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Research Article

Tiers of ontology and consistency constraints in geographical information systems

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Abstract. Consistency constraints placed on a database to assure, that values incorporated in the database are consistent, are a well known foundation of Geographical Information Systems. Unfortunately in real situations rules for consistency constraints are not so clear, and inconsistent ontologies are common place, not least in geographical information, covering as it does a much wider realm than many other information systems I have suggested elsewhere 5-tiers of ontology for GIS. Such an ontology can integrate different ontological approaches in a unified system. In this paper the relation of the 5-tier ontology and consistency constraints is explored, and it is shown that different constraints are appropriate to different tiers.

1. Introduction

Consistency constraints are included in all descriptions of how Geographic Information Systems should be built (Laurini and Milleret-Raffort 1991, Worboys 1995). It is generally assumed that a set of rules which assure consistency can be added to a database (Zaniolo *et al.* 1997), and also to a GIS. These rules are simple formulae which test if a value or a set of values is consistent. The database system then guarantees that all data stored in the database are respecting these rules (this is enforced by the so-called transaction system; Gray and Reuter 1993). I have described such approaches as early as my PhD thesis (Frank 1983).

Unfortunately, all practical situations are much less clear: rules for consistency constraints suggested in the literature have been very simplified examples and in many practical systems the same concepts have been guidelines rather than strict rules. How to handle rarely occurring exceptional situations remains an open problem.

A database and, consequently, a GIS is based on one—not necessarily consistent—ontology. Philosophers have proposed many different ontologies. Despite hundreds of years of effort, it has been impossible to reconcile the differences between them and to establish a single, widely accepted ontology. Inconsistencies in the founding ontology for a database create problems later during usage. The demand for large ontologies which cover major parts of human activities has led to the CYC and similar projects (Lenat *et al.* 1990). I suggested the construction of re-usable ontologies (Frank 1997). Today, the production of 'ontology' is an emerging business (ONTOS 2001). Consistency constraints are an important, but often neglected, part of these ontologies.

The design of Geographic Information Systems, which cover information about objects and properties in the world with respect to their location (Longley *et al.*

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1999), involves ontologies. Indeed, such systems are ontologically more demanding than ordinary administrative information systems. They span a much larger diversity of kinds of things: from the description of the elevation of the surface of the earth to the description of the natural land cover (woods, fields, etc.) and morphology (mountains, valleys, etc.). They also include man-made features like roads and buildings as well as artificial boundaries between a range of different sorts of political and administrative units (Smith 1995). This broad range of 'kinds of things' covered leads, as will be shown in this paper, to very different kinds of consistency rules.

I have suggested that an ontology for GIS and other, large scale, physical reality related systems should be built as a coordinated set of tiers of ontology (figure 1). Tier 0 of the ontology assumes that there exists a physical reality, which may best be imagined as a four-dimensional continuous field of attribute values. This could be considered as the ontology proper, where the following tiers are perhaps more akin to what some authors would assign to the realm of epistemology. Tier 1 covers the point-wise observation of this reality by cognitive agents. Tier 2 discusses how agents form objects from point-wise observations; this is somewhat similar to Aristotle's metaphysics. Tier 3 embraces social reality in the sense of Searle (1995) and other socially constructed elements (Berger and Luckmann 1996). Tier 4, finally, deals with the ideas cognitive agents have about the world.

An ontology constructed from tiers can integrate different ontological approaches in a unified system. In particular, it can deal with the classical problem of GIS—namely the integration of vector and raster data (Peuquet 1988, Winter and Frank 2000) and merge a plenum, continuous space ontology with Aristotle's 'natural kind' ontology of objects. We can also integrate the ontology of 'social reality' described by Searle (1995).

A very extensive description of the tiered ontology will appear as a book chapter discussing ontology for spatio-temporal databases (Frank, in press, *a*); a brief description stressing the integration of multiple ontologies was presented at the Wittgenstein Symposium (Frank, in press, *b*). The current paper focuses on consistency constraints; it demonstrates how database consistency constraints are part of the ontology and shows that the interpretation of consistency constraints is related to the tiers of the ontology.

