Core concepts of spatial information for transdisciplinary research

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Geographic information science is coming out of its niche behind the systems, in order to contribute to transdisciplinary research. To succeed, this move requires a conceptual consensus on what spatial information is and how it can be used. The article proposes a set of ten core concepts of spatial information, intended to be meaningful to scientists who are not specialists of spatial information: location, neighbourhood, field, object, network, event, granularity, accuracy, meaning, and value. Each concept is briefly characterized by the questions it helps answer and the roles it plays across disciplines and scales. The need to map between different uses of the concepts is identified as a major research challenge.

Keywords: trandisciplinarity; spatiality; core concepts of spatial information.

Introduction

Two decades after Michael Goodchild's call for a *science behind the systems* (Goodchild 1992), geographic information science faces an even larger opportunity: to contribute its expertise through transdisciplinary approaches to the major challenges of humanity. Consider biodiversity, climate change, cultural heritage, debt, energy, water, natural hazards, health, poverty, or security – spatial information at global, regional, and local scales is essential for addressing each of these challenges. They all require a better understanding of, and better decisions about, the location and interaction of things in space and time.

Transdisciplinary research is characterized by addressing problems that are "not confined by the boundaries of a single disciplinary framework" (Wickson et al. 2006) and seeking knowledge about how to solve them by integrating multiple disciplines in the context of deciding on social policies. Transdisciplinary approaches are often based on profoundly spatial notions, for instance risk or sustainability. Increasingly, they also use spatially explicit models, at multiple scales, of phenomena like carbon emissions or genetic variation.

A showcase for the successful use of spatial information across disciplines and scales is deforestation monitoring in the Amazon (Aguiar et al. 2007). Combining satellite imagery with ground sensor measurements and socio-economic data in spatial models and time series produces deforestation patterns. Presenting these to farmers, decision makers, law enforcement organizations, and citizens at annual, quarterly, and even daily intervals has helped reduce the depletion rate of our planet's lungs dramatically, while also revealing some alarming fluctuations[1].

The point of this example is that spatial information ties together scientific disciplines and societal stakeholders in policy decisions. The common focus on the spatial and temporal aspects of a phenomenon (the Amazon and the processes acting on it) prevails over disparate interests and unifies different perspectives. Massive supplies of sensor data, obtained remotely and *in situ*, cover now large parts of the world at multiple granularities. Increasingly, they are becoming available in open access form. This data “deluge” (Bell et al. 2009) creates tremendous opportunities for integrating the partial views of disciplines and stakeholders, striving for a more comprehensive understanding of phenomena in space and time.

Transdisciplinary uses of spatial information require seeing it as an enabler for societal problem solving across disciplinary boundaries, more so than as the subject of a discipline of its own. The achievements of geographic information science (Goodchild 2010) enable it now to support scientists of many disciplines in understanding and exploiting spatiality in their theories and models (Janelle & Goodchild 2011). Seeking

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[1] http://www.economist.com/blogs/dailychart/2011/05/deforestation

solutions to problems faced by humanity is certainly no lesser goal than seeking better theories about spatial information.

Yet, linguists, economists or biologists interested in forming or testing a spatial hypothesis have to dig into GIS manuals, spatial analysis libraries, and OGC or ISO standards, even just to find out whether a spatial perspective may be useful for their purposes. To support them better, a set of concepts is needed that connects spatial data and analyses to problems within and across disciplines. This set should involve spatial concepts, but also *information* concepts (for example, granularity or meaning), which have an equally strong influence on spatial hypotheses and analyses.

A growing number of projects[2] suggest that a conceptual view of spatial information has the potential to contribute broadly to the understanding of environmental, social, and cognitive processes. Theory building, in a “spatial turn” of any discipline, requires a foundation in concepts of spatial information. The list of “foundation concepts in spatial thinking” proposed in (Janelle & Goodchild 2011) was the first comprehensive and synthesizing attempt at capturing spatial thinking in a small set of concepts without disciplinary, mathematical, or technological biases. It is similar to the list proposed here, but emphasizes spatial thinking rather than spatial information and its properties. In practice, the latter aspect results in the inclusion of (non-spatial) “information concepts” like meaning and value in this work.

