Social constructs, from marriage to ownership, all appear as real to us as physical forces or electricity, but are meaningful only in the social context.

Social reality includes all the objects and relations which are created by social interactions. Human beings are social animals and social interaction is extremely important. The reason to separate physical reality, object reality and socially constructed reality is the potential for differences in observations: within errors of observations, the results of observations of the same point in time and space should be the same. The construction of objects can be based on the uniformity of various properties, and thus objects may be formed differently – for example, the definition of forest can be based on various criteria and thus leads to different extensions of a ’forest’ (indeed one should speak of different kinds of forest: legal forest, land-use forest, forest as physical presence of trees, etc.); differences for object formation can be traced back to different methods in classification if enough care is applied to the domain-specific interests and procedures.

For socially constructed reality, agreement between different agents from different contexts in the construction is not to be expected. Objects are named with different names in different languages and only naïve persons assume that there are exact translations between terms. Not even countries using the ’same’ language, apply the same terms with corresponding meaning; well known is the motto ”England and the United States are separated by a common language” based on various examples of differences in vocabulary; the same applies to Germany, Switzerland and Austria. Each country, specifically each cultural system, creates its own ’conceptualization’ of the cultural organization. The results are quite different conceptual systems, and one must not expect that the same concept in different cultures will have the same meaning. There is a European attempt to extend the WordNet dictionary with five European languages to make it multi-lingual.

The names and the concepts are only meaningful within the defining social context. They are not binding outside of this context. What is quite easy to accept with regard to different languages is more difficult to understand with respect to smaller cultural communities: public agencies, administrations, etc.; each creates its own vocabulary and logical organization of the part of reality and cultural institution it is concerned with. It is surprising to see how different the terminology and the concepts of law in Austria, Switzerland and Germany are; neither do the terms correspond, nor do they have the (exact) same meaning. What Austrians call ’Kataster’, a map and a list of the parcels, is the ’Liegenschaftskarte’ in Germany. Even smaller communities create their own terminology: the laws for urban planning are in the competence of the Bundesland (federal state) in Austria; therefore there are nine laws, each creating its own set of terms which have meaning within this set of rules.

Terms in one Bundesland but do not correspond to the same or to other terms used in another Bundesland. Nobody assumes that the different branches in the administration of a town relate the same concept to the word 'building'; the prototypical case, a single family dwelling, may be included everywhere, but the treatment of special cases – very small utility constructions, underground constructions, etc. – will vary. Using the concept of radial category [1.164], one can say that agencies create radial categories, which partially overlap. This makes the construction of databases, or the integration of databases from different origin, very difficult. The smallest common denominators must be found by human specialists; attempts of automatic database schema integration at best provide helpful tools [1.55].

1.10.2 Names

Objects have names – especially persons – and these names are perceived as 'real' properties of the things. The proponents of remote sensing images of the environment always need to be reminded that remote sensing cannot see the names of towns [1.124], nor the boundaries of countries. Sometimes physical phenomena indicate where boundaries are, sometimes not; towns can be seen, but not their names, because all these elements are not part of the physical reality (which we analyzed in the previous two sections).

It is culturally assumed that names of things are stable. It is improper to change one's name (except for women when they marry in most of western Europe) or use multiple names (only criminals and artists do this). Everybody has to have a name (including 'the artist formerly known as Prince'). Culture assumes for many important things (but not all) that there exists functions

```
getname :: obj -> name
findObj :: name -> env -> obj
```

Names are clearly a social construct in the sense of Searle [1.170]. Names can come in many forms: as strings of characters, as numbers (e.g., the names of the days of a month) or as arbitrary strings (social security numbers, license plates of cars, serial numbers, etc.). Names are always on a nominal scale – only comparison for equality is a relevant operation – and often a lexicographic ordering is exploited for searching (e.g., in telephone directories). Some names, especially surnames, are structured in such a way that they hint to relationships between people: Peter Smith maybe the father of Paul Smith (or his brother, or completely unrelated).

Many uses of names rely on a small context, in which the name is likely unique. The best example is the use of Christian names to identify people, there are thousands of 'Rudi' living in Vienna, but within the context of my department, 'Rudi' is unique (not so for 'Martin'). Usually the context of a situation is sufficient to disambiguate a statement and identify the person. One should not be tempted to think that the usual combination of Christian name and family name is the person: there are three persons with the same name 'Martin Staudinger' listed in the Vienna phone directory!

1.10.3 Institutional Reality

Much of what seems very real is, at a second glance, far from real. Neither status, honor or marriage, nor ownership are physically real. A large number of the constructions of social reality are related to institutions, especially the legal system. We concentrate here on legal concepts, as they are the most important for the construction of spatio-temporal databases, for example, about land ownership and the planning of the use of space.

Administration and law has a need to simplify the infinitely complex world to general rules which can be applied generally and uniformly. The complex judgment if a child is mature enough to act as an adult person is replaced by a summary rule which links the age of the person to its classification as a minor, not capable of making legally binding decisions, or an adult. Such rules are important for an efficient functioning of our modern world, where we deal with a large number of strangers and regulate our interactions based on few, typically quickly observable, properties: instructions given by a person in a police uniform are followed when we drive a car, but the same signs made by a non-uniformed person will go mostly unobserved.

Searle observed that some speech acts are not descriptive of reality like 'the forest is green' which can be true or not depending on the color of the forest, but are constitutive – they create the described fact. The most famous example is certainly "I declare you husband and wife", which, if spoken by a duly authorized person and after the proper interrogations, creates the fact 'marriage' [1.169]. Often institutions associate specific treatments – fixed in rules and laws – with such constitutive acts. Incorporation of a company, marriage or submitting a letter of resignation constitute legal facts; these legal facts have well-defined consequences which are evident, when the constitutive act is made. The institutions typically keep registries of these constitutive facts, a registry of deeds is an example, or provide a document as evidence of the fact, for example, a driver's license or a marriage certificate. Confusing are 'birth certificates', where the certificate does not constitute the fact that somebody was born – this is an ontological problem of tier 3 – but constitutes the legal acceptance that birth was given at a specific location and time, which has consequences like conferring nationality – for example, a birth certificate from an U.S. registry is sufficient for entry into the USA.

Searle in his theory of institutional facts starts with the observation that paper money is nothing else than printed paper, but that this special kind of printed paper has a particular function within the context of a society. He sees that 'special printed paper' serves as 'money' in the context of a national economy. In the theory provided by Searle to explain institutional facts, the formula 'x serves as y in the context of z' is very important, but not likely to cover all aspects of social reality [1.182]. This 'x counts as y' assigns to the physical object x (from ontological tier 3) a specific function y. The meaning of the function y and the rule that x counts as y are both part of the context, for example, the legal institution. The function y, for example, 'ownership', is then defined in the context of the legal system: ownership links a person to a piece of land, the owner of a piece of land can sell this land or can use it to secure a debt, etc. The meaning of ownership is fully defined within the legal system of a country. The German Grundgesetz says ”ownership is guaranteed within the limits of the law...”, clearly pointing out the social and legal context in which the term must be understood. On the other hand, some Reform Country has defined new institutions, avoiding the term ’ownership’ for land; in the opinion of experts, if a piece of land can be owned, sold, inherited and mortgaged, there is no substantial difference to ’ownership’ (in the meaning of the context of European or American law), independent of the word that this country uses [1.119].

Important for the application of spatio-temporal databases to land registration is the separation between the physical properties of things in the world, for example, boundary markers, buildings, streets and rivers, and the legal facts. Competent surveyors can measure the positions of boundary markers. There should not be cause for debate about the result. Similarly, the reconstruction of a boundary using the documented measurements in the registry is a (mostly) physical process and not dependent on a legal context.