I am not interested here in terminological discussions and I use terms like 'ontology' in a generic way; Guarino (1997) has shown the many different uses of the term by different authors and I do not want to add to this list. My approach is empirical and stresses our daily experience in interacting with the world as a source of knowledge to build ontologies.

In this paper, every tier is described briefly and then the special questions posed for consistency constraints for this kind of data are addressed. This demonstrates that consistency constraints for each tier require substantially different solutions. The conclusions summarize and contrast these approaches.

Tier O: human-independent reality
Tier 1: observation of physical world
Tier 2: objects with properties
Tier 3: social reality
Tier 4: subjective knowledge

Figure 1. The five tiers of ontology.

2. Physical reality seen as an ontology of a four-dimensional field

The physical laws which describe the behaviour of the macroscopic world can be expressed as differential equations, which describe the interaction of a number of properties in space—the whole seen as forming a continuum. A number of properties can be observed for each point in space and time: colour, the forces acting at that point, the material and its properties (like mass, melting point temperature, and so on). Movement of objects can be described as changes in these properties. The description of reality via differential equations (e.g. the description of forces in a plate under a load) is widely used in mechanical and civil engineering, geology, etc. This view is also quite natural for most 'global systems' studies (Mounsey and Tomlinson 1988).

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

$$f(x, y, z, t)=a$$

The processes occurring in this physical reality have spatial and temporal extensions: some are purely local and happen very fast; others affect very large regions and are very slow. The processes of objects moving on the tabletop are fast (m sec^{-1}) and the spatial extent is small (m); movement of persons in cities is again fast (m sec^{-1}) and the movements of the buildings very slow (mm annum^{-1}); geological processes affect large areas (1000 km^2) and are very slow (mm annum^{-1}). One can thus associate different processes with different frequencies in space and time (Fraser 1981). Each science has a certain scope: it is concerned with processes in a specific spectrum of space and time which interact strongly; other processes, not included in this scope, appear then to be either so slow or so fast that they can be considered constant.

Space and time form together 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 which 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 easily observable for humans in a simple form ($s=vt$, etc.). Other sciences, for example, 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 univalued function is equivalent to the assumption that there is only one single space-time world and excludes 'parallel universes' as parts of reality.

2.1. *What follows for consistency constraints?*

Physical reality is understood as following the 'natural laws', i.e. rules which are thought to be universally valid and of which we have knowledge from empirical observations. The speed of an object is related to the acceleration by the formula $v=at$; water flows under the influence of gravity downhill. As these rules are universally valid, they are good candidates to be included in an information system as constraints on the data. Data which violates such rules is most likely in error.

The formulation of natural laws appears fixed and precise. For example, the speed of a coin in my pocket while I walk in a train is the vector addition of the different velocity vectors, $v_s=v_a+v_b+v_c$. This 'universal rule' is only a valid approximation and usable if all velocities are very small in comparison with the speed of light—otherwise the more complex Lorenz-Transformations describe the situation better. Gravity provides examples more relevant for GIS: for water runoff calculations only the direction of the gravity vector is used and its value is not considered; for commercial applications, the value of gravity is considered constant (i.e. the principle of conservation of mass is equivalent to conservation of weight of objects).

This example demonstrates a general trend: widely applicable rules describing physical laws are not as universal as often implied. They are typically simplified to cover typical applications. They are valid for disciplinary viewpoints, i.e. specific combinations of size of objects and temporal resolution. They require adaptation for applications outside of these limits.

3. Observation of physical reality

Agents observe the physical reality with their senses or with technical instruments—at the current time, the 'now'. Results of observations are measurement values on some measurement scale (Stevens 1946), which may be quantitative or qualitative.

Observation with a technical measurement system such as remote sensing comes very close to an objective, human-independent observation of reality. Many technical systems allow the synchronous observations of an extent of space at the same time, for example, remote sensing of geographical space from satellite. A regular grid is used and the properties observed are energy reflected in some bands of wavelength; typically the visible spectrum plus some part of infrared.

