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Spatial data standards in view of models of space and the functions operating on them

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Abstract

A new architecture for GIS is presented based on a systems view of geographical space as it is popular in geography. Starting with concepts of spatial modelling, current GIS standards are examined for their suitability to support different modelling concepts. A thorough look at GIS functions then leads to a proposal for a classification scheme that not only helps design a software system, but which could also support general teaching of GIS concepts. For proof of concepts, a prototype of the new architecture was developed which finally turned into a geo-data-server product.

Keywords: Geographical models; GIS architectures; GIS functions; Geo-data-server; OpenGIS

1. Introduction

A great diversity of products on the market call themselves geographical information systems (GIS), and there is no single definition to help distinguish between them. With the rapid expansion of the GIS market over the last 10 years, it became apparent that the diversity of terms, notions and functionality in the different GIS has a negative impact on the productive use of GIS: users spend a lot of a project's time learning the particular concepts of a software, and implementation specific details have to be fully understood to assure the quality of the results. But even more dangerous for the future of GIS technology, there are hardly any experts who have a broad view of the whole field of GIS and who can provide a clear framework for project implementation. The labour market consists of specialists in one or the other software and in one or two application domains. As a consequence, a majority of installations only partly fulfil the expectations, data acquired in costly procedures are only used in a suboptimal way and there is a strong dependency of an organisation on the persons who established the GIS database.

Software design has improved with more GIS developers adopting a structured analysis–design–implementation cycle, as proposed by the modern software development methods. Current object-based and object-oriented GIS software packages are an expression of this redesign of the late '80s and early '90s. But the integration of geographical concepts with the GIS software must go further than just a redesign of existing software. A nice shell cannot hide the still apparent mismatch between concepts of spatial sciences with their task on the one hand and the functionality provided by the GIS technology on the other hand.

Because of pressure from customers with heterogeneous GIS environments, and also because the promising forecasts of the early '90s were not fulfilled, GIS software companies finally accepted the need for standardisation of at least the data part of GIS. Other groups, like the OpenGIS Consortium or the ISO Technical Committee 211, want to go even further by

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standardising GIS functions in order to be able to develop interoperable systems.

These standardisation efforts, so far, are still dominated by discussions at a technical level, mainly with the interest to prolong the life of legacy systems. The fundamental discussion on models of space and on user tasks has only started with little echo so far (Gatrell, 1983, 1991; Worboys, 1995, 1996; Albrecht and Kemppainen, 1996). Yet it would be most important as part of the analysis in a full software development life cycle, to look at underlying concepts and how they could be modelled in a computer system.

This paper examines several issues relevant for an integrative analysis of the functionality and architecture of GIS. The guiding principle is to build adequate models of real world phenomena with the help of a computer system. The modelling tools to be provided should be simple for the casual user, but also powerful and flexible. A simple functions classification scheme is presented that takes account of the unique character of geodata, although still being general enough to be integrated with other computer applications. It is assumed that a new architecture, building on universal concepts, increases usability and helps to overcome several of the actual obstacles to the dissemination of GIS technology.

2. Tasks of geographical information systems

Current users of GIS certainly have an idea on what a GIS can be used for. For the dissemination of the GIS technology, however, one should ask potential users about what they are looking for in a geographical computer application, in order to adjust the design to the needs of a much wider user community. By identifying problems in adoption of the technology one can obtain some fundamental design criteria that can help develop GIS software for a wider use. In this study, the quest for these crucial obstacles to technology dissemination was based on the analysis of concepts of geographical science and their comparison with GIS concepts.

Within the application domains of GIS, one can observe a — not necessarily chronological — evolution of thought. It has progressed from a

- data-oriented view through
- analysis and processing to a
- model based approach.

The *data view* sees GIS as an intelligent digital atlas, that can absorb enormous quantities of data about the Earth's surface and produce map output adapted to an actual need. The *analysis and processing view* builds on the digital atlas, but perceives GIS rather as a digital spatial analysis tool kit. The interest is in discovering spatial coincidences and detecting patterns. The *model based view* integrates the concepts of the two previous approaches, namely the storage and processing of geographical data, but this is not the focal point. The basic interest is to create a model or representation of real world phenomena in a computer so that manipulations on that model can be performed to analyse and predict real world behaviour without having to run an experiment in the 1:1 scale. The model based approach clearly goes beyond traditional map usage in planning and decision making. It provides structure and connectivity between the elements of a map (and other non-spatial elements) that allow for an evaluation and simulation of dynamic systems in space. The objects to be handled are not cartographic entities but elements and processes of spatial systems.

The workflow to establish and utilise a model representation extends from *problem perception and analysis*, *model building*, *data collection*, *data structuring* and *input* into the computer system through *query*, *analysis*, *synthesis* and *output* to *interpretation* and *decision making*. Embedded in a decision making process, the GIS is just a part of the solution, namely the one that provides an 'information product' expected to be useful to solve the decision problem at hand. The purpose of GIS in such an environment is to support the user in the tasks of *model building*, *visualisation*, *comparison*, trying to *understand the model*, to *simulate* and to *interpret* the results. This is a much more active role of the computer system that has to act like an advisory expert that 'knows' about the semantics of data and functions.

