Geographical Information Engineering in the 21st Century

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Abstract

This paper discusses the challenges facing GIS designers in the 21st century. We argue that GI engineers lack a sound theoretical basis that would allow them to make best use of new technologies that handle geospatial data. Considering three important topics for the new generations of GIS (change, semantics, and cognition) we show that GIS theory is in a state of flux. Thus, researchers and engineers need to cooperate more for the new generation of GIS to be built in the best possible way.

1 Introduction

Although the term 'geographical information science' (*GIScience*) is well-established in the scientific literature, the idea of geographical information engineering (*GIEngineering*) has received much less attention by both

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researchers and practitioners. The idea of GIS (Geographical Information System) dates from Roger Tomlinson's pioneering work in the 1960s (Tomlinson 1972). The term 'Geographic Information Science' stems from the early 1990s (Goodchild 1992b), labelling a field that had developed in the 1970s and 1980s because of the need of the scientific foundation to further advance spatial information handling. The existence and evolution of GIS has motivated a significant part of the research agenda for GIScience. In the 1980s and early 1990s, there were papers describing the design of a GIS (Morehouse 1992; Herring 1992). As the discipline of GIScience evolved in the 1990s and early 21st century, there is a limited amount of published research on how GIScience has influenced the design and evolution of GIS technology. This is surprising, considering the widespread use of GIS technology that helped to promote GIScience as a scientific discipline.

During the 1980s and 1990s, the scientific results produced by researchers in this area helped to set up the current billion dollar industry of Geographical Information Systems (GIS). GIS is now regularly being used as a corporate tool to manage large geospatial databases, and as a research tool for understanding our environment. However, almost all current GIS applications use static data, which represent temporal information and information on change too simply, if at all. The new generation of GIS, called GIS-21 (or "GIS for the 21st century") will be different from GIS-20 (or "GIS for the 20th century"), thanks to scientific and technological advances. These advances include the distributed spatial processing on the Web and a new generation of mobile devices and remote sensors.

Ideally, there would be a stable corpus of scientific knowledge that would be the basis for the GI engineer's practice. Currently, such corpus exists only for GIS-20, mostly in the form of the OGC standards. *What about GIS-21, which will use new technologies like constellations of earth observation satellites, sensor networks, and mobile devices?* Based on the authors' experience on both sides of the trenches (research and technology), we consider GI engineers lack a sound theoretical basis that would allow them to make best use of these technologies. This paper aims to show why this happens, and how the GIScience and GIEngineering communities could cooperate to build reliable products that are also innovative.

In this light, this paper considers some questions: "*In what ways does GIS-21 differ from GIS-20? What would GI engineers need to know to build GIS-21? Is the relevant scientific knowledge organized and stable? How could GIscientists and GIEngineers cooperate?*" In what follows, we provide our views on these topics. We are aware that a full response would be hard. However, we consider that providing partial guidance and insights based on experience is useful for both communities.

2 From GIS-20 to GIS-21

We define geographical information engineering as "*The discipline of systematic construction of geographical information systems and associated technology, drawing on scientific principles. It also includes adapting existing technology to fit user and societal needs and the technical, legal and economic evaluation of GIS technology*". This definition highlights the crucial role of the scientific principles as a basis for sound engineering. But there is a fundamental difference in the scientist and the engineers' approach. Fred Brooks says that "*the scientist builds in order to study; the engineer studies in order to build*" (Brooks Jr. 1996). A good engineer studies the literature and chooses which scientific principles are relevant for his task. Following his advice, it is important the GI engineer gains a critical understanding of the science produced in his field.

How does Brooks' view apply to geographical information systems? To answer this question, we need to consider how hard it is to set up the scientific basis for a GIS. To start, consider defining a "geographical information system". In the 1980s and 1990s, a GIS was a stand-alone system that provided methods for input, storage, processing and display of geospatial data. In the 2000s, the technology was extended to corporative systems that support multiple users with a spatial database. Use of the Internet further broadened the technology, by allowing building of web-based visualisation and processing tools. The new generation of mobile devices allows geospatial data to be accessible almost anywhere. Thus, any information system that integrates, stores, edits, analyzes, shares, and displays geospatial data can be considered as a 'GIS'.