Observation through sampling of many points of the environment is also effected by our eyes and similarly used by robots, where TV cameras sample the field in a regular grid. They are to guide the actions of the robot in manipulating objects or guiding its movements through buildings (Kuipers 1998).

Observation of reality is always marked by imprecision—the knowledge we acquire is never perfect. The technical effects of our measurement systems allow us at best measurements up to 10^{-13}, which is, incidentally, much worse than the theoretical limits imposed by Heisenberg's uncertainty principle.

3.1. *Consistency constraints for observations as statistical tests*

Consistency constraints must allow for observation errors. If coordinate values for two points are previously stored in the database and an observation for the distance is entered, one must not expect the observed measurement to be accurately the same as the computed distance value. Any observation which is consistent with the statistical distribution of measurement values according to the expected error is consistent with the data.

The theoretical difficulties associated with the storage of coordinate values have led us to propose to store the results of the measurements and to construct a GIS on the base of measurements, not the stored coordinates (Buyong *et al.* 1991, Buyong 1992, Haunold *et al.* 1997). Consistency checks for newly entered measurements in a measurement-based GIS are then the same as the methods of testing measurements to eliminate gross errors. One compares the results after adjustment and identifies those which are most unlikely. T-statistics are typically used (Kreyszig 1973). It is clear that a simple comparison of input values with values computed from the database is not sufficient to determine if a newly entered measurement is consistent with previous measurements.

4. Objects with properties

Our cognitive system is so effective because, from the array of sensed values, it forms individuals, which are usually called objects, and it reasons about them.

Thinking of tables and books and people is much more effective than seeing the world as consisting of data values for sets of cells, regularly subdivided across a grid (three-dimensional cells, often called voxels). It is economical to store properties of objects and not deal with individual raster cells. Experience has taught us how to structure reality as collection of objects. As John McCarthy and Patrick Hayes have pointed out:

> ...suppose a pair of Martians observe the situation in a room. One Martian analyses 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. (McCarthy and Hayes 1969, p. 33)

Our experience in interacting with the world has led to the most appropriate subdivision of continuous reality into individuals. The latter are most often continuous in space and endure in time. 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 more economical and more direct mode of reasoning with individuals: the array on the tabletop is divided into individuals at the boundaries where cohesion between cells is low; a spoon consists of all the material which moves with the spoon when I pick it up and move it to a different location. This is obviously more effective than efforts to reason about the content of each cell. In an ever-changing world, individuals are typically formed in such a way that many of their properties remain invariant over time, which further simplifies reasoning. Animals and most plants form individuals in a natural way.

The cognitive system operates very quickly 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 and a vase. The detection of 'affordances' of objects is immediate and not a product of conscious reasoning. The identification of affordances implies a breakup of the world into objects: the objects are what we can interact with (Gibson 1979).

Cognitive science has demonstrated that small infants as early as 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 it is not possible for us to scrutinize them. There are a number of well-known effects where the same image is interpreted in different ways, for example, the well known Necker-cube which can be seen as cube or a corner, but not both at once. But such examples are rare. The default process assigns objects univocally.

Humans have a limited set of interactions with the environment—five senses to perceive it and operations like walking, picking up—and these operations are common to all humans. Therefore the object structure—at least at the level of direct interaction —is common to all humans and it provides the foundation on which to build the semantics of common terms (Lakoff 1988). In general, the way individual objects and object types are formed varies with the context, but is not arbitrary. This commonality in the basic experiences of all humans gives sufficient grounding for the semantics of everyday words, but also for establishing common ontologies.

4.1. *Consistency constraints for objects as invariants through operations*

Ontologists suggest a subdivision of rules for objects into sufficient and necessary conditions (OIL 2001). These rules describe properties which all objects must have all the time; sufficient conditions are enough to determine the type of an entity, necessary conditions are properties all objects of this type have, but it is not permitted to deduce from these properties alone that an entity is of a particular type. This relates to the categorization system proposed initially by Aristotle, which forms categories based on properties of objects. Constitutive rules may, for example, state that students are human beings, or that dogs are animals. Software support exists, which deduces the constitutive rules for each entity from general, multi-level descriptions.