Smith has separated fiat and bona fide boundaries [1.174]. Bona fide boundaries exist in reality: they may be natural boundaries, like those enjoyed by an island, watersheds, or clearly monumented artifact; the physical reality constitutes the boundary, the registry only points out that these physical elements are the boundary and may contain measurements or other observation values, which can be used to reconstruct the boundary. For fiat boundaries, the registry gives the exact location in terms of observation, and competent surveyors are required to indicate the location of the boundary in the real world. In this case, the registry constitutes the boundary and its location. Practically, this difference is important when the location of a boundary in the registry and the boundary in reality do not correspond – which one is the ruling one? In most countries, for bona fide boundaries, reality wins; for fiat boundaries, the registry wins.

Confusion in databases of institutional facts may arise from an incomplete separation what are recordings of constitutional facts, which cannot be wrong by definition, and which are facts based on observation of physical reality, which can, obviously, be incorrect descriptions of reality. One can demonstrate that a value does not describe a real property correctly – by inspection of the appropriate place; one cannot demonstrate that a constitutive registration is wrong. However, one can prove that the process that leads to its constitution was not following the prescribed rules and therefore the registration should be void.

1.11 Ontological Tier 4: Modeling Cognitive Agents

Agents acquire and construct knowledge about the world – the physical and the social world – in which they exist. The knowledge they construct is not necessarily and automatically corresponding to reality. Cognitive agents use the accumulated knowledge to derive new knowledge from the accumulated knowledge and make decisions using derived knowledge about actions.

The cognitive system of human beings is very similar to the aggregated cognitive behavior of organizations: They collectively acquire knowledge, which is subject to similar effects which result in only partial correspondence between reality and the knowledge accumulated. The treatment here, which deals mostly with the effects and does not concentrate on the processes and the influences on processes which lead to non-conformance of accumulated knowledge, need therefore not differentiate between single cognitive agents – mostly humans, but to some degree also animals – and organizations seen as cognitive agents.

1.11.1 Logical Deduction

Cognitive agents are capable of logical deduction. From the knowledge accumulated other facts are deduced and used to guide the actions of the agent. Logical deduction can be very simple; for example, a database lookup to check if a person is a client of a bank or to find out how many years a student is already enrolled in the university, which is a simple calculation starting with the year of his first enrollment. More complex deductions are checks if a student can graduate, which must consider a number of requirements.

The rules used for deduction are built into application programs and database query languages. The latter usually follow the axioms pointed out by Reiter [1.160]:

- the domain closure assumption
- the unique name assumption
- the closed world assumption

These axioms are closed to assumptions built into legal rules and regulations and administrative customs – they are not universally applicable. For example, for spatial databases, the closed world assumption is usually not valid: from the absence of knowledge that a tree or a building exist on a parcel one must not conclude that there are no trees or buildings on the parcel; it is possible that a tree has grown since the last observation or that a building has been erected without informing the authorities (figure 1.26). The details about an owner of a parcel do not demonstrate that this person is still alive. Spatial information systems require more complex reasoning than ordinary administrative processing [1.58].

1.11.2 Two Time Perspectives

A cognitive agent must separate two time perspectives: There is the time in which the world evolves: trees sprout, buildings are constructed, and people die at certain points in time. Second, there is the time at which these facts are entered into the database: Trees are observed and entered into the database, buildings are surveyed and shown on maps, death records are filed; these acts of ’knowledge acquisition’ occur at a certain point in time – measured along the same time line, but different instants: for each event, two instants are relevant: when it occurred and when knowledge was acquired.

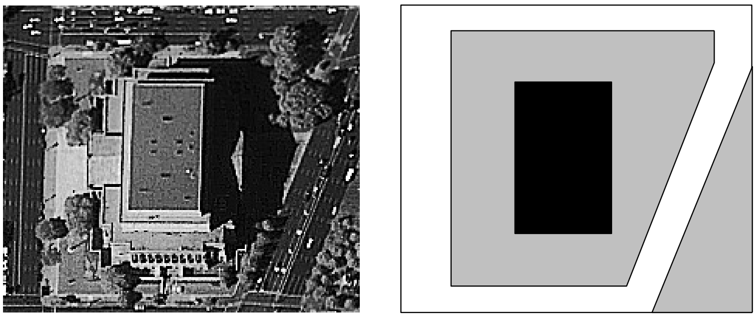

Fig. 1.26. The map does not show all!

From an agent's perspective, the database (or his own collection of knowledge) is a time-varying value – changing in discrete steps at each transaction. Therefore, the semantics of a temporal database can be understood as a function from time to a snapshot database, 'as of time t' queries can be expressed as a-temporal queries to the snapshot database valid at t.

$$database \rightarrow time \rightarrow snapshot\, database \tag{1.18}$$

There are a number of difficulties arising from the combination of a time-varying collection of facts with a deduction system:

The result of a deduction from a snapshot database is – sound deduction rules assumed – a single result. The result becomes time varying for a time-varying database: depending what data are collected, a deduction yields a different result: the request to withdraw $500 from my account is denied today (balance only $150), but after I received a $1000 reimbursement from a company, the same request to withdraw $500 is granted.

If the results of deductions are stored, then a fact acquired later can make the result invalid and the stored result of the deduction must be identified and corrected (monotonicity of the logic; usually not given). This is usually described as 'belief maintenance problem', when agents deduce beliefs from their knowledge and knowledge added later requires a revision of these beliefs. From simple observation in an environment one may deduce that green fruits are unripe and not edible, and red fruits are ripe and sweet; this empirical rule must be revised after tasting of ripe, green figs or grapes, and a more sophisticated rule for ripeness must replace the simple one [1.102].

Social fairness often leads to rules where not the date of a fact, but when an agent learned about it, is important. The social system does not punish honest 'not-knowing' if the agent has made all reasonable efforts to discover the facts. For example, the knowledge of the law is assumed, but only after it has been officially published. A case can be brought before a court within a certain deadline and the deadline is counted not from the offending act, but from the time the plaintiff has learned (or could have learned if diligent) of the act.

In other instances, legal rules depend on having knowledge or not; in European cadastral law, the 'bona fide' buyer is protected, even if he buys from a non-owner. In all such cases, it is crucial how much an agent knew, when a fact became true and when an agent learned about it. The registry of deeds or the cadastre is one of the legal domains where most detailed rules were developed over the centuries [1.78]. Entering a legal fact in a registry often creates the assumption that all parties concerned do know about the fact, because they can access the information if interested.

1.11.3 Sources of Knowledge

Agents acquire much knowledge through communication with other agents and not from direct observations. This knowledge is 'hearsay' in legal terminology [1.19] and considered of much lower reliability than what is directly and immediately observed by an agent. Human beings are extremely well equipped to keep information from different sources separated and maintain a mental link from the information to the source. Reuter has pointed out that databases are not prepared to keep track of collections of facts which form areas of consistency, but are not overall consistent [1.204].

1.12 Summary: Ontological Commitments necessary for a Spatio-Temporal Database

Using a spatio-temporal database implies the acceptance of the ontological commitments built into it. The previous sections discussed these commitments in detail. The conclusions are summarized here:

1.12.1 Existence of a Single Reality

We assume – as generally is the case in the positivist philosophy of science and engineering – that there is a single reality in which we live, and which we gain knowledge of. This assumption results form empirical evidence that I and everybody else live and interact with the same objects, following the same physical laws. Effects of the actions of another person can be seen and others can see the effects of my actions.