Not all these tasks need a computer system to be carried out. The strengths of the computer, namely to organise large quantities of data, to treat them and to display them in a graphical form, support the human being in taking better informed decisions. Knapp (1994) identified four tasks for a scientific visualisation software to support spatial scientists: locate, identify, compare and associate. These tasks are mainly related to dealing with a large number of objects in space that need to be visualised and brought into a context to further stimulate thought processes in a human user of the system. The user's duties are then to deduct consequences of what he/she visually analyses and to feed them into optimisation and deliberation procedures, both on the computer and in the mind. The whole process is aimed at distilling information in order to take decisions. Decision making is by far not an isolated exercise. It is integrated into an organisational context. This organisational context determines the emphases from model building to decision making. It acts like a filter through which real world issues are looked at. It is this selective view that makes exchange of geographical data so difficult. There is not a general model of reality but fragments of models that serve a specific purpose. This has to be kept in mind when looking at fundamental models of space and the objects therein.

3. Modelling space

3.1. Spatial phenomena and models

The fundamental question for a model-based approach is how spatial phenomena are described. Current GIS software provides geographical features in the form of points, lines and areas with their respective attributes and symbology information, as well as rasters and related look-up tables, reflecting the data view on GIS. Models of dynamic spatial relations and spatial processes (cf. Takeyama and Couclelis, 1997) cannot be expressed adequately with these tools. For a more comprehensive answer, some modern concepts and models from geography and their comparison with GIS can provide ideas on how to improve the software for a wider use.

Leser (1980) gives a detailed overview of different concepts of perception and description of geographical space and its content. Comparing his outline of the history of geographical concepts with GIS software, it is obvious that the design of GIS largely neglects the conceptual developments of the last fifty years and also the early beginnings of the science with works from Humboldt, Ritter or Goethe (cf. also Harvey, 1996). Despite the intentions of some early designers of GIS, it is only with methodical rigour that holistic descriptions of spatial phenomena can be created in GIS. This is demonstrated by several projects at ITC with the ILWIS system, where a morpho-hydrographic unit is the basis of all deliberation (Meijerink, 1988), or at the University of Basel with the *process-oriented modelling* approach where spatial processes are modelled with an underlying geo-ecosystem model that links parameters by process equations (Huber, 1994).

Geography examines dynamic systems with spatial manifestations in the form of landscapes and 'townscapes'. There is no limit to the phenomena examined in such systems as long as there is relevance of the examined elements for the functioning of the system and the system has a spatial expression. That being satisfied, the description of spatial phenomena should build on the following definition:

> A 3-D section of the Earth's surface is represented as a system, composed of elements and relationships. A spatial phenomenon is an element of a system that has direct or indirect spatial expression in a geographical location.

Such systems are depicted in a qualitative form by graphs composed of storages, flows and regulators. For a quantitative description the following three types of models are commonly used (Baccini and Bader, 1996):

- models derived from primary principles (based on laws of nature);
- phenomenological models (combination of primary principles with empirically established correlation) and
- data models (description of phenomena by means of data).

The term data model here is not to be confused with the same term in computer science. It means describing real world processes by providing data instead of providing formulae. The data model is the most frequently used model type for the description of geographical phenomena. Examples are maps or time series of physical or demographic measurements. The obvious problem with data models is that they are only valid for the observed entities and regions and they cannot be generalised and applied elsewhere. A transfer of a data model is like using a town plan of Barcelona to find a street in Buenos Aires.

Phenomenological models, on the other hand, can be applied in different environments and usually provide valuable results for singular process descriptions. Still they depend on experimental parameters that have to be determined in a field situation. Often, the view of a process is narrow in phenomenological models, so they can only be applied with caution in a spatial context. A well known example of a phenomenological model is the Darcy equation for water movement in the soil. Despite its validity for small homogeneous volumes of soil, this equation will produce unrealistic results in the heterogeneous real world situation of a 10-hectare field. Only if a permeability parameter is determined for each square meter of the field can an approximately correct result be obtained. But this is again a data model with no possibility to be transferred elsewhere. In the spatial context, phenomenological models are closely linked to data models.

The most fundamental type of models, the one based on primary principles, applies also to geographical systems, but seldom appears in a pure form in the systems equations. Either they are implicit in the structure of the system (e.g. by catering for the preservation of the principle that no matter or energy can be lost), or they are used to analyse and verify the other types of models, i.e. the data models and the phenomenological models. It is more of a philosophical question, whether data models are most important in spatial sciences because of the tradition of geography as a descriptive science or whether the nature of the object of geographical studies dictated a descriptive approach.

The extended view of a GIS that models spatial systems includes the regular concepts of representing spatial phenomena in maps. Therefore it can build on existing GIS infrastructure. In addition, new concepts are introduced that intrinsically link spatial objects to form higher level units, called geographical systems, that are closer to an integrative view of spatial phenomena than a map. Going back to the distinction of data, analysis and model based views, the idea of spatial phenomena as a system corresponds to a model based view. The system is a model of the real world that has proven useful in geography and other spatial sciences and one would like to represent it appropriately in GIS. For a new architecture of GIS, the main concern is now in finding additional concepts that have to be supported to allow for a systems approach to modelling.