The properties identified in the constitutive rules are often the same properties which are used to identify the objects—or at least should be very closely related to them. Objects are formed to achieve simple invariants and a limited set of interactions through operations. Unfortunately, it is not yet clear how the rules to form objects and the operations applicable to these objects and the sufficient and necessary conditions of ontologies interact.

Not all properties which seem to be natural candidates for such rules are really constitutive. Dogs are often specified as 'can bark', 'have four legs', etc., but from such a set of attributes it does not follow that my neighbour's dog, which lost a leg in an accident, is no longer a dog.

The Aristotelian approach to categorization leads to practical problems. One may define birds as animals that can fly—considering flying as a necessary property. Modern linguistics and psychology generally assume 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—the latter two kinds of birds both cannot fly (Rosch 1973, 1978). Linguistic analysis suggests that the ways objects are structured are closely related to operations one can perform with them, and empirical data support this (Jackendoff 1983, Fellbaum 1998).

Consistency constraints for objects which are considered radial categories must allow gradual membership—perhaps fuzzy sets (Zadeh 1965) or rough sets (Worboys 1998) are the appropriate method for a formal treatment. It must be possible to store entities which are in a class without having some of the necessary properties (dogs with 3 legs, birds which cannot fly).

5. **Social ontology**

Human beings are social animals; language allows us to communicate and to achieve high levels of social organization and division of labour. 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 modelled according to biological properties, for example, the kin system (Lévi-Strauss 1967), or property rights derived from physical possession, can be refined and elaborated to the complex legal system of today's society.

5.1. *Consistency constraints for social ontologies are restricted to context*

Following Searle's approach, the social ontology is typically based on an assertion which links a physical object X to a social meaning Y in a context Z: *X counts as Y in context Z* (Searle 1995). The semantics of the socially constructed term (the Y in Searle's formula) is meaningful only in the context listed. Consistency constraints which may link the socially constructed term to the physical object are only valid in this context, but not in others. It is therefore necessary to model the context in the database and to restrict the consistency constraints to apply only to one or the other context. For example, a consistency constraint may determine that an adult is a person older than 18 years, but this must be limited to the context Switzerland, whereas in Austria the corresponding consistency constraint is 'older than 19 years'.

As long as databases contain only data from one country or a single company, there is only a single context. Databases spanning multiple contexts must model for each socially constructed object the context to select the correct consistency constraint. The design of a database for a global company, where administrative data from all parts of the world were integrated to produce high-level management information data, demonstrated the difficulty to decide what 'full-time' or 'part-time' employee were meaning in different countries; we could not see how to integrate the data from different national subsidiaries—a special case of 'intra-company' interoperability.

Names

The types of proper and common names used in our various natural languages are clearly the result of a social process: proper names are words used for individuals, which identify objects in ways which are different from predicates to select individuals based on a unique set of properties. Such socially agreed identifiers seem to be a property 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, and each is valid in its context. 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 single dinner.

The translation of terms between different languages shows that the set of objects covered in one language with one term does not correspond to a set of objects covered with the (best translated) term in another language. Mark has discussed the correspondence of terms for lakes and ponds in English, Spanish and French (Mark 1993). These differences show when one attempts to translate consistency constraints for lakes from English to French—not the same consistency constraints apply to 'lake' and 'lac'!

Institutions created by social rules

Social systems construct rules for their internal organization (Berger and Luckmann 1996), e.g. 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), and so on. Institutions are extremely important in our daily life and appear to us as real; who would deny the reality of companies, such as the 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 (Medak 1999, 2001).

The consistency constraints for legal objects are obviously restricted to the validity of the corresponding law. In Austria, there are at least five different definitions of forest; one of them does not require trees on the land! Consistency constraints must therefore separate these words as polysemous (words with the same form, but different meaning) and link each to the corresponding law. Further changes in laws— which occur regularly— can change the context. The model of context must therefore include temporal limits of the context (as well as spatial and thematic ones).

6. 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 behaviour under conditions of incomplete knowledge (Neumann and Morgenstern 1944, Davis 1983, Baird *et al.* 1994).