1.12.2 Values for Properties can be Observed

Our knowledge of the world is through the observation of values of observable properties. Models may link observable values to assumed properties, which are not directly observable. Observations are linked to the point in time and space when they were made.

1.12.3 Assume Space and Time

The notion of space and time were the object of extensive philosophical debate. Human life is in space and time and our bodily functions lead to space and time as two fundamental categories of our experience. Time is unidirectional and observed processes are, in general, not reversible in time. Space is characterized – here we can follow the famous definition of geometry by Hilbert – by invariant properties for groups of transformations [1.20].

1.12.4 Observations are Necessarily Limited

Observations are necessarily with limited precision in the observed value as well as in the point in time and space they are related to. This is a physical fundamental limit (Heisenberg's uncertainty principle), but in all practical cases, the uncertainties are much larger than the physical limits and due to imprecise practical observation processes. Most of the data collected are just precise enough for the purpose, and therefore, in absolute terms, quite imprecise.

1.12.5 Processes Determine Objects

Humans do not usually consider the world as consisting of data values for individual point observations. For economy of cognitive processes, sets of similar observations are grouped to form objects. These objects have properties which remain invariant under common operations. The invariance of form of objects through translation and rotation (which form a group) is fundamental for our understanding of solid bodies, i.e., for most of the objects of our daily life. Objects seem to be 'real', but one must always remember that they depend on the classification used for their formation and therefore alternative ways of 'carving' the world in objects are possible. Some classifications are extremely closely related to fundamental operations of the human body and are therefore likely 'universals' (i.e., the same for all human cultures); others are not. Objects endure in time and have an identity which links observations of an earlier time with observations at a later time. Even when we are not watching, our car parked in the road keeps its color (it actually fades slowly) and the height of the Himalayan mountains remains the same (it actually raises slowly). Object identity is usually represented with identifiers in the data collection.

1.12.6 Names of Objects

To keep track of the identity of objects, various methods for naming are used by the social system. People have names and cars have manufacturer numbers and license plates to make them unique and to make it easy to find the same object again without constant supervision. Unnamed objects, like the fork you are eating with, remain only 'your fork' as long as you constantly keep track of its location to differentiate it from other forks.

1.12.7 Social, Especially Institutionally Constructed Reality

The social system constructs relations between objects, which are very important for human living and seem very real, but are not part of physical reality: marriage (as opposed to parenthood) or ownership (as opposed to physical possession) are social concepts and only related to physical reality. Much data used for modern administration concern such socially – especially institutionally – constructed reality [1.170].

1.12.8 Knowledge of an Agent is Changing in Time

The knowledge an agent, a single human being, or an organization maintains, cannot be a true and perfect model of reality. Agents use their knowledge to make decisions about actions. The representation of reality is not only of limited precision (see above), but also varies in time. Facts in the world are later represented in the knowledge base. With each fact the time of occurrence and time of entry into the knowledge collection is associated. This is often called 'valid time' and 'database time' [1.185]. A specific decision was correct yesterday, but with the additional knowledge gained since, is wrong today. Social fairness dictates that decisions of agents are judged with respect to what they could have known, not the perfect knowledge available later.

1.13 Conclusion and Future Work

For spatio-temporal databases a careful review of the ontological bases on which programs rest is necessary. The assumptions built in must be documented carefully.

Integration of data from different sources is one of the dominant problems of today's practical use of spatial and spatio-temporal databases. Investigation into the ontological bases of such data collections is a research direction from which essential contributions to solve the real and immediate problems are expected. This is demonstrated by the commercial interest in ontologies. The division of ontology into tiers in this chapter identifies different levels of commitment and agreement between different data collections. Observation of physical reality is more likely to be similar for similar data sources; the constructions of social reality are necessarily context dependent, and will differ for collections originating in different sources. The tiers selected reflect these differences in expected agreement, respectively disagreement, between data sources. The description of the tiers point to methods to overcome the differences and to integrate different data sources within the limits of their ontological common base. The multi-tier ontology extends the difference between ontology and epistemology philosophers have argued for centuries.

Progress in the Chorochronos project in this respect evolved around the move from a first-order logic based investigation to a second-order architecture [1.110]. In this framework, time-varying 'moving' values and points can be manipulated, and are properly typed. It appears that many of the ontological problems discussed currently [1.107] are related to the concept of type and the type systems of programming languages are not exactly the type systems necessary for databases. A type system for a programming language is generally defined as a set of type classes. Object instances have a specific type, which means that the operations defined in the type class are applicable to the object instance [1.32]. Type systems for programming language are developed with the goal to allow certain checks on the program code such that a large class of errors can be detected statically (i.e., during compilation) and static errors cannot occur during the execution of a program. Types in the sense of programming languages are static. Object instances cannot change their type during execution (unless they go through a specific 'type conversion' operation) [1.31]. This concept of type is suitable for the short duration of a program run, but is not suitable for a temporal database, where long-term representation is the objective. It clashes with an ontological type concept: with graduation a student becomes an alumni and sometimes an employee – but his identity as a human being continues. A number of extensions of a type system with 'mix-ins' etc., have been proposed to deal with such cases [1.7]. But none covers all the cases. A review of the five-tier ontology with a powerful type system, for example, based on Hindley-Millner type inference and classes [1.123], is likely to yield valuable insights into the connection between type system and ontology.

Linguists use the concept of 'ontological categories' to describe types (in the sense of applicable operations) which cannot be changed: a solid body cannot become an event; a parcel (a piece of land) cannot become a material or a point. A boundary point, however, can cease to be a boundary point, but continues as a point: it can never become an event.

The ontology presented here is designed with the construction of a computational model in mind, following the suggestions in section 1.4. The contribution possible from a strongly typed language and polymorphism based on a class structure will be explored then.