The work presented here attempts to cut across disciplinary and technological boundaries, by defining a set of *core concepts of spatial information,* intended to support a broader use of spatial information in science and society. It highlights the fact that such concepts are human constructions, varying from domain to domain, and

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[2] Some examples with a variety of goals are http://www.csiss.org, http://spatial.ucsb.edu, http://www.teachspatial.org, http://spatiallearning.org, http://www.le.ac.uk/gg/splint, http://uspatial.umn.edu, http://spatial.uni-muenster.de, http://spatial.linkedscience.org.

requiring mappings across disciplines. Therefore, the set of core concepts only represents a first step toward an effective support for transdisciplinary work, preparing further research on conceptual mappings.

The article describes the integrative function of spatial information in section 2 and defines its use of some basic terms in section 3, before discussing the criteria for choosing and the choice of core concepts in sections 4 and 5, concluding with an outlook in section 6. Given the setting of this special issue, the discussion addresses geographic information specialists, targeting further collaborative theory building before exposing the concepts to other disciplines in future work.

Spatial Information as an Integrator

The information needed for transdisciplinary research is typically distributed over a vast range of domains, formats, and languages, reflecting the many different perspectives to be considered. One of the most powerful information integrators across such information silos is a spatial and temporal reference (Janowicz 2010), either implicit (for example, by referring to events or persons) or explicit (for example, through place names or coordinates). So far, this property of spatial information has mainly been exploited technologically, through attempts at broadening the use of GIS and related technologies, but not conceptually, asking what concepts support information integration.

Existing Attempts at Transdisciplinary Integration

Research and development around geographic information science have been trying for almost two decades to integrate spatial information into mainstream information technology as well as into science and society at large. Local efforts on campuses or in municipalities have brought together actors across disciplines and departments to improve their operations. At a global level, however, technological and institutional efforts still dominate conceptual ones.

The vision of OGC (the Open Geospatial Consortium) went from, originally, ‘The complete integration of geospatial data and geoprocessing resources into mainstream computing’ to today's ‘Realization of the full societal, economic and scientific benefits of integrating electronic location resources into commercial and institutional processes worldwide.’[3]

The expectation behind the many large-scale efforts to create Spatial Data Infrastructures (SDI), nationally and internationally, is that more of the purported 80% of decisions in society with a spatial component will become informed by spatial information, thereby improving business, governance, and science. But SDI initiatives, similar to and in close connection with standards organizations, tend to focus on technical and institutional questions, often cultivating an insider view of spatial data and services rather than a demand-driven problem-solving perspective. In the broader information infrastructure context, major progress toward large-scale integration through spatial information has happened through imagery and map data provided by companies (such as Google or Microsoft) and social networks (such as Open Street Map or Wikimapia).

Standing out as two related integration efforts with a conceptual emphasis are the Center for Spatially Integrated Social Science (CSISS) at the University of California Santa Barbara (UCSB) and the more broadly conceived spatial@ucsb center. They have shown how spatial thinking and spatial information help integrate

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[3] http://www.opengeospatial.org/ogc/vision

heterogeneous data sources as well as approaches of different disciplines to a broad range of problems.

New Opportunities

Understanding social and physical processes through spatial thinking and analysis is nothing new, but as the mentioned efforts demonstrate, benefits today from unprecedented varieties of technologies and data. This confluence of technological and scientific developments creates unique opportunities to achieve integration through spatial information at more sophisticated levels. Some on-going developments are

- the *spatial turn* in the humanities and social sciences (Warf & Arias 2009);
- the *technological advances* in collecting and using spatial information by specialists and citizens;
- the growing importance of *data-intensive approaches* in science (Hey et al. 2009);
- the *online availability* of massive amounts of data, many of them with an implicit or explicit spatial reference;
- the emergence of *simpler data models and formats* for spatial data, for example KML[4];
- the *linking of data* across domains through Linked Open Data[5].