The knowledge possessed by a person or an organization increases over time, but it lags necessarily behind the changes on the side of reality. Decisions are made based on this not quite up-to-date knowledge. Fairness dictates that the actions of agents are judged not with respect to perfect knowledge, but rather 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 'it is easy to be wise after the event'.

A fundamental aspect of modern administration is the concept of an audit: administrative acts must be open to inspection so that it can be established whether they were performed according to the rules and regulations. 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 public administration, had at a certain time. This leads to the bi-temporal perspectives usually differentiated in a database: the time a fact becomes true in the world and the time the agent acquires knowledge of this fact (Snodgrass 1992).

6.1. *Consistency constraints to enforce similarity in operation of employees*

If an agent is formed by a number of autonomous sub-agents, i.e. a corporation or public agency, which acts through its employees, then consistency rules are necessary to express the agency's common understanding of reality and they serve to enforce that the agency's view of the world is applied by each autonomous sub-agent (i.e. employee).

If a database contains the viewpoints of different autonomous agents, then it becomes very difficult to understand when the knowledge of two agents is contradictory. It is obvious that different agents have different knowledge, even concerning the same objects. When can one say that the knowledge of one agent is inconsistent? If two agents report physical observations, for example, the length of a road, then with some margin of error, the values should agree (see §3 for discussion on observation errors). If the two agents report judgments, for example, about the hospitality encountered in a village, one must not expect values to be similar, not even correlated.

7. Computational model of a tiered ontology

The design of the tiered ontology is oriented towards the construction of a computational model and this makes it well suitable to deal with consistency constraints.

Misunderstandings and terminological difficulties in various texts on ontology, but also the problems experienced with differences in the interpretation of terms have led us to investigate computational models which reduce our reliance on natural language terminology. Algebras define terms up to an isomorphism without regress to other, previously defined terms, which is exactly what is necessary to define the behaviour of objects in the real world or their simulated behaviour in an information system. We should have, as far as possible, an isomorphism between real world and information system. The two realms, real world and information, are connected by the experience of the agent interacting with the world based on his knowledge.

Certain parts of the ontology have been translated into computational models in a multi-agent setting (Weiss 1999). Multi-agent systems, the way we use them, are systems in which we simulate agents, including their bodies and perceptual and cognitive systems, in a simulated world. We have completed one such simulation in which one agent explores a simplified city and then draws a map, which is later used by another agent to navigate (figure 2). We have also completed a simulation for social reality (Bittner, in preparation), wherein the meanings of terms like 'ownership' and 'land' are defined. Agents then follow the rules of real estate law in dealing with the simulation. It seems possible to construct a computational model of the complete five tiers of the ontology in this framework.

The models we have built are formally checked for completeness of descriptions, i.e. that all parts which are used to define a concept are in turn defined somewhere else in terms of a very simple set of primitives. Checking that the types of inputs and outputs correspond—which can be done automatically—gives additional confidence that the model is logically consistent (Milner 1978, Jones 1994). Running the computational model finally allows us to test whether the model reflects correctly the intended behaviour. We found the public domain functional language Haskell (Peterson *et al.* 1996) extremely useful for constructing such models.

8. Conclusions

In today's world of networked information systems, the clarification of the ontological bases used to collect and manage data becomes ever more important. Questions of interoperability (Goodchild *et al.* 1998) are very often essentially ontolo-

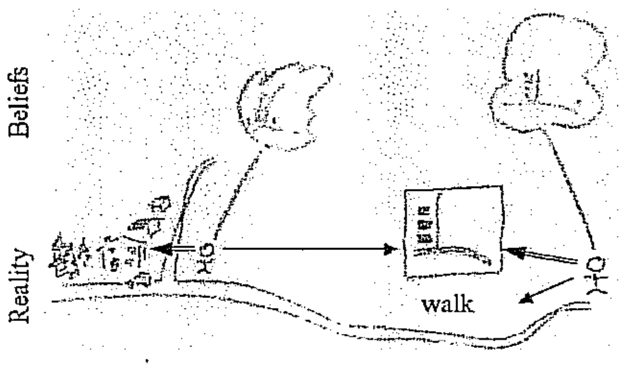

Figure 2. An agent producing a map and another agent using a map for navigation (Frank 2000).

gical questions, especially the integration of database schema and consistency constraints from different sources. In this environment practical ontologies—ontologies, which work—become necessary. They can help us to understand how to integrate data from different sources into a single system. In this contribution the special issue of consistency constraints as a method to eliminate erroneous data during input or integration was related to ontological differences. The topic of constraints for data integration will be further explored in the REVIGIS project (REVIGIS 2000).