Although the ways of using geospatial data are multiple, there is a common basis for all different types of GIS. It is here the centuries-old tradition of cartography that comes to rescue. We have grown familiar with the abstractions involved in map-making which include a two-dimensional projection of the earth's surface and assigning boundaries. Thus, setting up the scientific principles for dealing with 2D static data was relatively straightforward. An early landmark was the *Harvard Papers on Geographical Information Systems* (Dutton 1978). Next, came Egenhofer's work on topological spatial relations (Egenhofer and Franzosa 1991), Couclelis' discussion of field and object models (Couclelis 1992), and Goodchild's work on spatial data modelling (Goodchild 1992a). Frank and Egenhofer showed how object-oriented GIS would work (Egenhofer and Frank 1992). Their work had an immediate influence on the design of SPRING (Câmara et al. 1996), a free GIS that has a large user base. Later, other products such as ArcGIS adopted the object-oriented model.

This sound scientific basis on issues of 2D data structures, modelling and display enabled a generation of GIS technology to emerge, most of them sharing similar design principles. This led to the establishment of standards on the field, an effort led by the Open Geospatial Consortium. GI engineers that develop GIS-20 products benefit from the substantial intellectual effort that went into setting up the OGC standards.

No such comfortable solution exists for GIS-21, where new technologies are a major force. Take the Internet. The abstractions encapsulated in OGC's Web standards (WMS, WCS, WFS, WPS) deal mostly with a non-cooperative environment. Using OGC's standards, users have access to information produced by others, mostly for visualization. The user is thus a passive consumer of information produced elsewhere. However, emerging Web applications emphasize cooperation and interaction. Using social networks in the Internet, GI engineers will build collaborative systems that go beyond the simple OGC abstractions.

Consider also geosensors, which provide a 'virtual' connection with the environment, and allow new approaches to the study of environmental processes. These new sources of information were not available earlier due to high cost of measurement or to inaccessibility for analysts. Current OGC standards associated with geosensors focus on low-level communication and issues such as fault tolerance, reliability, and scalability. These standards do not consider how to transform sensor data into information for monitoring the environment. This transformation will need the capacity to model the processes measured by sensor networks. GIS-21 systems need to move from low-level details to high-level domain conceptualizations about change.

Remote sensing images provide a further source of new data for understanding our environment. The new generation of remote sensing satellites already launched or planned for the next decade will provide much new data. Consider land imaging. Most images of the Earth's land surface come from a single source: the LANDSAT series of satellites. LANDSAT covers the Earth every 16 days with 30 meter resolution. From 2010 onwards, there will be a constellation of land imaging satellites, providing free moderate resolution (20-50 meter) images every two days for the whole planet. There will be many high-resolution satellites (2 meter resolution or better) that will provide frequent detailed information. This deluge of remote sensing data will allow new image analysis techniques. An environmental GIS-21 should be able to *search for changes* in a sequence of remote sensing images instead of the current *search for content* on a single image (Câmara et al. 2001). The emphasis should not be placed on simple *image classification* procedures, but on *capturing dynamics* over the landscape. Using multitemporal remote sensing data, GIS-21 tools should be able to describe the change trajectories at local and regional scales.

Thus, the relatively comfortable situation in the 1990s, where a shared conceptualization of GIS helped both designers and users to develop similar products, no longer holds. There is no longer a ‘typical GIS’. The new scientific and technological challenges created a new set of essential difficulties for the new generation of GIS. These challenges include modelling the semantics of communication of spatial concepts, understanding change in space and time, and developing information extraction methods for massive data sources. These problems are hard, and will remain so.