With these new opportunities, the challenge to geographic information science has become *to contribute to explanations in and across disciplines through hypotheses about spatiality*. From Dr. Snow's insight on the transmission of cholera to the recent discoveries that the human gene pool as well as the human language pool each have a

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[4] https://developers.google.com/kml/documentation/

[5] http://lodum.de/about

single origin (which happens to be in southern central Africa for both), some of the most impressive uses of spatial thinking addressed questions that were not even spatial in themselves, but were answered by spatial hypotheses.

Solutions to non-spatial problems can also benefit from spatial reasoning in metaphorical spaces, such as data cubes in data mining, information landscapes in information retrieval, or conceptual spaces in semantic modelling. This metaphorical extension is possible because space and time organize our knowledge as a whole (Janowicz 2010). Mnemonic techniques are a simple and familiar example of how we exploit space in daily life to remember things like shopping items or points in an argument.

Defining Spatial Information

To establish some common ground for the subsequent discussion of core concepts, it may be useful to first define a basic understanding of the spaces considered, spatial referencing, spatial information, spatial data, and the role of spatial information concepts.

Space and spaces

Spatial is more than geographic. Smaller spaces than those of geography (atoms and subatomic particles, molecules, crystals, cells and organs) as well as larger ones (planets, galaxies, the whole universe) characterize entire disciplines using and producing spatial information. This information is sometimes, and could more often be, modelled and analysed using GIS techniques, such as mapping or network analyses. Such intra-disciplinary (but extra-geography) spatial analyses benefit from a high-level conceptual view of spatial information, clarifying the nature of spatial properties, relations, and interactions.

The spaces where interdisciplinary and transdisciplinary challenges arise are primarily those of human experience, involving mostly geographic and smaller (but still perceivable) spaces. Using a slightly modified version of Montello's classification (Montello 1993), these include

- *geographic* spaces (such as a neighbourhood in a city or a river catchment);
- *indoor* spaces (such as a room or a hallway);
- *body* spaces (such as a human body or organ);
- *tabletop* spaces (such as a desktop or workbench); and
- *images* of anything.

Problems in smaller and larger spaces (such as cells, atoms or galaxies) as well as the higher-dimensional spaces (such as those used in statistics or data mining) are typically understood through mappings to these experiential spaces. Multi-scale problems, requiring spatial thinking and analyses across scale levels, are also supported by a conceptual view of spatial information at scales of human experience.

Geographic spaces are the ones for which we have the most advanced general-purpose information technologies. This gives geographic information science a privileged status in dealing with spatial information in transdisciplinary research.

Spatial Referencing

Information becomes spatial through spatial referencing, typically using coordinates, mileage numbers, spatial relations, or place names and other identifiers. Spatial reference systems, for example the World Geodetic System 1984 (WGS'84), serve to share such references unambiguously across information communities. Geographic spaces have the most sophisticated theories, models, and tools for spatial referencing, an overview of which is given in ISO standards 19111 and 19112[6]. The spatial reference systems defined for geographic spaces can either be used directly or adapted to spaces of interest at other scales. Their most prominent forms are geographic coordinate reference systems, which have been further standardized in the form of the so-called EPSG (European Petroleum Survey Group) Codes[7].

Yet, spatial referencing is a much broader concept than coordinates and does not even require geometric models, as useful as they are for computations. Developments in the semantic web have vastly expanded the utility of place names and other natural language identifiers for places in geographic and other spaces. Gazetteers are reference systems to interpret place names (Hill 2006). Transdisciplinary work relies heavily on gazetteers and other spatial reference systems as well as mappings between them.