3.2. Models of space

Let us now look at some fundamental models of space. In cartography, and later on also in the GIS domain, two complementary views of space are established (cf. Couclelis, 1992, Worboys, 1995). The first one considers space as a pre-existent set of locations each of them having a property. This concept can be called the *absolute space*, or, like in cartography, a *continuum*. The second view sees space as inexistent as long as there are no discrete objects present. Space is then defined by the relationship between objects. This concept can be called the *relative space*, and the objects in it represent a *discretum*. To assign a geographical meaning to these concepts of space, it is assumed that they are linked to the surface of the Earth, though they could be treated independently. The discrete view is boundary-oriented, whereas the continuous view is value-oriented. This means that for a discrete object like a house or a land parcel the spatial aspect is determined by its boundary, while in a continuum like altitude or air pressure, the interest is in the value at a given location. There are phenomena that are better modelled with one or the other approach, therefore they are complementing each other.

The two views are complementary in that they can be referenced to each other, but they cannot be converted into each other without losing the original meaning. Probably the best synthesis of the two has been made by Gatrell (1983, 1991), who proposed the definition of space as a relation on a set of objects. On this basis, continuous spatial reference systems were calculated from the properties of relationships between objects. The aim of such an endeavour was to represent space the way it is perceived rather than the way it is measured based on an abstract concept. The fact is that perceived spaces determine much more our spatially relevant behaviour than abstract spaces, as can be seen in studies of mental maps where factors such as the subjective assessment of the security of streets in a town or experiences with traffic jams are more dominant in the choice of itineraries than the pure metric distance. Multidimensional scaling (MDS) is one method to calculate such an adapted spatial context, that is actor and interaction-oriented.

3.3. Elements in space

Having established the discrete and the continuous model of space, the next question is how to represent geographical phenomena in space. In continuous space, the basic distinction is on the location: we need some coordinates to retrieve a value of the continuum and when changing the coordinates, the properties are likely to change also. A second spatial unit is the regularly shaped neighbourhood, i.e. the unit of space through which a location can be brought into a relation with its surroundings. The relation is usually unidirectional from the neighbourhood to the location, where the sum of the characteristics of the neighbourhood is used to qualify the central location. Examples of this are the calculation of slope or curvature of a surface. A third unit of relevance is the region. This is an arbitrarily shaped area, or in other terms, a discrete object of a two-dimensional extent. Unlike the neighbourhood, the region is an object with an own existence, independent of a location in the continuum. Therefore, relations between the location and the region can be in both directions, from the locations to region, defining a spatial aggregation process, and from the region to all the locations within it, defining a space dependent transformation function.

Discrete objects are points, lines and areas as they are supported in most current GIS. A distinction has to be made for areas: they can be dispersed and spatially independent, or they can be space filling, i.e. a given extent of a study area is fully filled with nonoverlapping objects.

The systems view of geographical phenomena requires dynamic objects. According to the classification of Claramunt and Thériault (1996) there are several process types for discrete objects in a dynamic model. Objects may play a role when they appear, disappear, move, transform or diffuse something. The singular object as such is less important than the fact that it takes part in a process. Such an approach asks for the implementation of a process modelling component not currently available in GIS.

When modelling processes in a continuum, the question of discretisation and visualisation arises. A snapshot of a process can be made by determining process units, i.e. area objects in which the process shows homogeneous behaviour (Huber, 1994). To create a more dynamic impression, consecutive process states can be displayed in form of animation sequences or with parametric process descriptions, like vector fields. A major step towards continuous modelling in GIS was made by Takeyama and Couclelis (1997) who introduced the concepts of relational and meta-relational maps to express spatial influence on each location in an independent manner.

The systems approach adds yet another concept, namely, that *relationships* between spatial objects can be modelled and qualified explicitly. This means that a spatial object can be linked to another one of the same or a different type, or a relationship can be established between an object and its neighbouring or underlying continuous space. By this means, the modeller of an application can clearly specify the structure of a system. The enduser, on the other side, can analyse complex issues in an easy but meaningful manner by following the different links within a system. Data elements now appear in a coherent structure that supports the intended meaning of the objects and not in the form of independent layers that are only connected through spatial coincidence. Spatial actions and interactions can now be directly defined and simulated.

Static analysis of spatial phenomena leads to *patterns of distribution* depicting the spatial state of a system. The analysis of the spatial dynamics is by expression of *processes* or *flows*, either in static process units describing areas of homogeneous course of a process or by providing trajectories and quantities of transported matter, energy or more complex system elements. Spatial action and interaction is a concept that goes further than the usual analysis of spatial coincidence. It asks for an analysis of dynamic change. It also leads to another view of GIS functions as will be discussed later.

4. Data models in geodata standards

The dynamic model of geographical phenomena introduced some new elements that are not frequently found in GIS software. Nevertheless, this project tried to build as much as possible on existing data models, so as to be able to use the wealth of existing geographical data. The new features should then be introduced by a support structure similar to the data dictionary in relational database management systems. The information stored in such a support structure on the one hand should provide the necessary background information to the enduser about the features and relationships in the system, although on the other hand it should enable the system to run operations on data automatically.

With this assumption, a particular analysis was undertaken to establish the base geodata model for a new GIS architecture that allows to adequately model spatial systems. The hypothesis for this analysis was that if current geodata standards are examined and compared, the fundamental requirement for a logical data model can be established. This logical data model can then be extended to support spatial systems and their dynamics without compromising past investments in spatial data.

Six standards were examined (cf. Schneider, 1997 for details) with the sole purpose to select for each component of a geodata model the best solution. A ranking was never intended and would obviously not make any sense given the different purposes of the selected standards. The examined standards are the spatial data transfer standard (ANSI, 1995), the content standard for digital geospatial metadata (FGDC, 1994), the geo tag image file format (GeoTIFF) (Ritter and Ruth, 1995), the open geodata interoperability specification (OGIS, 1996), the CEN/TC 287 geographic information standard (CEN/TC 287, 1996) and the Swiss data exchange mechanism for land information systems (Interlis) (Projektleitung RAV, 1991).