3 Change, Cognition, and Semantics: Three Critical Issues

As discussed above, GIS have evolved from automated mapping applications to a set of technologies concerned with information about processes in the human environment. To grasp the full extent of the difference between GIS-21 and GIS-20 we will consider three critical issues for GIS-21 applications that were mostly absent of GIS-20 designs. These are *change, semantics, and cognition*. In this section, we will give an outline of the main research challenges in these areas. In the next section, we will focus on the GIEngineering challenges for modelling change in more detail.

3.1 Change

Representing change in GIS-21 is not only an issue of handling time-varying data. It also concerns how objects acquire or lose their identity, how their properties change, what changes happen simultaneously, and what the laws of nature and the interactions among people that bring about change. Time can be viewed as an independent entity of the universe, a dimension in which events occur in sequence. That is the view subscribed by Newton and used in the tradition of experimental physics. A second view is to consider time as an intellectual structure within which humans sequence and compare events. This second view is the tradition of Leibniz and Kant. These two opposing views lead to the controversy in the philosophy of time over whether extension in time is analogous to extension in space, the so-called 3D/4D controversy. For a further philosophical discussion of spatio-temporal concepts, see Grenon and Smith (2003), Galton (2004) and Frank (2003).

Given the unsolved 3D/4D controversy, when a GI engineer has to design of a GIS that deals with change, he faces difficult choices. The first and most difficult question is: “*How can a GIS represent change?*” The engineer’s practical answer is “*it depends on the nature of the data*”. We consider the following broad choices.

For applications that involve moving objects, such as transportation, location-based, and or animal-tracking systems, there are some basic decisions about what details and constraints are to be represented. For autonomous objects on well-defined path (such as roads), we can use the ideas of *trajectory* and associated operations, along the lines proposed by Güting and Schneider (2005). In this case, change is stored implicitly in the objects' position. Applications whose concepts draw on Hägerstrand's "time geography" (1967) involve modelling personal choices (Miller 2003).

Cadastral applications need a different approach, as they undergo incremental change (as when a parcel is divided). Change is both a property of each object and the result of actions in these objects from external forces. A GIS-21 for cadastral applications should be able to capture both (a) the geographical entities subject to change and (b) the *goals* associated to the causes that cause these entities to change. A good starting point for the GI engineer of cadastral applications is the bitemporal spatial model of Worboys (1994) and Medak's model of lifestyles (2001). These models can be extended into a set of spatio-temporal types (Bittencourt et al. 2007). A more complete alternative is to use the event calculus proposed by Worboys (2005) to develop an application that would include both objects and events as primitives. Events (*occurrents*) correspond to the procedures that perform changes in objects (*perdurants*). Event modelling requires setting up the constraints, conditions, and operations that set off object evolution.

Environmental applications pose a different challenge for the GI engineer. Humanity is changing the rural and urban landscapes at an unprecedented pace, and human transformations of ecosystems and landscapes are the largest source of change in the natural systems on earth. GIS-21 should provide a computing environment for modelling human-environment interactions in ways that can be understood by practitioners from different disciplines. It should provide good information extraction tools from remote sensing images and from geosensors. For example, a remote sensing image is a measurement that captures snapshots of change trajectories. An environmental GIS-21 should be able to *search for changes* instead of the *search for content*. The emphasis should not be placed on simple *object matching and identification* procedures, but on *capturing dynamics* over the landscape (Silva et al. 2005).

In resume, finding a unique theory of spatio-temporal models and operators is an arguably unsolvable problem. This irremovable complexity is a direct result of the ambiguity when defining 'time'. The GI engineer who wants to represent change needs first to define the needs and constrains of his application and then choose a suitable approach, from the many available scientific proposals.

3.2 Semantics

We start to build a GIS by recognising objects in the real world and assigning geographical locations to them. This means that any GIS includes much semantics, a fact neglected until recently. Recognizing how important semantics is for interoperability and for intelligent GIS, some researchers proposed that GIS should be ontology-driven (Fonseca et al. 2002). Semantics also motivated institutions to build spatial ontologies. However, the applicability of such large ontologies remains limited and is mostly useful as means of documentation. Using ontologies for interoperability remains a difficult task, since the matching problem is hard to solve.