Spatial Information

Spatial information answers questions about themes in space and time. All its varieties result from treating these three components as fixed, controlled, or measured (Sinton 1978). For example, information about buildings fixes time, controls theme (buildings), and measures space (location, shape, height etc.). Spatial information is spatiotemporal by default in today's practice, so that there is normally no need to distinguish spatiotemporal from spatial information. In fact, Sinton already stated that useful geographic information needs a record of observation time. For non-geographic spaces, this applies as well.

A unified treatment of space and time turns Sinton's structure into the geo-atom <x, z>, which links a position x in space-time to a attribute-value z (Goodchild et al. 2007). The position and the attribute both require typing (what type of location

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[6] http://www.isotc211.org/Outreach/ISO_TC_211_Standards_Guide.pdf
[7] http://www.epsg-registry.org/

description X? what type of attribute Z?), which has led to syntactic variations of the atom stating the Z part and the dependence of z on x explicitly, for example <x, Z, z(x)>. The geo-atom answers the questions *what is there?* (looking for z, given x) and *where is this?* (looking for x, given z). The dualism of these two questions is characteristic for spatial information.

Spatial Data

Spatial data as such are not spatial information, but generate it once humans interpret them. For example, *1-5-3 Yaesu* is spatial data and can be interpreted in the right context as the address of a post office in a ward of Tokyo[8]; the same goes for *6p21.3*, the locus of a gene in a chromosome[9].

Spatial data are increasingly delivered by web services. These are often designed to answer specific questions and are therefore closer to spatial information than naked data. For example, a web map service (WMS) produces data portraying some theme for a given time and area. But the services themselves or their outputs are still not information, as their data and computations need human interpretation.

Concepts of Spatial Information

Concepts are the mental mechanisms needed to interpret data and computations. For example, the concept of location is needed to interpret addresses or gene loci, and the concept of value is needed to interpret copyright regulations for spatial data. A concept, as these examples show, is a human construction needed for understanding. It is less about physical reality in the sense of human environments than about the reality of data and computations and their use in communication, referring to physical reality.

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[8] http://en.wikipedia.org/wiki/Japanese_addressing_system

[9] http://en.wikipedia.org/wiki/Locus_(genetics))

Concepts of spatial information are defined here as *concepts to interpret spatial data or computations*. They are neither of something in the world, nor of representations in computers, but results of conceptualizations. For example, the concept of a field is a conceptualization applied to phenomena like temperature or collective motion, which are represented by, for example, raster or point data in a GIS. The field is the modelling concept, not the model and not the modelled phenomenon. Ignoring this distinction has produced some confusion in standards for spatial information (Probst et al. 2004).

Concepts of spatial information include *spatial concepts*, which serve to reason about space, and *information concepts* to reason about spatial information. The latter may be spatial or not. An example of the former is location, referring to space and being used to interpret spatial data. An example of the latter is the concept of value, which refers to spatial information, but is not spatial. An example of both is granularity, which is a spatial measure, but is also used to interpret spatial data. The co-existence of such content and representation concepts is characteristic for all information sciences.

Choosing Core Concepts

How should the core concepts be chosen? The given definition (stating that they serve to interpret data and computations) assures that their choice is grounded in actual geographic information. A concept that is not represented by data or computations shall not be on the list. Such a computational approach has the advantage of delivering tools “for free”, once a domain theory or hypothesis has been formulated in the core concepts. It represents a counter-position to starting from a theoretical, formal, or cognitive approach. One could alternatively ask, for example, which notions in mathematics are required to understand spatial information. While this would reveal notions like neighbourhood and network (graph), concepts like event or granularity might not turn up, despite their fundamental role in understanding spatial information. Or, one could take a cognitive approach and pick the concepts based on cognitive or linguistic theories, such as those of image schemas or linguistic prepositions. This approach might also miss out some notions, for example, accuracy or value. Yet another idea would be to start with a foundational ontology and look for its spatial and information concepts. While this may lead to more comprehensive results, it begs the question what concepts to include and at what level of generality.