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Bibliography

1.1 K. Al-Taha. *Temporal Reasoning in Cadastral Systems*. Ph.D., University of Maine, 1992.
1.2 J. Allen. Maintaining knowledge about temporal intervals. *Communications of the ACM*, 26(11):832–843, 1983.
1.3 ANSI/X3/SPARC. Study group on database management systems, interim report 75-02-08. *SIGMOD*, 7(2), 1975.
1.4 I. Asimov. *Earth is Room Enough.* Doubleday, New York, 1957.
1.5 A. Asperti and G. Longo. *Categories, Types and Structures - An Introduction to Category Theory for the Working Computer Scientist.* Foundations of Computing. The MIT Press, Cambridge, Mass., 1 edition, 1991.
1.6 D. G. Baird, R. H. Gertner, and R. C. Pickr. *Game Theory and the Law*. Harvard University Press, Cambridge, Mass., 1994.
1.7 F. Bancilhon, C. Delobel, and P. Kanellakis. *Building an Object-Oriented Database System - The Story of O2*. Morgan Kaufmann, San Mateo, CA, 1992.
1.8 A. Barr and E. A. Feigenbaum. *The Handbook of Artificial Intelligence*. W. Kaufman; HeirisTech Press, Los Altos, CA; Stanford, CA, 1981.
1.9 M. Barr and C. Wells. *Category Theory for Computing Science.* Prentice Hall, 1990.
1.10 P. L. Berger and T. Luckmann. *The Social Construction of Reality*. Doubleday, New York, Anchor Books edition, 1996.
1.11 D. Bernasconi. *Rahmenkonzept zur Gestaltung eines Datenmanagementsystems Siedlungsentwässerung.* Doctoral thesis, ETH Zurich, 1999.
1.12 G. Birkhoff. Universal algebra. In *First Canadian Math. Congress*, pages 310–326. Toronto University Press, 1945.
1.13 G. Birkhoff and J. D. Lipson. Heterogeneous algebras. *Journal of Combinatorial Theory*, 8:115–133, 1970.
1.14 S. Bittner. *Die Modellierung eines Grundbuchsystems im Situationskalkül*. Diploma thesis, Universität Leipzig, 1998.
1.15 T. Bittner. *Rough Location*. PhD, Technical University, 1999.
1.16 T. Bittner. Approximate temporal reasoning. In *AAAI Workshop on Spatial and Temporal Granularity, Time2000*, 2000.
1.17 T. Bittner and J. Stell. A boundary-sensitive approach to qualitative location. *Annals of Mathematics and Artificial Intelligence*, 24:93–114, 1998.
1.18 T. Bittner and J. Stell. Rough sets in approximate spatial reasoning. In *Proceedings of RSCTC 2000*, Lecture Notes in Computer Science. Springer-Verlag, Berlin, 2000.
1.19 H. C. Black. *Black's Law Dictionary*. West Publishing, pocket edition, 1996.
1.20 L. Blumenthal and K. Menger. *Studies in Geometry*. W.H. Freeman, 1970.
1.21 G. Booch, J. Rumbaugh, and I. Jacobson. *Unified Modeling Language Semantics and Notation Guide 1.0.* Rational Software Corporation, San Jose, CA, 1997.
1.22 S. Borgo, N. Guarino, and C. Masolo. A pointless theory of space based on strong connection and congruence. In L. Carlucci and J. Doyle, editors, *Principles of Knowledge Representation and Reasoning (KR96)*. Morgan Kaufmann, 1996.
1.23 S. Borgo, N. Guarino, and C. Masolo. Stratified ontologies: the case of physical objects. In *ECAI'96, Workshop on Ontological Engineering*, Budapest (August 1996), 1996.
1.24 K. Buehler and L. McKee, editors. *OpenGIS Guide: An Introduction to Interoperable Geoprocessing, Part 1 of the Open Geodata Interoperability Specification (OGIS)*. The Open GIS Consortium, Inc. (OGC), 35 Main Street, Suite 5, Wayland, MA 01778. Available from http://ogis.org/., 1996.
1.25 P. A. Burrough and A. U. Frank. Concepts and paradigms in spatial information: Are current geographic information systems truly generic? *International Journal of Geographical Information Systems*, 9(2):101–116, 1995.

1.26 P. A. Burrough and A. U. Frank, editors. *Geographic Objects with Indeterminate Boundaries*, volume 2 of *GISDATA Series*. Taylor & Francis, London, 1996.
1.27 T. Buyong and W. Kuhn. Local adjustment for measurement-based cadastral systems. *Journal of Surveying Engineering and Land Information Systems*, 52(1):25–33, 1992.
1.28 T. Buyong, W. Kuhn, and A. U. Frank. A conceptual model of measurement-based multipurpose cadastral systems. *Journal of the Urban and Regional Information Systems Association (URISA)*, 3(2):35–49, 1991.
1.29 I. Campari. Uncertain boundaries in urban space. In P. A. Burrough and A. U. Frank, editors, *Geographic Objects with Indeterminate Boundaries*, volume 2 of *GISDATA*, pages 57–69. Taylor & Francis, London, 1996.
1.30 I. Campari and A. U. Frank. Cultural aspects and cultural differences in geographic information systems. In T. L. Nyerges, D. M. Mark, R. Laurini, and M. Egenhofer, editors, *Cognitive Aspects of Human-Computer Interaction for Geographic Information Systems - Proceedings of the NATO Advanced Research Workshop, Palma de Mallorca*, volume 83 of *NATO ASI Series D*, pages 249–266. Kluwer Academic Publishers, Dordrecht, 1995.
1.31 L. Cardelli. Type systems. In A. B. Tucker, editor, *The Computer Science and Engineering Handook*, pages 2208–2236. CRC Press, 1997.
1.32 L. Cardelli and P. Wegner. On understanding types, data abstraction, and polymorphism. *ACM Computing Surveys*, 17(4):471 – 522, 1985.
1.33 R. Casati, B. Smith, and A. C. Varzi. Ontological tools for geographic representation. In N. Guarino, editor, *Formal Ontology in Information Systems*, pages 77–85. IOS Press, Amsterdam, 1998.
1.34 R. Casati and A. C. Varzi. *Holes and Other Superficialities.* MIT Press, Cambridge, Mass., 1994.
1.35 R. Casati and A. C. Varzi. *Parts and Places*. The MIT Press, Cambridge, Mass., 1999.
1.36 CEN. Geographic information - data description: Metadata. Draft standard, CEN/TC 287/WG2, 1995.
1.37 S. Ceri, P. Fraternali, and S. Paraboschi. XML: Current development and future challenges for the database community. In C. Zaniolo, P. C. Lockemann, M. H. Scholl, and T. Grust, editors, *Advances in Database Technology - EDBT 2000 (7th Int. Conference on Extending Database Technology, Kontanz, Germany)*, volume 1777 of *Lecture Notes in Computer Science*, pages 3–17. Springer-Verlag, Berlin Heidelberg, 2000.
1.38 J. Chevallier. Land information systems - a global and system theoretic approach,. In *FIG International Federation of Surveyors*, volume 3, page paper 301.2, Montreux, Switzerland, 1981.
1.39 N. Chrisman. *Exploring Geographic Information Systems*. John Wiley, New York, 1997.
1.40 J. Clifford and A. Croker. Objects in time. *Database Engineering*, 7(4):189–196, 1988.
1.41 CODASYL. Report of the data base task group. Technical report, April 1971 1971.
1.42 A. Cohn, Z. Cui, and D. Randell. Exploiting temporal continuity in qualitative spatial calculi. specialist meeting, NCGIA, May, 8-11 1993.
1.43 A. Cohn and N. Gotts. The 'egg-yolk' representation of regions with indeterminate boundaries. In P. Burrough and A. U. Frank, editors, *Geographic Objects with Indeterminate Boundaries*, volume GISDATA II. Taylor & Francis, London, 1996.
1.44 J. Corbett. Topological principles in cartography. Technical Paper 48, Bureau of the Census, US Department of Commerce, 1979.
1.45 R. S. Corp. UML notation guide, 9/1/97 1997.
1.46 H. Couclelis. People manipulate objects (but cultivate fields): Beyond the raster-vector debate in GIS. In A. U. Frank, I. Campari, and U. Formentini, editors, *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, volume 639 of *Lecture Notes in Computer Science*, pages 65–77. Springer-Verlag, Berlin, 1992.
1.47 H. Couclelis and N. Gale. Space and spaces. *Geografiske Annaler*, 68B:1–12, 1986.

1.48 R. Cover. The XML cover pages, url: http://www.oasis-open.org/cover/xmlandsemantics.html, 1998.

1.49 N. A. Cressie. *Statistics for Spatial Data*. Wiley Series in Probability and Mathematical Statistics. John Wiley, New York, 1991.

1.50 H. B. Curry and R. Feys. *Combinatory Logic*. North Holland, Amsterdam, 1956.

1.51 CYC. The CYC corporation web page, url: http://www.cyc.com/tech.html, 2000.

1.52 P. F. Dale and J. D. McLaughlin. *Land Information Management - an introduction with special reference to cadastral problems in third World countries*. Oxford University Press, Oxford, 1988.