4.1. Evaluation criteria

The aim of the analysis was to obtain a complete logical geodata model, comprising all elements that are usually found in such models. After a first analysis of all six standards, the following criteria for the evaluation of a geodata standard were established:

- metadata elements: a data model needs a proper description of the data, both in human and machine readable form;
- description of the spatial reference system: geodata have to be related to the surface of the Earth in an unequivocal manner, therefore, a complete and flexible description of the spatial reference system is required;
- geometry model: there must be suitable geometric primitives to represent spatial objects and continuous fields;
- topology model: there must be a suitable model to express topological relationships between spatial objects;
- modelling capabilities for attributes: there must be a way of describing attributes of spatial objects;
- description of spatial functions: the standard should include functions acting on the data elements;
- coherence of the different elements of the description (metadata, geometry, topology, attributes, etc.): the description of all parts of the model must be coherent so that geometry, attribute, topology and metadata elements for each object are unequivocally linked together;

- data definition language used: data should be describable in a clear, flexible and powerful data definition language;
- modularity of models: data models should be modular so that an already defined model can be included in another one;
- completeness in definition of the terminology: all concepts and terms required for the standard should be completely defined;
- notations: notations used in the standard should be explained appropriately;
- official documentation: the documentation of the standard should be complete, readable and useful for the work with the standard;
- efficiency of modelling: modelling should be efficient by providing productive tools and concepts for reuse of existing models;
- existing software: there should be software that supports the modelling and data transfer defined with a standard; and
- compatibility with other standards: the standard should be able to accommodate other standards.

Only a few of these criteria are specific for geodata while the rest can be similarly applied to other data modelling standardisation efforts. The geographical elements are the spatial reference system, the geometric and the topological models.

4.2. *Appreciation of the selected standards*

Given the purpose of the evaluation, namely to select good portions of different standards to develop a complete geodata model for implementation, it would not be appropriate to present a table comparing the different standards that were explicitly designed for different purposes. Furthermore, some of the standards are not definitively approved, whereas other established ones like SAIF or DIGEST, were not considered in this evaluation. Therefore, the different standards are only briefly commented here, with an emphasis on the strong features of each. A more detailed appreciation can be found in Schneider (1997).

SDTS is a complete and consistent standard for the transfer of spatial data. Because it covers nearly all aspects of geodata, except for interoperability, it is rather complex. The adapted solutions for the covered domains are all well conceived, particularly the geometric and the topological models. SDTS is an open standard that can be extended if necessary. It can also cooperate with other standards like FGDC Metadata and GeoTIFF. The quality of the documentation is high.

The FGDC Metadata standard is a complete standard for metadata about spatial data. It is very intensive in terms of data elements to be provided. In spite of its suitability, for implementation of the Geo Server prototype (Section 5) preference was given to the metadata part of CEN for its higher flexibility.

GeoTIFF is useful and complete for its purpose, i.e. the transfer of geo-referenced raster data. Particularly the spatial reference model of GeoTIFF needs attention: it is based on the specifications of the European Petroleum Survey Group (EPSG, 1995) and provides a gradually more integrated code for different types of coordinate systems.

The OpenGIS abstract specifications were not clear at the time this study was carried out. Some components were well elaborated, such as the modelling process from real world phenomena to a semantic computer model. Other parts were vague and presented in an incoherent manner. The different submissions for implementation models on ODBC, CORBA, OLE/COM and Internet, however, are much more concrete and in some respect even too pragmatic. The interest of the submitters — mainly all large companies in the GIS market — to support legacy systems without major modifications clearly shines through: the OpenGIS technology will allow for transparent access to all kinds of GIS, therefore, in ambiguous questions preference was given to well-known solutions, rather than to innovative ones.

CEN/TC 287 is also still under development. The documents released so far are of high quality and consistentcy. CEN/TC 287 left the best impression overall of the six standards that were examined. Particular strengths are in the domains of geometry, topology, definition of query functions and metadata. EXPRESS, the data definition language chosen by CEN/TC 287 proved to be versatile, even though the original version lacked the geometrical data types required in GIS.

The Swiss Interlis has a strong data description language component. Besides data description, other components were largely neglected as they are not within the scope of Interlis.

5. A prototype of the GEO Server

The Geo Server prototype implements a logical data model with the concepts of geographical features, multiple geometries, reference systems and metadata. A first prototype was made on a relational database, followed by a second prototype as an object-extension to an object relational database. The interface is designed according to the OpenGIS SQL implementation specifications. Data modelling at a conceptual level is covered by the complementary project MADS (Parent et al., 1995), also at the database laboratory of EPFL. For the full spatial modelling tool kit, a systems modelling component is still missing that would allow for the qualification of relationships between geographical features and other elements of the system.

5.1. Design overview

The first Geo Server is a set of generic data models that are instantiated by importing data into the database system. Some fixed tables are required — similar to the data dictionary — where the server can store information to get access to data that is already on the server. All other tables are generated when data is introduced. Fig. 1 gives an overview of the architecture. The second prototype uses a SQL 3 interface with user defined data types and user defined functions. It is more integrated in the DBMS. Though academically interesting, the generic data models were dropped and replaced by more rigid, but also more robust system tables.