For a GI engineer, the most useful results in this area are insights into the problem of spatial semantics. These insights direct an engineer to build representations and interfaces that are more precise in their definition. A useful work is the distinction between continuants and occurrents on a spatio-temporal ontology, the so-called SNAP-SPAN ontology (Grenon and Smith 2003). Also useful is Frank's idea of 'tiers of ontology' (2001). He shows there are different levels of abstraction in a GIS. Frank's approach is relevant to GIE, since he takes a practical approach. Using this approach to build a GIS, the GI engineer would first select which tiers of ontology he will focus. For example, a remote sensing image processing software would transform between data on Frank's tier 1 (*observations of physical world*) to data on tier 2 (*objects with properties*). This is a possible way for building GIS that use semantic properties, even in a limited extent.

3.3 Cognition

Spatial cognition concerns the study of knowledge and beliefs about spatial properties of objects and events in the world (Montello 2001). The field is intensely multidisciplinary, with contributions from linguistics (Lakoff and Johnson 1980), psychology (Tversky 1993), and computer science (Freksa 1991; Krieg-Brückner and Shi 2006). GIScientists have been studying spatial cognition since the early 1990s, stressing issues such as navigation and wayfinding, spatial communication via language, and cognitive maps. Their research highlights how important cognition is for human use of space (Mark and Frank 1991).

From a GI engineer's viewpoint, new mobile devices with navigation possibilities have opened a big opportunity for GIS-21 applications. They range from map-based navigation systems in cars and mobile phone to intelligent transport applications. In the long-term view of transportation, different modalities (train, bus, car) would be linked. The user would be guided to the most efficient one based on his plans, route congestion, and environmental preservation. The main drawback for the engineer's design is the absence of proven formal models for spatial cognition. Arguably, achieving a formal approach to cognition would be akin to solving the problem of consciousness (Searle 1997). The sheer complexity and variety of processes that interact in spatial cognition prevents a formal approach from being sufficient as a unique basis for sound GI engineering. In other words, engineers use good formal models plus a fair amount of hacking.

Early efforts on spatial cognition stressed image schemata and linguistic issues (Mark and Frank 1991; Kuhn and Frank 1991) and on human-centered views of space, described as "naïve geography" (Egenhofer and Mark 1995). Such research revealed many insights, but no comprehensive theory emerged. The main drawback for the GI engineer's planning to use results from spatial cognition in his tools is the scarcity of proven formal models.

Formal models exist only in a limited number of cases. Frank's papers on qualitative spatial relations (Frank 1996) show that it is possible to define cardinal directions with predicate calculus and relations. However, as Frank notes in a recent work (Frank 2007) one of the main challenges in spatial cognition is the intricacy of the formal models that describe even problems of limited scope. The sheer complexity of spatial cognition prevents a formal approach from being a basis for sound engineering. Nevertheless, the GI engineer can gather many interesting ideas for practical applications from works such as (Golledge 1999) and (Egenhofer and Golledge 1998). The discussions on "query-by-sketch" (Egenhofer 1997) are also noteworthy of this practical view.

4 Building New Tools to Model Change: An Engineering View

The previous section shows the theory on critical issues related to GIS-21 is still in flux. But we must move forward. Thus, in this section, we consider a concrete case: considering what we know today, how do we design a GIS-21 application to model environmental change?

This section describes briefly the major decisions on the design of TerraME, a tool for making models that combine society and nature (Carneiro 2006). Modelling the relations between the social and the natural environments is a hard task. It involves collecting data, building up a conceptual approach, implementing, simulating, calibrating, validating, and perhaps repeating one or more steps again. There is no proven scientific paradigm for human-environmental modelling. Different approaches exist in the literature, such as statistical modelling and agent-based modelling. After considering what is there, TerraME designers decided to be as flexible as possible and to use sound advice whenever available. They made the following choices:

1. *Using a programming environment that supports higher-level functions*: As Andrew Frank has shown, generic higher-order functions are necessary for sound GIS type definitions (Frank 1999). Frank also argues that *functional programming* is a good basis for formal modelling of spatial data (Frank and Kuhn 1995). Following his advice, TerraME uses Lua, an open-source extensible scripting language that is simple and expressive (Ierusalimschy 1996). Lua's important advantage from other existing scripting languages (such as Phyton and Perl) is its support for functional programming and higher-order functions.
2. *Requiring Spatio-Temporal Database support*: TerraME has an interface to the TerraLib database environment. TerraLib provides many functions that are not part of the OGC standards, such as support for raster and spatio-temporal data (Câmara et al. 2008). TerraLib's spatio-temporal database design has been inspired by the ideas of Güting and co-authors (Güting and Schneider 2005; Güting et al. 2003).
3. *Designing a Nested-CA model*: TerraME uses a flexible, policy-free approach. Rather than choosing a single modelling technique (such as statistics or agent-based approach), TerraME provides a set of "building blocks" for model development. These "building blocks" include the ability to specify the spatial, temporal, and analytical components of the model separately. Thus, a large variety of approaches (and their combinations) can be expressed in TerraME.

5 A Problem and a Possible GIEngineering Solution: A Global Forest Information System

In this section, we briefly describe a challenging problem for GIEngineering and outline a possible solution that considers some of the issues raised in Section 3. We consider the problem of setting up a Global Forest Information System (GFIS), designed to enable knowledge sharing about forests. Its motivation is preserving the world's rain forests, one of the major environmental challenges of our generation. Rain forests are home to most the world's biodiversity, and play a major role in climate regulation and in the hydrological cycle.

Despite their richness and their ecological services, large areas of the world's rain forests are under increasing pressure of deforestation caused by human action. However, there is much doubt about the extent of worldwide deforestation (Kintisch 2007). Ideally, all rainforest nations should produce detailed estimates and publish them on the Web, so there could be independent confirmations and concerted action. In practice, capacities differ substantially. Currently, Brazil is the only country that publishes detailed wall-to-wall maps of deforested areas in the Internet. Thus, a Global Forest Information System could help, by providing a web-based and cooperative approach that would allow countries, international organizations, NGOs and private companies to find, share, and produce information on the world's rain forests.

Designing a Global Forest Information System is a typical GIS-21 task. It needs a combination of tools that allow *reasoning about change*, provide *semantic information about the rain forests*, and *support cognitive navigation* over the world's tropical belt. The proposed GFIS design uses the Digital Earth metaphor, where geographical location is the common denominator. Diverse content such as satellite images, spatial data infrastructures, geobrowsers, research data, laws and policies, and citizen-provided information could be indexed, searched, discovered, and used by any interested parties. GFIS would enable people to interact based on their specific talents, interests, and experience. Thus, the GI engineer in charge of developing GFIS would need to adapt Web-based tools and techniques, such as social networking, content management, and mapping to the Digital Earth context. Fig. 1 presents this vision schematically.

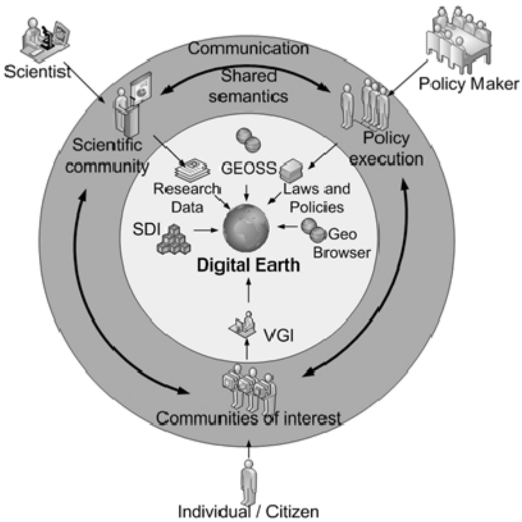

Fig. 1. The Global Forest Information System as a Digital Earth metaphor.