We have sketched a program of a tiered ontology, where different approaches are used on each tier. We follow an empirical approach, and integrate different ways of forming an ontology to achieve a practically useful solution. This tiered ontology clarifies the different types of consistency constraints applicable in databases which attempt to describe the real world. Our experiments so far suggest that computational models for ontology are possible, and that consistency constraints can be integrated in this model in a much more differentiated way than possible previously.

The different tiers separate different types of consistency constraints:

- The limitations imposed by the physical world are restrictions which are observed by all objects. They may, however, be more or less approximated and thus different formulations are possible and it may be necessary to select a less approximated formula. We show here the well-known, but not necessarily relevant, example of addition of relative velocity, comparing the standard Newtonian mechanics with the relativistic formulae using Lorenz transformations.
- Observations are necessarily with some observation error. Consistency does not exclude two measurements as contradicting, as long as the contradiction is within the limits of the measurement error. To collect systematically observations and to reliably integrate them, logical consistency constraints are not sufficient. We have proposed to use measurement-based systems (Buyong *et al.* 1991, Buyong 1992, Haunold *et al.* 1997).
- Socially constructed reality is valid only within a context. The consistency constraints are therefore applicable only for the context and the database must model context. Context may be restricted to single law texts and may have temporal limits in the duration during which a specific form of a law is valid.
- The knowledge collected by cognitive agents is not necessarily consistent. There are numerous examples for people holding contradictory beliefs about the world, often without any negative effects. If the cognitive agent is an organization with sub-agents acting for it, i.e. having employees, then consistency constraints are necessary to assure that the data is collected and represented according to the rules fixed for the agency.

In general, it seems that context should be added to databases. This was suggested by Andreas Reuter in his keynote for EDBT 2000; he was confronted with the problem of constructing a database with the results of biochemical experiments. Communities of researchers hold incompatible views and data is consistent only within such research communities. Consistency constraints—at least the ones concerning socially constructed facts or the ones applicable to knowledge bases—can be represented as beliefs of different agents.

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References

BAIRD, D. G., GERTNER, R. H., and PICKER, R. C., 1994, *Game Theory and the Law* (Cambridge, Mass.: Harvard University Press).

BERGER, P. L., and LUCKMANN, T., 1996, *The Social Construction of Reality* (New York: Doubleday).

BITTNER, S., in preparation, An Agent-based Model of Reality in a Cadastre, Ph.D. thesis, Technical University Vienna, Vienna.

BUYONG, T., 1992, Measurement-based Multi-Purpose Cadastral Systems, Ph.D. thesis, University of Maine, Orono.

BUYONG, T., KUHN, W., and FRANK, A. U., 1991, A conceptual model of measurement-based multipurpose cadastral systems. *Journal of the Urban and Regional Information Systems Association (URISA)*, 3, 35–49.

DAVIS, M. D., 1983, *Game Theory* (Minneola, NY: Dover Publications).

FELLBAUM, C., (editor), 1998, *WordNet: An Electronic Lexical Database* (Cambridge, Mass.: The MIT Press).

FRANK, A., 1983, Datenstrukturen für Landinformationssysteme—Semantische, Topologische und Räumliche Beziehungen in Daten der Geo-Wissenschaften, Ph.D. thesis, ETH Zürich.

FRANK, A. U., 1997, Spatial ontology: A geographical information point of view. In *Spatial and Temporal Reasoning*, edited by O. Stock (Dordrecht: Kluwer Academic Publishers), pp. 135–153.