5.2. Concepts supported by the GEO Server

The Geo Server supports the following concepts:

- Geographical features: geographical features are atomic entities. Their properties are modelled in the form of attributes.
- Metadata: the Geo Server has a store for information about the data it hosts, their geometric representations and the related spatial reference systems.
- Geometrical representations: geometrical representations of geographical objects can be points, lines, arcs and surfaces in two dimensions.
- Spatial reference: each geometrical object has a spatial reference system associated to it.
- Multiple representation of geographical objects: each geographical object can have multiple geometrical representations in multiple spatial reference systems.

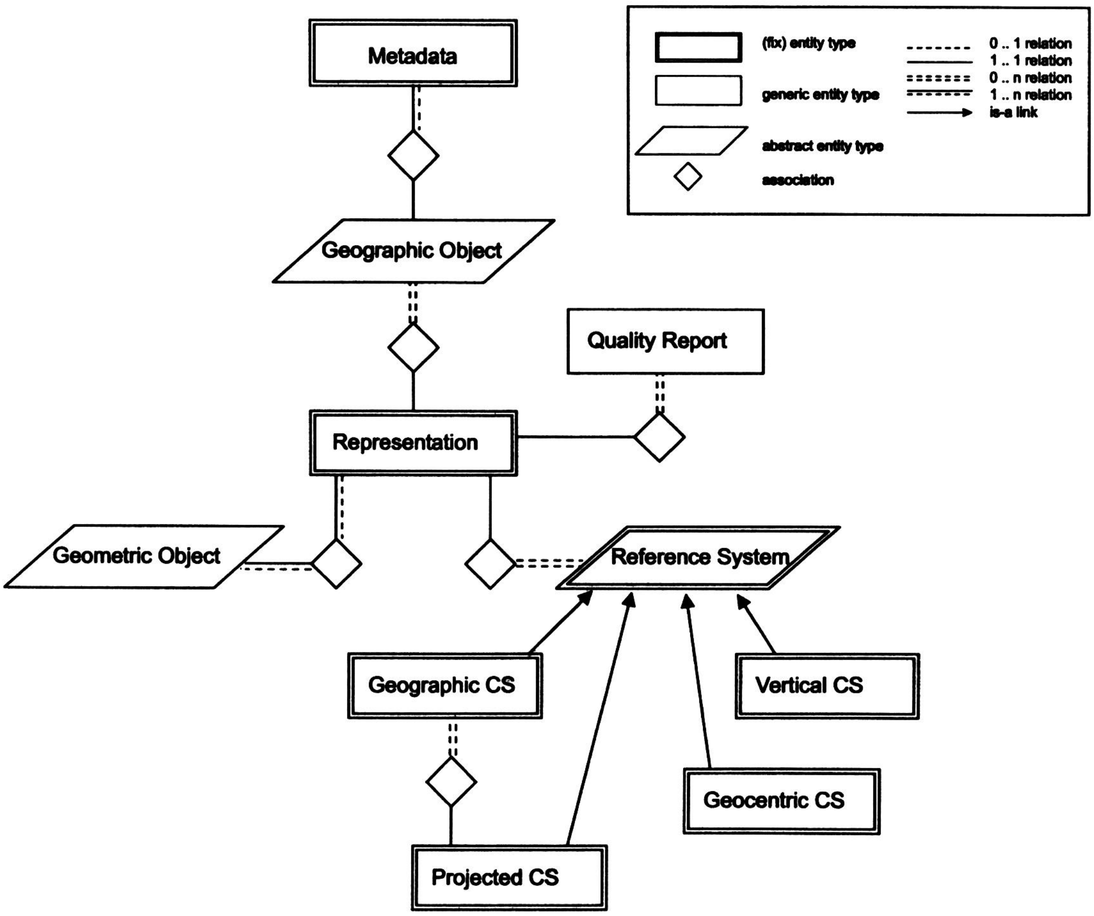

Fig. 1. Simplified data model of first Geo Server prototype.

The first prototype of the Geo Server does not yet support explicit topology, temporal extension and continua. The concepts implemented so far are based on CEN/TC 287 (metadata, geometry, topology and attributes), EPSG (1995) in GeoTIFF (spatial reference system), SDTS (for definitions of geometrical and topological elements) and OpenGIS SQL implementation specifications (type and function interfaces).

The Geo Server is first of all a means to store geographical data in an application independent way on a DBMS. The full benefit of such a new architecture in a client/server environment, however, only reveals, if the server is able to provide GIS functionality. Standardisation of GIS functions is still in its infancy. In order to be able to test the new design, a considerable effort had to be made in the direction of a GIS functions classification.

6. A classification for GIS functions

Few GIS function classifications have been reported in the literature. The topic was neglected probably because of the more fundamental and also more heated debate about data structures. However, the use of information is the first and foremost reason to establish a GIS and the functions are the tools to prepare the data for that use. Dangermond (1983), Berry (1987), Goodchild (1987), Rhind and Green (1988), de Man (1988), Tomlin (1990), Maguire and Dangermond (1991), Burrough (1992), Knapp (1994) and Albrecht (1994, 1996) are some of the prominent publications in this field. These authors used different approaches, so their results are not easily comparable.

To describe a computer processing function, the following criteria can be applied:

- the meaning of the function,
- the objects or models it operates on and
- the type of results it yields.