People and scientists from various disciplines often have multiple, and sometimes inconsistent, views on reality. This multiplicity brings a challenge for modelling. For instance, understanding deforestation requires a view of the problem from different perspectives: those of environmental experts, of policy makers, and of the common citizens. Each of them uses specific concepts, and treats problems and observations in different geographic scales, time granularities, and semantic categories. Thus, we propose the GFIS interface has three panels (see Fig. 2): a semantic representation view, a geographic information view and a document view. On the right-hand panel (documents), the application provides means to disseminate scientific data, laws and policies, and historical (baseline) data. On the central panel, we envisage geographic information (GI) as the glue among all other kinds of information. GI can be used to link scientific data and models to laws and policies, to blogs and independent reports. This way, GI might be able to connect information resources in unexpected and innovative ways. Navigation in the central panel should also consider multiple temporal and spatial scales. The user could have a global world view of a given year, or a local view of multi-temporal change.

On the left-hand panel (semantics), the application should also provide ways to improve understanding of rainforest conservation and monitoring. The user would be able to see the geographic information, browse documents related to it, and highlight main concepts. By navigating through these concepts, the user might ultimately learn about methods, expressed as workflows, which in turn link to executable models. Workflows are effective ways of communicating information about a data processing procedure. Using workflows would be a useful way for GFIS to show the differences between the different data processing tools it provides.

Fig. 2. Vision: GlobalForest would enable multiple perspectives.

By supporting multiple perspectives, GFIS would work a ‘learning space’ about the world’s rain forests. Navigation in the central panel triggers change in the left panel (semantics) and right panel (documents). Consider that a user would navigate to the Brazilian Amazonia. The central panel would allow him to find different types of geospatial data about his region of interest. Using the semantic panel, he would select a topic of interest (e.g., manatee habitats) and the documents of the right panel would be automatically chosen to match the spatial region and the semantic topic. He could also select a model of manatee growth cycle from the semantic interface, run this model in the visualization interface, publish the information in the document interface and compare his results with those of other researchers.

Using GFIS, a developing nation could produce information about their rain forest. First, its specialists would look at the results and methods used by other countries that have similar characteristics. Data necessary for the inventory would be retrieved from the GFIS database. GFIS would offer the computer infrastructure to run the chosen methods remotely. Local researchers could interact with other experts using GFIS learning space, checking and improving the accuracy of their results. The results would be loaded back to GFIS' learning space. This would encourage neighbouring countries to use GFIS to do their national inventories. It will also increase the awareness of the problem in that region and support continuous monitoring.

6 Final Remarks: GI Engineers and GI Scientists Need to Cooperate

The preceding sections showed that much research is needed and, for GIS-21 tools, remains on a state of flux. Building the GIS-21 generation will be a tough job. The established paradigm of "mapping, spatial query and visualization" (used for 2D static data) does no longer capture the essence of the information. New technologies such as mobile sensors and new challenges such as modelling global environmental change need innovative solutions, directly tailored for the problem in question. GI engineers will not find references that provide a consistent and stable corpus of knowledge that allows them to concentrate on the technological challenges. This should be a cause for concern by both sides. GIScience will always be technologically motivated. Scientists use new tools as a source of inspiration for the next challenges. Should this innovation cycle slow down, then both sides stand to lose.

For the GI engineer, there is a lot to learn from the GIScience literature. For example, Andrew Frank's works are useful references for the GI engineer. His approach combines rigorous methods with a practical viewpoint, which are the typical tools of good engineering. However, it is unrealistic to expect the GI engineer to find his way through the hundreds of papers of GIScience. The GI engineer will find no straightforward scientific solutions to tough problems in areas such as spatial cognition, semantics and change modelling. Addressing this challenge goes beyond the engineers' typical capabilities. It is up to the scientists to face the problem and to promote synthesis efforts that could help to build a stable basis for GIS-21.

Thus, the GIScience research agenda should consider the needs of the GI engineers of the 21st Century. Scientists need to develop GIEngineering into a field of research and teach it as a discipline. There should be a concerted effort to look at the current GIScience literature and identify those topics, which are relevant. By considering both directions of scientific-technological connection in spatial information, researchers and practitioners will both benefit from an increased dialogue.

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