The question at what level of generality the concepts should be chosen is hard to answer. For example, should motion be on the list or is the more general concept of event a better choice? The strategy adopted here is to generalize as much as possible, but at most to a level where the concept can still be considered common sense. Thus, occurrent or perdurant would have been overly abstract notions (generalizing over processes and events, possibly also states), but event captures motion, growth, diffusion, and other happenings in space, while still being a common sense notion. Also, there should clearly not be several dozen core concepts and it makes sense to target a set that one can grasp as a whole.

The research reported here is empirical, in the sense of allowing for falsification by spatial data or computations that cannot be interpreted through any of the proposed concepts or, conversely and less likely, by demonstrating that it is impossible to implement a concept in a computational environment. Support for the chosen concepts comes from the fact that the synthesis in (Janelle & Goodchild 2011) of concepts relevant to the social sciences produced a similar list (with the above-mentioned difference in non-spatial information concepts).

Ten Core Concepts of Spatial Information

The discussion of the proposed core concepts of spatial information begins with location and neighbourhood, followed by the pair of field and object. It continues with the spatial concepts of network and event, and ends with the information concepts of granularity, accuracy, meaning, and value. It has been observed that this sequence suggests a natural pairing of the concepts (Janelle 2012) and this idea will be explored in future work. All concepts are given a high level qualitative description, without referencing the vast literature that exists on each of them, as no reasonable number of references could do justice to the breadth of any concept.

< Figure 1 here >

Location

Spatial information is always linked to location in some way - but what exactly is location and how does it play this central role? Location information answers *where* questions: *where are you? where is the appendix? where are this morning's traffic jams? where did Admiral Nelson die?*

Perhaps counter-intuitively, location is a *relation*, not a property. Nothing has an intrinsic location, even if it always remains where it is. The house you live in can be located, for example, by a place name, an address, directions, or various types of coordinates. All of these location descriptions express relations between the *figure* to be located (your house) and a chosen *ground* (a named region, a street network, coordinate axes). How one locates things, i.e., what ground and what relation one chooses, depends on the context in which the location information is produced and used. When grounds become salient, as in the case of places, they tend to be thought of as “locations” in the sense of an object.

Spatial reference systems standardize location relations and turn them into attributes, describing positions in a system. Yet, when data use multiple reference systems (for example, latitude and longitude as well as projected coordinates), locations need to be understood as relations and interpreted with respect to their grounds (for example, the Greenwich meridian and equator).

Neighbourhood

Relating different phenomena through location is fundamental to spatial analysis. The great power of such locational analyses results from the fact that nearby things are more related than distant things, known as Tobler's First Law of Geography, based on its first explicit statement in (Tobler 1970), but applicable to many (if not all) kinds of spaces. Nearness, or rather the neighbourhood answering the question *what is near*, is therefore a natural companion concept to location.

Neighbourhoods are commonly thought of as regions, characterizing spatial *context*. For example, a city neighbourhood is a region of a city, typically defined by social or topographic properties and processes; the neighbourhood of a person (also known as “aura”) is relevant in intra-personal and social contexts. Topology, as one kind of mathematical theory of spaces, takes neighbourhood as its fundamental notion to express the same idea of a spatial context.

Definitions of near and neighbourhood are not only context-dependent, but also necessarily vague. Even if the context to be captured (for example, the region from which one can walk to a bus station) is specified, the neighbourhood remains imprecisely defined. Consequently, neighbourhoods normally have no crisp boundaries.

The classical technique to compute neighbourhoods is that of buffering, which produces a region of some width around something. Such a geometric approach captures the physical or social factors underlying a neighbourhood more or less well.

For example, a buffer of 300 Meters around a bus station may not capture actual walking distances very well, even if the distances are measured along walking paths.

Field

Fields describe phenomena that have a scalar or vector attribute everywhere in a space of interest, for example air temperatures on the earth's surface. Field information answers the question *what is here?*, for example *what is the temperature here?,* where *here* can be anywhere in the space considered. Generalizing the field notion from physics, field-based spatial information can also represent attributes that are computed rather than measured, such as probabilities or densities.