FRANK, A. U., 2000, Communication with maps: A formalized model. In *Spatial Cognition II (Int. Workshop on Maps and Diagrammatical Representations of the Environment, Hamburg, August 1999)*, Lecture Notes in Artificial Intelligence, edited by C. Freksa, W. Brauer, *et al.* (Berlin Heidelberg: Springer-Verlag), **1849**, pp. 80–99.

FRANK, A. U., in press, *a*, Ontology for spatio-temporal databases. In *Spatiotemporal Databases: The Chorochronos Approach*, Lecture Notes in Computer Science, edited by T. Sellis (Berlin: Springer-Verlag).

FRANK, A. U., in press, *b*, The rationality of epistemology and the rationality of ontology. In *Rationality and Irrrationality, Proceedings of the 23rd International Ludwig Wittgenstein Symposium*, edited by B. Smith and B. Brogaard (Vienna: Hölder-Pichler-Tempsky).

FRASER, J. T., (editor), 1981, *The Voices of Time* (Amherst: The University of Massachusetts Press).

GIBSON, J., 1979, *The Ecological Approach to Visual Perception* (Hillsdale, NJ: Erlbaum).

GOODCHILD, M. F., EGENHOFER, M., FEGEAS, R., and KOTTMANN, C., (editors), 1998, *Interoperating Geographic Information Systems (Proceedings of Interop '97, Santa Barbara, CA)* (Norwell, MA: Kluwer).

GRAY, J., and REUTER, A., 1993, *Transaction Processing: Concepts and Techniques* (San Francisco, CA: Morgan Kaufmann).

GUARINO, N., 1997, Understanding, building, and using ontologies: A commentary to 'Using Explicit Ontologies in KBS Development', by van Heijst, Schreiber, and Wielinga. *International Journal of Human and Computer Studies*, **46**, 293–310.

HAUNOLD, P., GRUMBACH, S., KUPER, G., and LACROIX, Z., 1997, Linear constraints: Geometric objects represented by inequalities. In *Spatial Information Theory—A Theoretical Basis for GIS (International Conference COSIT'97)*, Lecture Notes in Computer Science, edited by S. C. Hirtle and A. U. Frank (Berlin Heidelberg: Springer-Verlag), **1329**, pp. 429–440.

JACKENDOFF, R., 1983, *Semantics and Cognition* (Cambridge, Mass.: MIT Press).

JONES, M. P., 1994, *Qualified Types: Theory and Practice* (Cambridge University Press).

KREYSZIG, E., 1973, *Statistische Methoden und ihre Anwendungen* (Göttingen: Vandenhoeck & Ruprecht).

KUIPERS, B., 1998, A hierarchy of qualitative representations for space. In *Spatial Cognition—*

An Interdisciplinary Approach to Representing and Processing Spatial Knowledge, LNIA 1404, edited by C. Freksa, C. Habel, *et al.* (Berlin Heidelberg: Springer-Verlag), pp. 337–350.

LAKOFF, G., 1988, Cognitive semantics. In *Meaning and Mental Representations*, edited by U. Eco, M. Santambrogio *et al.* (Bloomington: Indiana University Press), pp. 119–154.

LAURINI, R., and MILLERET-RAFFORT, F., 1991, Using integrity constraints for checking consistency of spatial databases. In *Proceedings of the GIS/LIS '91 Proceedings* (ACSM-ASPRS-URISA-AM/FM), pp. 634-642.

LENAT, D. G., GUHA, R. V., PITTMAN, K., PRATT, D., and SHEPHERD, M., 1990, CYC: Toward programs with common sense. *Communications of the ACM*, 33, 30–49.

LÉVI-STRAUSS, C., 1967, *Structural Anthropology* (New York: Basic Books).

LONGLEY, P., GOODCHILD, M., MAGUIRE, D., and RHIND, D., (editors), 1999, *Geographical Information Systems, Volume 1: Principles and Technical Issues; Volume 2: Management Issues and Applications* (New York: John Wiley & Sons).