A semantic classification based on the meaning of a function always remains subjective. Nevertheless, if it is developed in a determined application context, it can considerably support the users of a software, because they can clearly associate the function with a task they want to perform. Classifications according to the objects processed or produced by a function (the signature of the function) are simple and unambiguous. The problem with such an approach is, however, that the resulting classes are far from the users' perception and therefore not easily applicable for the design of user interfaces. Nevertheless, they can provide a first clearly structured analytical framework for classification.

Albrecht (1996) coined the term of *universal GIS functions* as a basic set of GIS functions that is generally applicable on any data structure. Interpreting the term as more application-oriented he also states that these functions could be used to build all but the most exotic applications. Surely, his work is leading in the discussion on GIS function classifications. It would still be interesting to further examine this aspect of universal applicability. There are — particularly among the query functions — functions that apply universally to all spatial situations in all spatial subject matters, for example functions that answer questions like 'what is where?', 'what is next to something?' or 'what is within x km from location y?'. For analysis as well, there are methods that are applied the same way in different application domains, like for instance 'how do two object types overlap in a given area?'. On the other hand, there are functions that are very specific to an application field, such as the calculation of electrical currents in a network of power lines and transformers or the determination of land forms for natural hazard assessment. The enduser is interested in both, the general functions and the specific functions, the first for ad hoc analyses, the latter to be able to perform complicated repetitive tasks in a productive manner. Definitely, these two types of functions are at different levels of complexity. The more universal functions have the character of atomic functions, while the more specific applications are more like integrated tasks. A set of universal atomic GIS functions can probably be defined in the near future. A universal task classification (Calkins and Obermeyer, 1991) can also be developed, but its practical application will need to overcome some obstacles related to concepts and terms of specific application fields. There is no consensus about concepts and terminology in different spatial sciences and, up to now, GIS only added fuel to the fire by introducing own terms and concepts. Adoption of the technology will only improve if concepts can be unified and matched to the concepts of applied science. This will permit the users to stick to their common language whereas introducing more powerful tools and methods.

The elaboration of a task-oriented classification could be approached by creating groups of functions that are common to almost all GIS applications and that help distinguish a GIS from other general domains like statistics, word processing or scientific visualisation. This is the approach followed in this paper. In a top-down approach, GIS functionality is subdivided into general subsystems and specific GIS functions are given as examples for each subsystem to stress on the typical GIS character. These exemplary functions are not all at the same level of complexity, some are really atomic, others are integrated. The aim is to present the functions at a level that is relevant for the tasks a user wants to perform with a GIS. Such a common base for application building in the form of a function classification has a major advantage that, although being specific enough for an application, questions related to geodata handling can still be communicated across application domains, similar to statistics or scientific visualisation.

6.1. Function groups

The classification proposed in this paper divides the GIS into general function groups. These groups represent components or subsystems of the system and as such they have defined interfaces that allow them to be combined with other subsystems to build an application. The main services are model, input, reference, structure, database management, query, edit, analyse and output. These terms are similar to those used in other computer applications, although the specificity

Table 1
Proposal for a classification scheme for GIS functions. The aim of such a classification scheme is universal applicability. Classification criteria for this particular scheme are: division into functioning subsystems, user task orientation and the signature of functions

Function group:	**Model**
Definition:	create a model of real world phenomena within the computer
Interface	
Input:	mental model of a phenomenon to be described and processed by the computer (can be on paper as a formal or informal description)
Output:	data description and data structures in the database management system
Precondition:	data structure for fixed data description data (metadata) that are stored for each phenomenon (i.e. the base installation of the Geo Server)
Postcondition:	generated data structures ready to receive data of the specified type
Members	
Describe object set:	provide general description and build data model for the phenomenon to be modelled using the building blocks, rules and concepts provided by the system
Describe procedure:	predefine sequences of functions that can be applied to an object set
Associate object sets:	define and qualify links between object sets; This is the set of functions, where the definition of interdependencies within a system can be defined; Associations between objects can be expressed as data models, equations or even as sketches where a user can graphically define how two elements influence each other or how a system component develops over time
Function Group:	**Input**
Definition:	data interface through which the system receives concrete descriptions ('data models', cf. Baccini and Bader, 1996) of real world objects
Interface	
Input:	external object descriptions from files, digitiser, scanner etc.
Output:	internal object descriptions in the database
Precondition:	data source in any external form (paper map, aerial photographs, satellite imagery, GPS data, field data); data model for the data to be imported
Postcondition:	populated internal data structures
Members	
From file:	read in a data file from an external transfer format
From digitiser:	run a digitising program and store the data in the respective structures in the database
From scanner:	run a scanning program and store the data in the respective structures in the database
From GPS:	run a GPS recording program and store the data in the respective structures in the database
Function Group:	**reference**
Definition:	build a connection between data and a reference system; These functions are primarily used for data sets that were not collected for geographical evaluation in the first place or that arrived in a raw form from automated or manual data acquisition procedures
Interface	
Input:	data describing objects that can be related to space (may be referenced, unreferenced or even distorted)
Output:	spatial data with a defined reference system
Precondition:	data representing objects or object sets
Postcondition:	data with a defined spatial reference
Members	
Register:	identify locations in the input data and assign locations in the target reference system to them
Transform reference:	transform the input data to the target reference system according to registration
Change projection:	transform the input data to the target reference system according to specified input and output projection systems
By object relationships:	create a spatial reference system based on the relationships between objects (using for example multidimensional scaling, MDS)