1.53 E. Davis. *Representation of Commonsense Knowledge*. Morgan Kaufmann Publishers, Inc., San Mateo, CA, 1990.

1.54 M. D. Davis. *Game Theory*. Dover Publications, Minneola, NY, revised edition, 1983.

1.55 T. Devogele, C. Parent, and S. Spaccapietra. On spatial database integration. *IJGIS*, 12(4 - Special Issue):335–352, 1998.

1.56 C. Eastman. *Database Facilities for Engineering Design*, volume 69. 1981.

1.57 M. Egenhofer. What's special about spatial - database requirements for vehicle navigation in geographic space. *SIGMOD Record*, 22(2):398–402, 1993.

1.58 M. Egenhofer and K. Al-Taha. Reasoning about gradual changes of topological relationships. In A. U. Frank, I. Campari, and U. Formentini, editors, *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, volume 639 of *Lecture Notes in Computer Science*, pages 196–219. Springer-Verlag, Heidelberg-Berlin, 1992.

1.59 M. Egenhofer and A. U. Frank. Connection between local and regional: additional "intelligence" needed. In *FIG XVIII International Congress of Surveyors*, Toronto, Canada (June 1-11, 1986), 1986.

1.60 M. Egenhofer, A. U. Frank, and J. Jackson. A topological data model for spatial databases. In A. Buchmann, editor, *SSD'89 - Design and implementation of large spatial databases*, Lecture Notes in Computer Science 409, pages 271–186. Springer, 1989.

1.61 M. J. Egenhofer. A formal definition of binary topological relationships. In W. Litwin and H.-J. Schek, editors, *Third International Conference on Foundations of Data Organization and Algorithms (FODO)*, volume 367, pages 457–472, Paris, France, June 1989, 1989. Springer-Verlag, Berlin Heidelberg, Germany (FRG).

1.62 M. J. Egenhofer. *Spatial Query Languages*. Ph.D., University of Maine, 1989.

1.63 M. J. Egenhofer and R. D. Franzosa. Point-set topological spatial relations. *International Journal of Geographical Information Systems*, 5(2):161–174, 1991.

1.64 M. J. Egenhofer and D. M. Mark. Naive geography. In A. U. Frank and W. Kuhn, editors, *Spatial Information Theory - A Theoretical Basis for GIS*, volume 988 of *Lecture Notes in Computer Science*, pages 1–15. Springer-Verlag, Berlin, 1995.

1.65 H.-D. Ehrich. Key extensions of abstract data types, final algebras, and database semantics. In D. e. Pitt, editor, *Category Theory and Computer Programming; Tutorial and Workshop Proceedings*, volume 240 of *Lecture Notes in Computer Science*. Springer, 1985.

1.66 H.-D. Ehrich, M. Gogolla, and U. Lipeck. *Algebraische Spezifikation abstrakter Datentypen*. Leitfäden und Monographien der Informatik. B.G. Teubner, Stuttgart, 1989.

1.67 C. Eschenbach. *Zählangaben - Maßangaben*. Studien zur Kognitionswissenschaft. Deutscher Universitätsverlag, Wiesbaden, 1995.

1.68 C. Eschenbach. On representation and descriptions of spatial socio-economic units. In A. U. Frank, J. Raper, and J.-P. Cheylan, editors, *Life and Motion of Socio-Economic Units*. Taylor & Francis, London, 2001.

1.69 C. Eschenbach and L. Kulik. An axiomatic approach to the spatial relations underlying left-right and in front of-behind. In *KI'97*, 1997.

1.70 ESPRIT. The esprit project web page, url: http://www.cordis.lu/esprit/src/intro.htm, 2000.

1.71 G. Fauconnier. *Mappings in Thought and Language*. Cambridge University Press, Cambridge, UK, 1997.

1.72 C. Fellbaum, editor. *WordNet: An Electronic Lexical Database*. Language, Speech, and Communication. The MIT Press, Cambridge, Mass., 1998.

1.73 J. Ferber, editor. *Multi-Agent Systems - An Introduction to Distributed Artificial Intelligence*. Addison-Wesley, 1998.

1.74 F. T. Fonseca and M. J. Egenhofer. Ontology-driven geographic information systems. *Geographic Information Systems*, 8:385–399, 1994.

1.75 G. Franck. Time, actuality, novelty and history. In A. U. Frank, editor, *Life and Motion of Socio-Economic Units*. Taylor & Francis, London, to appear.

1.76 A. U. Frank. *Datenstrukturen für Landinformationssysteme - Semantische, Topologische und Räumliche Beziehungen in Daten der Geo-Wissenschaften*. Dissertation, ETH Zürich, Institut für Geodäsie und Photogrammetrie, 1983.

1.77 A. U. Frank. Qualitative temporal reasoning in gis-ordered time scales. In T. C. Waugh and R. G. Healey, editors, *Sixth International Symposium on Spatial Data Handling, SDH'94*, volume 1, pages 410–430, Edinburgh, Scotland, Sept. 5-9, 1994, 1994. IGU Commission on GIS.

1.78 A. U. Frank. An object-oriented, formal approach to the design of cadastral systems. In M. J. Kraak and M. Molenaar, editors, *7th Int. Symposium on Spatial Data Handling, SDH '96*, volume 1, pages 5A.19–5A.35, Delft, The Netherlands, 1996. IGU.

1.79 A. U. Frank. Spatial ontology: A geographical information point of view. In O. Stock, editor, *Spatial and Temporal Reasoning*, pages 135–153. Kluwer Academic Publishers, Dordrecht, 1997.

1.80 A. U. Frank. GIS for politics. In C.-R. Proceedings, editor, *GIS Planet '98*, Lisbon, Portugal (9 - 11 Sept. 1998), 1998. IMERSIV.

1.81 A. U. Frank. Metamodels for data quality description. In R. Jeansoulin and M. Goodchild, editors, *Data quality in Geographic Information - From Error to Uncertainty*, pages 15–29. Editions Hermes, Paris, 1998.

1.82 A. U. Frank. One step up the abstraction ladder: Combining algebras - from functional pieces to a whole. In C. Freksa and D. M. Mark, editors, *Spatial Information Theory - Cognitive and Computational Foundations of Geographic Information Science (Int. Conference COSIT'99, Stade, Germany)*, volume 1661 of *Lecture Notes in Computer Science*, pages 95–107. Springer-Verlag, Berlin, 1999.

1.83 A. U. Frank. Communication with maps: A formalized model. In C. Freksa, W. Brauer, C. Habel, and K. F. Wender, editors, *Spatial Cognition II (International Workshop on Maps and Diagrammatical Representations of the Environment, Hamburg, August 1999)*, volume 1849 of *Lecture Notes in Artificial Intelligence*, pages 80–99. Springer-Verlag, Berlin Heidelberg, 2000.

1.84 A. U. Frank. Socio-economic units: Their life and motion. In J. R. A. U. Frank, J. P. Cheylan, editor, *Life and Motion of Socio-Economic Units*. Taylor and Francis, London, to appear.

1.85 A. U. Frank and W. Kuhn. Cell graphs: A provable correct method for the storage of geometry. In D. Marble, editor, *Second International Symposium on Spatial Data Handling*, pages 411 – 436, Seattle, Wash., 1986.

1.86 A. U. Frank and W. Kuhn. A specification language for interoperable GIS. In M. F. Goodchild, M. Egenhofer, R. Fegeas, and C. Kottman, editors, *Interoperating Geographic Information Systems*. Kluwer, Norwell, MA, 1998.

1.87 A. U. Frank and D. Medak. Formal models of a spatiotemporal database. In K. Richta, editor, *DATASEM'99 - 19th Annual Conference on the Current Trends in Databases and Information Systems*, pages 117–130, Brno, Czech Republic (24-26 October, 1999), 1999. Dept. of Computer Science, Czech Technical University.