MARK, D. M., 1993, Toward a theoretical framework for geographic entity types. In *Spatial Information Theory: A Theoretical Basis for GIS COSIT'93*, Lecture Notes in Computer Science, edited by A. U. Frank and I. Campari (Berlin: Springer-Verlag), **716**, pp. 270–283.

MCCARTHY, J., and HAYES, P. J., 1969, Some philosophical problems from the standpoint of artificial intelligence. In *Machine Intelligence 4*, edited by B. Meltzer and D. Michie (Edinburgh: Edinburgh University Press), pp. 463–502.

MEDAK, D., 1999, Lifestyles—A Paradigm for the Description of Spatiotemporal Databases, Ph.D. thesis, Technical University Vienna, Vienna.

MEDAK, D., 2001, Lifestyles. In *Life and Motion of Socio-Economic Units*, edited by A. U. Frank, J. Raper and J.-P. Cheylor (London: Taylor & Francis), pp. 140–153.

MILNER, R., 1978, A theory of type polymorphism in programming. *Journal of Computer and System Sciences*, **17**, 348–375.

MOUNSEY, H., and TOMLINSON, R. F. (editors), 1988, *Building Databases for Global Science—Proceedings of the IGU Global Database Planning Project* (London: Taylor & Francis).

NEUMANN VON, J., and MORGENSTERN, O., 1944, *Theory of Games and Economic Behavior* (Princeton, NJ: Princeton University Press).

OIL, 2001, The Ontology Inference Layer Web Page, http://www.ontoknowledge.org/oil/.

ONTOS, 2001, The Ontos, Inc. Web Page, http://www.ontos.com.

PETERSON, J., HAMMOND, K., AUGUSTSSON, L., BOUTEL, B., BURTON, W., FASEL, J., GORDON, A. D., HUGHES, J., HUDAK, P., JOHNSSON, T., JONES, M., JONES, S. P., ALASTAIR, R., and PHILIP, W., 1996, Report on the functional programming language Haskell, Version 1.3.

PEUQUET, D. J., 1988, Representations of geographic Space: Toward a conceptual synthesis. *Annals of the Association of American Geographers*, **78**, 375–394.

REVIGIS, 2000, The REVIGIS Project Web Page, http://www.cmi.univ-mrs.fr/REVIGIS/.

ROSCH, E., 1973, Natural categories. *Cognitive Psychology*, **4**, 328–350.

ROSCH, E., 1978, Principles of categorization. In *Cognition and Categorization*, edited by E. Rosch and B. B. Lloyd (Hillsdale, NJ: Erlbaum), pp. 27–48.

SEARLE, J. R., 1995, *The Construction of Social Reality* (New York: The Free Press).

SMITH, B., 1995, On drawing lines on a map. In *Spatial Information Theory—A Theoretical Basis for GIS (International Conference COSIT'95)*, edited by A. U. Frank and W. Kuhn (Berlin Heidelberg: Springer-Verlag), pp. 475–484.

SNODGRASS, R. T., 1992, Temporal databases. In *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space* (International Conference of GIS—From Space to Territory), Lecture Notes in Computer Science, No. 639, edited by A. U. Frank, I. Campari, *et al.* (Berlin: Springer-Verlag), pp. 22–64.

STEVENS, S. S., 1946, On the theory of scales of measurement. *Science*, **103**, 677–680.).

WEISS, G., 1999, *Multi-Agent Systems: A Modern Approach to Distributed Artificial Intelligence* (Cambridge, Mass.: The MIT Press).

WINTER, S., and FRANK, A. U., 2000, Topology in raster and vector representation. *GeoInformatica*, **4**, 35–65.

WORBOYS, M. F., 1995, *GIS: A Computing Perspective* (London: Taylor & Francis).

WORBOYS, M. F., 1998, Imprecision in finite resolution spatial data. *GeoInformatica*, **2**, 257–279.

ZADEH, L. A., 1965, Fuzzy sets. *Information and Control*, **8**, 338–353.

ZANIOLO, C., CERI, S., FALOUTSOS, C., SNODGRASS, R. T., SUBRAHMANIAN, V. S., and ZICARI, R., 1997, *Advanced Database Systems* (San Francisco, CA: Morgan Kaufmann).