Table 2
Proposal for a classification scheme for GIS functions. The aim of such a classification scheme is universal applicability. Classification criteria for this particular scheme are: division into functioning subsystems, user task orientation and the signature of functions

Function group:	Structure
Definition:	translate geometric representation of spatial data from one data structure to another one (this is a hidden function group that can be called by the system when input or output data structures do not match the specification)
Interface	
Input:	data in any data structure
Output:	data in another data structure representing the same phenomena as the input data
Precondition:	existing data
Postcondition:	data in target data structure without loss of coherence in the data model
Members	
Join:	join objects or object sets that represent the same phenomena
Simplify:	reduce the level of detail of the shape of an object
Sliver removal:	remove objects smaller than a specified size or with a particular shape resulting as artefacts of 'analyse' functions
Vector to raster:	translation of vector data to raster data representing the same phenomena (i.e. without changing semantics)
Raster to vector:	translation of raster data to vector data representing the same phenomena
TIN to raster:	translation of TIN (triangulated irregular network) data to raster data representing the same phenomena
Function Group:	**Database management**
Definition:	manage geo-objects in the database and assure a consistent database with permanent, secure and concurrent operating
Interface	
Input:	commands
Output:	none
Precondition:	running database management system
Postcondition:	running database management system with a changed state
Members	
Insert geo-object:	insert the provided object at the specified place into the database
Update geo-object:	change the object description of a specified object according to instructions
Delete geo-object:	delete a specified object from the database
	Other members like commit, rollback, backup and recovery will be required as functions of the underlying database management system; They do not have a particular geographical aspect

will be added with the characteristic GIS functions of each group. Tables 1–5 display the function groups and give some examples of characteristic functions for each group.

This function classification is not elaborated in all its ramifications, and with other criteria, other maybe better classifications could be established. The benefit of classifying GIS function is in structuring the wealth of functionality and thus providing a means to communicate, teach and design GIS more easily.

7. Geo-information, tasks and data usage

This paper sketched out the approach to a new design of GIS with the following goals in mind:

- The use of geo-information should be spread to application domains outside the classical application fields of GIS, therefore, barriers to the use of GIS should be reduced or even eliminated.
- The modelling capabilities of GIS should be oriented towards the modelling requirements of practical geographical applications, where the systems view of spatial phenomena is predominant and several models of space are used besides the Euclidean model.
- Data models underlying the new design should be complete in a way that they can model most of the facets of geodata currently and previously discussed in several standardisation groups. It is hoped that what different standardisation committees have established is representative of the problems encountered to date in geodata modelling.
- Geodata handling should be integrated into the mainstream applications of database management and data analysis. A tight coupling with DBMS technology without adding unnecessary complexity seems to be the preferred approach.

Table 3
Proposal for a classification scheme for GIS functions. The aim of such a classification scheme is universal applicability. Classification criteria for this particular scheme are: division into functioning subsystems, user task orientation and the signature of functions

Function group:	Query
Definition:	extract object entities and their properties from the database according to specified criteria
Interface	
Input:	specification of objects to retrieve
Output:	data describing the objects meeting the specifications
Precondition:	running database management system
Postcondition:	running database management system; active cursor to access the retrieved data
Members	
By attribute:	specify properties of objects to be retrieved
By position:	retrieve all objects found at a specified location
By neighbourhood:	retrieve all objects found in a specified regularly shaped neighbourhood (buffer) of a location or an object
By region:	retrieve all objects found in an arbitrarily shaped region
By topology:	retrieve all objects meeting a specified topological relationship (adjacent, overlap, contain, connected) to a specified object
By subject matter:	retrieve all objects belonging to a specified information layer (similar to query by attribute)
Function Group:	**Edit**
Definition:	change objects' properties in the database
Interface	
Input:	object from the database
Output:	the same object, but with different attributes, shape or position
Precondition:	selected object from the database
Postcondition:	object changed in the database
Members	
Attribute value:	change the value of an attribute of an object
Geometry position:	change the position of an object, move
Geometry shape:	change the shape of an object
Function Group:	**Output**
Definition:	production interface of the system that displays in any form (map, report, transfer file) and on any media (screen, printer, file) the content of a database as specified by the user
Interface	
Input:	specification of the output (data selection, display parameters, format, media)
Output:	display product as specified
Precondition:	database and output device
Postcondition:	output product
Members	
Map composition:	combine objects of the database and layout elements to determine a cartographic image
Display map:	render visible a map on a computer screen
Display report:	render visible a report of data on a computer screen
Print map:	produce a map composition on a printer
Print report:	produce a report of data on a printer
Graphics file output:	produce a graphics file containing the visual part of a map composition
Data file output:	produce a data interchange file containing data of the database in an exchangeable format
Geo-file output:	produce a data interchange file containing full descriptions (schema and properties) of geographical objects in a well defined exchange format
Animate:	rendering of a sequence of process states of a spatial system

Table 4
Proposal for a classification scheme for GIS functions. The aim of such a classification scheme is universal applicability. Classification criteria for this particular scheme are: division into functioning subsystems, user task orientation and the signature of functions