1.88 A. U. Frank, B. Palmer, and V. Robinson. Formal methods for accurate definition of some fundamental terms in physical geography. In D. Marble, editor, *Second International Symposium on Spatial Data Handling*, pages 583–599, Seattle, Wash., 1986.
1.89 A. U. Frank, J. Raper, and J.-P. Cheylan, editors. *Life and Motion of Socio-Economic Units*. ESF Series. Taylor & Francis, London, in press.
1.90 A. U. Frank and M. Raubal. Formal specifications of image schemata - a step to interoperability in geographic information systems. *Spatial Cognition and Computation*, 1(1):67–101, 1999.
1.91 A. U. Frank, G. S. Volta, and M. McGranaghan. Formalization of families of categorical coverages. *IJGIS*, 11(3):215–231, 1997.
1.92 W. Franklin. Cartographic errors symptomatic of underlying algebra problems. In *First International Symposium on Spatial Data Handling*, pages 190–208, Zurich, Switzerland, 1984.
1.93 J. T. Fraser, editor. *The Voices of Time*. The University of Massachusetts Press, Amherst, second edition, 1981.
1.94 C. Freksa. Qualitative spatial reasoning. In D. M. Mark and A. U. Frank, editors, *Cognitive and Linguistic Aspects of Geographic Space*, NATO ASI Series D: Behavioural and Social Sciences, pages 361–372. Kluwer Academic Press, Dordrecht, The Netherlands, 1991.
1.95 A. Galton. Towards a qualitative theory of movement. In A. U. Frank and W. Kuhn, editors, *Spatial Information Theory (Proceedings of the European Conference on Spatial Information Theory COSIT '95)*, volume 988 of *Lecture Notes in Computer Science*, pages 377–396. Springer Verlag, Berlin, 1995.
1.96 A. Galton. Continuous change in spatial regions. In S. C. Hirtle and A. U. Frank, editors, *Spatial Information Theory - A Theoretical Basis for GIS (International Conference COSIT'97)*, volume 1329 of *Lecture Notes in Computer Science Vol.1329*, pages 1–14. Springer-Verlag, Berlin-Heidelberg, 1997.
1.97 R. Giblin. *Graphs, Surfaces and Homology*. Mathematics Series. Chapman and Hall, London, 1977.
1.98 J. Gibson. *The ecological approach to visual perception.* Erlbaum, Hillsdale, NJ, 1979.
1.99 J. Goguen. An introduction to algebraic semiotics, with applications to user interface design. In C. Nehaniv, editor, *Computation for Metaphor, Analogy and Agents*, volume 1562 of *Lecture Notes in Artificial Intelligence*, pages 242–291. Springer-Verlag, Berlin Heidelberg, 1999.
1.100 M. Goodchild. Geographical data modeling. *Computers and Geosciences*, 18(4):401–408, 1992.
1.101 M. F. Goodchild, M. Egenhofer, R. Fegeas, and C. Kottmann, editors. *Interoperating Geographic Information Systems (Proceedings of Interop '97, Santa Barbara, CA)*. Kluwer, Norwell, MA, 1998.
1.102 A. Gopnik and A. N. Meltzoff. *Words, Thoughts, and Theories*. Learning, Development, and Conceptual Change. The MIT Press, Cambridge, Mass., 1997.
1.103 D. Greene and F. Yao. Finite-resolution computational geometry. In *27th IEEE Symp. on Foundations of Computer Science*, pages 143–152. IEEE, 1986.
1.104 N. Guarino. Semantic matching: formal ontological distinctions for information organization, extraction, and integration. In M. T. Pazienza, editor, *Information Extraction: An Interdisciplinary Approach to an Emerging Information Technology*, pages 139–170. Springer-Verlag, Berlin Heidelberg.
1.105 N. Guarino. Formal ontology, conceptual analysis and knowledge representation. *International Journal of Human and Computer Studies. Special Issue on Formal Ontology, Conceptual Analysis and Knowledge Representation, edited by N. Guarino and R. Poli*, 43(5/6), 1995.

1.106 N. Guarino. Formal ontology and information systems. In N. Guarino, editor, *Formal Ontology in Information Systems (Proceedings of FOIS'98, Trento, Italy, 6-8 June, 1998)*, pages 3–15. IOS Press, Amsterdam, 1998.
1.107 N. Guarino and C. Welty. A formal ontology of properties. In R. Dieng and O. Corby, editors, *Proceedings of EKW-2000, 12th Int. Conference on Knowledge Engineering and Knowledge Management (2-6 October, 2000)*, Lecture Notes in Artificial Intelligence). Springer-Verlag, Berlin Heidelberg, 2000.
1.108 N. Guarino and C. Welty. Identity, unity and individuation: towards a formal toolkit for ontological analysis. In W. Horn, editor, *ECAI-2000, The European Conference on Artificial Intelligence (August 2000)*. IOS, 2000.
1.109 O. Guenther, K.-P. Schulz, and J. Seggelke, editors. *Umweltanwendungen geographischer Informationssystem*. Wichmann, Karlsruhe (Germany), 1992.
1.110 R. Gueting. Second-order signature: a tool for specifying data models, query processing, and optimization. In *ACM Sigmod Conference*, pages 277–286, Washington, DC, 1993.
1.111 I. Hacking. *The Social Construction of What?* Harvard University Press, Cambridge, Mass., 1999.
1.112 T. Hägerstrand. The propagation of innovation waves. *Lund Studies in Geography, Series B*, (4), 1952.
1.113 P. J. Hayes. Naive physics I: Ontology for liquids. In J. R. Hobbs and R. C. Moore, editors, *Formal Theories of the Commonsense World*, Ablex Series in Artificial Intelligence, pages 71–107. Ablex Publishing, Norwood, NJ, 1985.
1.114 P. J. Hayes. The second naive physics manifesto. In J. R. Hobbs and R. C. Moore, editors, *Formal Theories of the Commonsense World*, pages 1–36. Ablex Publishing Corp., Norwood, N.J., 1985.
1.115 J. Herring, M. Egenhofer, and A. U. Frank. Using category theory to model GIS applications. In K. Brassel, editor, *4th International Symposium on Spatial Data Handling*, volume 2, pages 820–829, Zurich, Switzerland, 1990. IGU, Commission on Geographic Information Systems.
1.116 W. Hodges. *A Shorter Model Theory*. Cambridge University Press, Cambridge, UK, 1997.
1.117 W. Hölbling, W. Kuhn, and A. U. Frank. Finite-resolution simplicial complexes. *GeoInformatica*, 2(3):281–298, 1998.
1.118 K. Hornsby and M. J. Egenhofer. Qualitative representation of change. In S. C. Hirtle and A. U. Frank, editors, *Spatial Information Theory - A Theoretical Basis for GIS (International Conference COSIT'97)*, volume 1329 of *Lecture Notes in Computer Science Vol.1329*, pages 15–33. Springer-Verlag, Berlin-Heidelberg, 1997.
1.119 ICPR. Discussion at the international conference on the development and maintenance of property rights, vienna, 12-15 january, 2000, 2000.
1.120 ISO. The international standardization organization web page. url: http://www.iso.ch/infoe/text.htm, 2000.
1.121 R. Jackendoff. *Semantics and Cognition*. MIT Press, Cambridge, Mass., 1983.
1.122 M. Johnson. *The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason*. University of Chicago Press, Chicago, 1987.
1.123 M. Jones. *Qualified Types: Theory and Practice*. Cambridge University Press, 1994.
1.124 W. Kent. *Data and Reality - Basic Assumptions in Data Processing Reconsidered*. North-Holland, Amsterdam, 1978.
1.125 S. Kripke. Semantical analysis of modal logic. *Zeitschrift fuer Mathematische Logik und Grundlagen der Mathematik*, 9:67–96, 1963.
1.126 S. Kuan. *Geodetic Network Analysis and Optimal Design*. Ann Arbor Press, Chelsea, Mich., 1996.

1.127 B. Kuipers. A hierarchy of qualitative representations for space. In C. Freksa, C. Habel, and K. F. Wender, editors, *Spatial Cognition - An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Artifical Intelligence*, pages 337–350. Springer-Verlag, Berlin Heidelberg, 1998.
1.128 G. Lakoff. *Women, Fire, and Dangerous Things: What Categories Reveal About the Mind*. University of Chicago Press, Chicago, IL, 1987.
1.129 G. Lakoff. Cognitive semantics. In U. Eco, M. Santambrogio, and P. Violi, editors, *Meaning and Mental Representations*, pages 119–154. Indiana University Press, Bloomington, 1988.
1.130 G. Lakoff and M. Johnson. *Metaphors We Live By*. University of Chicago Press, Chicago, 1980.
1.131 D. G. Lenat, R. V. Guha, K. Pittman, D. Pratt, and M. Shepherd. CYC: Toward programs with common sense. *Comm. ACM*, 33(8):30 – 49, 1990.
1.132 P. Lockemann and H. Mayr. *Rechnergestützte Informationssysteme*. Springer-Verlag, Berlin, 1978.
1.133 J. Loeckx, H.-D. Ehrich, and M. Wolf. *Specification of Abstract Data Types*. John Wiley and B.G. Teubner, Chichester, UK and Stuttgart, 1996.
1.134 S. MacLane and G. Birkhoff. *Algebra*. Macmillan, New York, 1967.
1.135 J. McCarthy and P. J. Hayes. Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer and D. Michie, editors, *Machine Intelligence 4*, pages 463–502. Edinburgh University Press, Edinburgh, 1969.
1.136 N. McCoy and T. Berger. *Algebra: Groups, Rings and other Topics*. Allyn and Bacon, London, 1977.
1.137 D. Medak. *Lifestyles - A Paradigm for the Description of Spatiotemporal Databases*. Ph.D. thesis, Technical University Vienna, 1999.
1.138 D. Medak. Lifestyles. In A. U. Frank, J. Raper, and J.-P. Cheylan, editors, *Life and Motion of Socio-Economic Units*. Taylor & Francis, London, in press.
1.139 H. Meixner and A. U. Frank. GI policy - study on policy issues relating to geographic information in europe. Final Report of a Project "GI Policy" in the IMPACT Program ftp://ftp.echo.lu/pub/gi/gi_poli.zip, European Commission DG XIII, July 1997 1997.
1.140 M. Minsky. *The Society of Mind*. Simon & Schuster, New York, 1985.
1.141 D. Montello. How significant are cultural differences in spatial cognition? In A. U. Frank and W. Kuhn, editors, *Spatial Information Theory - A Theoretical Basis for GIS*, volume 988 of *Lecture Notes in Computer Science*, pages 485–500. Springer-Verlag, Berlin, 1995.
1.142 J. Morrison. The proposed standard for digital cartographic data. *Amer. Cartographer*, 15(1):9–140, 1988.
1.143 H. Mounsey and R. F. Tomlinson, editors. *Building Databases for Global Science - Proceedings of the IGU Global Database Planning Project, Tylney Hall, Hampshire, UK, 9-13 May 1988*. Taylor & Francis, London, 1988.
1.144 G. Navratil. *An object-oriented approach to a model of a cadaster*. M.Sc., Technical University of Vienna, 1998.
1.145 J. Neumann von and O. Morgenstern. *Theory of Games and Economic Behavior*. Princeton University Press, Princeton, NJ, 1944.
1.146 J. Nutter. Epistemology. In S. Shapiro, editor, *Encyclopedia of Artificial Intelligence*. John Wiley & Sons, New York, 1987.
1.147 OGC. The open GIS consortium web page. url: http://www.opengis.org, 2000.
1.148 OMG. The object management group web page. url: http://www.omg.com, 2000.
1.149 ONTEK. The ontek corporation web page url: http://www.ontek.com/mikey/current.html, 2000.
1.150 J. A. d. C. Paiva and M. J. Egenhofer. Robust inference of the flow direction in river networks. *Algorithmica*, to appear.

1.151 J. A. d. C. Paiva, M. J. Egenhofer, and A. U. Frank. Spatial reasoning about flow directions: Towards an ontology for river networks. In L. Fritz and J. Lucas, editors, *International Society for Photogrammetry and Remote Sensing. XVII Congress*, volume 24/B3 Comission III of *International Archives of Photogrammetry and Remote Sensing*, pages 318–324, Washington, D.C., 1992.
1.152 J. Peterson, K. Hammond, L. Augustsson, B. Boutel, W. Burton, J. Fasel, A. D. Gordon, J. Hughes, P. Hudak, T. Johnsson, M. Jones, E. Meijer, S. P. Jones, A. Reid, and P. Wadler. The haskell 1.4 report. *http://haskell.org/report/index.html*, 1997.
1.153 D. Peuquet, B. Smith, and B. Brogaard. The ontology of fields: Report of the specialist meeting held under the auspices of the varenius project, bar harbour, maine, june 1998. Technical report, NCGIA, 1999.
1.154 S. Peyton Jones, J. Hughes, and L. Augustsson. Haskell 98: A non-strict, purely functional language, 1999.
1.155 B. C. Pierce. *Basic Category Theory for Computer Scientists*. Foundations of Computing. MIT Press, Cambridge, Massachussetts, 1991.
1.156 S. Pigot and B. Hazelton. The fundamentals of a topological model for a four-dimensional GIS. In P. Bresnahan, E. Corwin, and D. Cowen, editors, *Proceedings of the 5th International Symposium on Spatial Data Handling*, volume 2, pages 580–591, Charleston, 1992. IGU Commission of GIS.
1.157 Protege. The protege project web page. http://www.smi.stanford.edu/projects/protege, 2000.
1.158 D. Randell and A. Cohn. Modelling topological and metrical properties of physical processes. In R. Brachmann, H. Levesque, and R. Reiter, editors, *First International Conference on the Principles of Knowledge Representation and Reasoning*, pages 55–66. Los Altos, CA: Morgan-Kaufmann, 1989.
1.159 D. A. Randell, Z. Cui, and A. Cohn. A spatial logic based on regions and connection. In R. Brachmann, H. Levesque, and R. Reiter, editors, *Third International Conference on the Principles of Knowledge Representation and Reasoning*, pages 165–176. Los Altos, CA: Morgan-Kaufmann, 1992.
1.160 R. Reiter. Towards a logical reconstruction of relational database theory. In M. L. Brodie, M. Mylopolous, and L. Schmidt, editors, *On Conceptual Modelling, Perspectives from Artificial Intelligence, Databases, and Programming Languages*, pages 191–233. Springer Verlag, New York, 1984.
1.161 R. Reiter. *Knowledge in Action: Logical Foundations for Describing and Implementing Dynamical Systems*. in preparation.
1.162 B. L. Rhoads. Beyond pragmatism: The value of philosophical discourse for physical geography. *The Annals of the Association of American Geographers*, 89(4):760–771, 1999.
1.163 E. Rosch. Natural categories. *Cognitive Psychology*, 4:328 – 350, 1973.
1.164 E. Rosch. Principles of categorization. In E. Rosch and B. B. Lloyd, editors, *Cognition and Categorization*. Erlbaum, Hillsdale, NJ, 1978.
1.165 H. J. Rossmeissl and R. D. Rugg. An approach to data exchange: The spatial data transfer standard. In A. I. Johnson, C. B. Petterson, and J. L. Fulton, editors, *Geographic Information Systems (GIS) and Mapping – Practices and Standards*, pages 38–44. ASTM, Philadelphia, 1992.
1.166 F. Saussure de. *Cours linguistique generale*. Payot & Rivages, Paris, 1995.
1.167 M. Schneider. *Spatial Data Types for Database Systems*, volume 1288 of *Lecture Notes in Computer Science*. Springer-Verlag, Berlin-Heidelberg, 1997.
1.168 F. A. Schreiber. Is time a real time? an overview of time ontology in informatics. In W. A. Halang and A. D. Stoyenko, editors, *Real Time Computing*, NATO ASI Series. Heidelberg, 1994.
1.169 J. Searle. *Speech Acts*. Cambridge University Press, 1969.
1.170 J. R. Searle. *The Construction of Social Reality*. The Free Press, New York, 1995.