Function Group:	**Analyse**
Definition:	generate objects or object properties by analysis of existing objects; New objects or properties can be stored in the database (generated objects) with the danger of database inconsistency but with a performance advantage; Alternatively, virtual object types can be defined by an analysis recipe and the corresponding objects be created upon request; A distinction can be made between Boolean functions (producing one of the two values 'true' and 'false'), scalar functions (producing a scalar value), geometric functions (generating new geometrical representations), object functions (generating new objects) and continua functions (generating a continuous spatial description)
Interface	
Input:	selected object(s) from the database; analysis command
Output:	new properties, new geometrical representations, new objects or new continua (that could be stored in the database)
Precondition:	selected object(s) from the database
Postcondition:	new property(ies), object(s) or also a new object type(s) in the database or temporarily available as calculated items of a virtual description
Members	
Single object analysis	
Attribute analysis:	group of scalar functions calculating new attributes based on existing attributes of an object (comparable to column functions in SQL); Examples are length, area, perimeter, shape index, but also addition, subtraction, sine, square root etc.
Reclassify:	scalar or object function assigning a new attribute value to an object or creating a new object based on an existing attribute value by means of a look-up table or a scalar function (special case of attribute analysis)
Centroid:	geometric function determining the centroid of an object; Depending on the complexity of the boundary of an object, the centroid can lie inside or outside the boundaries
Buffer:	geometric function determining an equal distance area around an object
Object pair analysis (dyads):	
Position topology:	Boolean function determining characteristics of the relative position of two objects
Logical topology:	Boolean function determining if two objects are logically linked/connected
Distance:	scalar function to calculate different types of distances between object pairs, depending on the metrics of the underlying reference system (geodetic distance, geographic distance, manhattan distance, shortest path along a network, distance in a field of gravity or attraction, etc.)
Azimuth:	scalar function to calculate the bearing between two objects as related to North
Intersection:	geometric or object function to calculate the geometry of intersection between two objects or to generate an object with the intersection geometry
Association:	object function that creates and qualifies an association object between two objects; The geometric representation of an association object can be based on an aggregation or a intersection of the geometries of the objects involved; (An example is a shortest path object between two locations)

- The usability should also be reflected in the functionality provided by the system. Functions should be integrated to that level that is most frequently used across application fields and they should be grouped so as to give the user a useful guidance in performing a task in GIS.
- Information is the product of the work with GIS and therefore should the work with GIS be organised similar to a production process (cf. de Man, 1988). Thus, the processing units should be integrated tasks, rather than atomic functions for several reasons, but mainly to assure reproducibility and an effective production process.

Based on the theoretical framework presented in this paper and on the experience with a first Geo Server prototype, a commercial Geo Server product integrated in an object-relational database management system was developed. Benefits of the new architecture perceived so far are promising, but to achieve the goals of usability, task orientation and systems analysis, there is still a considerable way to go.

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Table 5
Proposal for a classification scheme for GIS functions. The aim of such a classification scheme is universal applicability. Classification criteria for this particular scheme are: division into functioning subsystems, user task orientation and the signature of functions

Object set analysis (set of objects of the same type)	
Spatial statistics:	scalar function determining the dependence of object values on the spatial position of an object (e.g. spatial auto-correlation)
Convex hull:	object function creating a convex hull around a set of objects
Voronoi:	geometric function calculating the area of influence for each object in relation to attribute values and positions of other similar objects
Triangulation:	object function creating a triangulation structure based on position and attributes of a set of objects
Generalise:	geometric function determining the geometric representation of objects in relation to a map scale and to other objects within the map; This operation is particularly problematic if results are stored in the database; It calculates new geometrical representations in dependence of a selected set of objects
Network:	object function generating a network object from selected objects and their relationships of connectivity
Distribution:	continua function calculating the spatial distribution of objects in terms of number of objects per spatial unit
Interpolate:	continua function (also a rendering function) that calculates probable object values in-between the objects of an object set; The interpolated values depend on position and attribute values of the objects, a selection function that determines which objects to consider for a given location and an interpolation function that determines an interpolated value based on the selected neighbouring objects
Object sets analysis (sets of objects of different types)	
Multivariate statistics	(correlation, contingency, etc.): scalar and continua functions yielding indices of relationship between object sets
Intersection:	object function generating intersection objects between sets of objects
Multicriteria analysis:	continua function indicating the suitability of a location based on objects (and continua) and their attributes
Continua analysis:	
Attribute analysis:	group of scalar functions calculating new attributes based on continua attributes of a location; This group of operations can be combined with the attribute analysis of singular objects; Distinction is only made because of the different input types
Reclassify:	object function creating new objects for areas of the continuum where values are within a specified range
Profile:	scalar function extracting values from the continuum for the location(s) of a discrete object
Catchment area:	object function calculating the area where processes are originating for a given object depending on configuration of objects, flow on a surface or visibility
Flow lines:	object function determining ways of most probable movement of objects on a surface
Feature recognition:	group of object functions extracting objects from a continua; Examples are unsupervised classification like cluster analysis, supervised classification like maximum likelihood or model based classification like process area determination
Change detection:	continua function determining degree of change from one stage to another one
Surface analysis (gradient and other derivatives):	set of continua functions calculating surface characteristics like gradient, aspect, absolute curvature, horizontal curvature, profile curvature, shading, etc. of a continuum
Dynamical analysis:	
Process analysis:	continua function determining the effects of a process in space
Simulate system:	evaluation over time of relationships of a spatial system as defined in the system model and instantiated by the data in the database; The output is of arbitrary type depending on the interest of the user in one or the other parameter of the system

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