1.171 P. Simon. *Parts - A Study in Ontology*. Clarendon Press, Oxford, 1987.
1.172 D. Sinton. The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In G. Dutton, editor, *Harvard Papers on GIS*, volume Vol.7. Addison-Wesley, Reading, MA., 1978.
1.173 B. Smith. An essay in formal ontology. *Grazer Philosophische Studien*, 6:39–62, 1978.
1.174 B. Smith. On drawing lines on a map. In A. U. Frank and W. Kuhn, editors, *Spatial Information Theory - A Theoretical Basis for GIS (Int. Conference COSIT'95)*, volume 988, pages 475–484. Springer-Verlag, Berlin Heidelberg, 1995.
1.175 B. Smith. Mereotopology: A theory of parts and boundaries. *Data and Knowledge Engineering*, 20 (1996):287–303, 1996.
1.176 B. Smith. Basic concepts of formal ontolgy. In N. Guarino, editor, *Formal Ontology in Information Systems*, pages 19–28. IOS Press, Amsterdam Oxford Tokyo, 1998.
1.177 B. Smith. Objects and their environments: from aristotle to ecological ontology. In A. U. Frank, J. Raper, and J.-P. Cheylan, editors, *Life and Motion of Socio-Economic Units*. Taylor & Francis, London, in press.
1.178 B. Smith. Ontology: Philosophical and computational. In L. Floridi, editor, *The Blackwell Guide to the Philosophy of Computing and Information.* Blackwell, Oxford, to appear.
1.179 B. Smith and B. Brogaard. Quantum mereotopology. In *Spatial and Temporal Granularity - Papers from the AAAI Workshop*, volume AAAI Technical Report WS-00-08, pages 25–31. AAAI Press, 2000.
1.180 B. Smith and B. Brogaard. Sixteen days, 2000.
1.181 B. Smith and K. Mulligan. Framework for formal ontology. *Topoi*, (2):73–85, 1983.
1.182 B. Smith and J. Searle. The construction of social reality: An exchange. *American Journal of Economics and Sociology*, 60, 2001.
1.183 H. Smith and K. Poulter. The role of shared ontology in XML-based trading architectures. *Communications of the ACM, Special Issue on Agent Software*, 1999.
1.184 R. Snodgrass. Temporal databases: Status and research directions. *SIGMOD RECORD*, 19(4, December):83–89, 1990.
1.185 R. Snodgrass. Temporal databases. In A. U. Frank, I. Campari, and U. Formentini, editors, *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space (Int. Conference GIS - From Space to Territory, Pisa, Italy)*, volume 639 of *Lecture Notes in Computer Science*, pages 22–64. Springer-Verlag, Berlin, 1992.
1.186 J. G. Stell. A lattice theoretic account of spatial regions, 1997.
1.187 S. S. Stevens. On the theory of scales of measurement. *Science*, 103(2684):677 – 680, 1946.
1.188 A. Tansel, J. Clifford, S. Gadia, S. Jajodia, A. Segev, and R. Snodgrass. *Temporal Databases.* Benjamin Cummings, Redwood City, CA, 1993.
1.189 A. Tarski. *Introduction to Logic and to the Methodology of Deductive Sciences.* Dover Publications, Mineola, N.Y., 1995.
1.190 S. Thompson. *Haskell - The Craft of Functional Programming.* International Computer Science Series. Addison-Wesley, Harlow, UK, 1996.
1.191 S. Timpf. *Hierarchical Structures in Map Series.* PhD, Technical University Vienna, 1998.
1.192 S. Timpf, G. Volta, D. Pollock, and M. Egenhofer. A conceptual model of wayfinding using multiple levels of abstractions. In A. U. Frank, I. Campari, and U. Formentini, editors, *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, volume 639 of *Lecture Notes in Computer Science*, pages 348–367. Springer Verlag, Heidelberg-Berlin, 1992.
1.193 C. D. Tomlin. *Digital Cartographic Modeling Techniques in Environmental Planning.* Doctoral dissertation, Yale Graduate School, Division of Forestry and Environmental Studies, 1983.

1.194 C. D. Tomlin. *Geographic Information Systems and Cartographic Modeling*. Prentice Hall, New York, 1990.
1.195 M. Turner. *The Literary Mind*. Oxford University Press, New York, 1996.
1.196 B. Tversky. Spatial perspectives in descriptions. In P. Bloom, A. Peterson, L. Nadel, and M. Garrett, editors, *Language and Space - Language, Speech, and Communciation*. MIT Press, Cambridge, MA, 1996.
1.197 A. Vckovski, K. E. Brassel, and H.-J. Scheck, editors. *Interoperating Geographic Information Systems (Interop '99, Zurich)*, volume 1580 of *Lecture Notes in Computer Science*. Springer-Verlag, Berlin, 1999.
1.198 A. Vckovski and F. Bucher. Virtual data sets - smart data for environmental applications, Dec. 1995 1998.
1.199 L. Vieu. A logical framework for reasoning about space. In A. U. Frank and I. Campari, editors, *Spatial Information Theory: Theoretical Basis for GIS*, volume 716 of *Lecture Notes in Computer Science*, pages 25–35. Springer Verlag, Heidelberg-Berlin, 1993.
1.200 P. Wadler. Monads for functional programming. In J. Jeuring and E. Meijer, editors, *Advanced Functional Programming*, volume 925 of *Lecture Notes in Computer Science*. Springer-Verlag, Berlin Heidelberg, 1995.
1.201 G. Weiss. *Multi-Agent Systems: A Modern Approach to Distributed Artificial Intelligence*. The MIT Press, Cambridge, Mass., 1999.
1.202 A. Wierzbicka. *Semantics - Primes and Universals*. Oxford University Press, Oxford, 1996.
1.203 M. Worboys. A model for spatio-temporal information. In P. Bresnahan, E. Corwin, and D. Cowen, editors, *Proceedings of the 5th International Symposium on Spatial Data Handling*, volume 2, pages 602–611, Charleston, 1992. IGU Commission of GIS.
1.204 C. Zaniolo, P. C. Lockemann, M. H. Scholl, and T. Grust, editors. *Advances in Database Technology - Proceedings of EDBT 2000 (Konstanz, Germany, March 2000)*, volume 1777 of *Lecture Notes in Computer Science*. Springer-Verlag, Berlin Heidelberg, 2000.