Fields are one of two fundamental ways of structuring spatial information, the other being objects. Both fix time, with fields resulting from controlled space and measured theme, and objects resulting from controlled theme and measured space. Time can also be controlled instead of fixed. Controlling it together with space leads to space-time fields; controlling it together with theme produces animations. Fields have been shown to be more fundamental than objects: so-called general field models are capable of integrating field and object views (Liu et al. 2008).

Since it is not possible to represent an attribute at infinitely many positions, the spaces of interest need to be discretized for explicit digital storage of fields. There are two ways to achieve this, either through a finite number of cells within each of which the attribute is assumed to remain constant or through a finite set of sample points with interpolation rules for positions between them. The cells jointly partition the space of interest and can all have the same shape (forming a regular grid of square, triangular, hexagonal, or cubic cells), as in raster models for spatial data; or they can have irregular shapes, adaptable to the variation of the attribute, as in finite element models or terrain representations. Similarly, point samples can be spaced regularly or irregularly.

A special kind of field captures attributes on two-dimensional surfaces, such as the surfaces of the earth or of the human body. These fields can be represented as so-called *coverages* and organized into thematic *layers*. The idea of a layer is rooted in traditional paper- or film-based representations of spatial information, such as maps, and the production of models from stacked transparent layers of data about a theme. The main computational use of layers is to *overlay* them, relating information about multiple themes or from multiple sources.

Object

Together with fields, objects provide the second fundamental way of structuring spatial information. They describe *individuals* that have an identity as well as spatial, temporal, and thematic properties. Object information answers questions about properties and relations of objects, such as *where is this object?, how big is it?, what are its parts?, which are its neighbours?, how many are there?*. It results from fixing theme, controlling time, and measuring space.

Many applications concern things that are *features* in the same way that noses are features of faces, i.e. parts of surfaces. Features depend on objects, but can be understood as a special case of them. The simplest way to carve out features from a surface is to name regions on it. Geographic places are the prototypical examples, carved out of the earth's surface by naming regions; but the same idea applies, for example, to regions on airplane wings, sails, or teeth.

The notion of an object implies *boundedness*. This does not mean that the object’s boundaries need to be known or even knowable, but that there are (crisp) limits outside of which there are no parts of the object. Crude examples of such limits are the minimal bounding boxes used for indexing and querying objects in databases.

Many objects (particularly natural ones) do not have crisp *boundaries* (Burrough & Frank 1996). Examples are geographic regions or body parts such as hands or heads. Differences between spatial information from multiple sources are then often caused by more or less arbitrary delimitations through context-dependent boundaries. For example, climate zones are vague by nature, and the variation in boundaries between different definitions matters less than the overall extent and location of the zones. Thus, whether modelling objects with explicit boundaries is necessary or desirable has to be carefully assessed for each application.

Many questions about objects and features can be answered without boundaries, using simple point representations with thematic attributes. For example, blood counts in laboratory samples or densities of hospitals in a city can be determined from point representations. Some questions, however, require explicit boundaries enclosing or separating objects. For example, the neighbours of a land parcel, the extent of a geological formation, or the health of blood cells are determined from boundary data.

Vector models for spatial data can capture, at various levels of sophistication, objects with or without boundaries. Processing vector data exploits the geometry of object representations to compute distributions, sizes, shapes, buffers, and overlays. Like surface fields in raster data, collections of features in vector data can be organized into thematic *layers*.

Two-dimensional feature models sometimes co-exist with three-dimensional object models, offering transitions back and forth between them. For example, your house may be represented as a feature of the earth's surface in a digital map, as a feature of street view images, and as a three-dimensional object. The resulting blended feature-object notion pervades geography, but also exists in biology and medicine (features of cells, organs, or bodies), and in imaging (features extracted from images of anything).

Network

Connectivity is central to space and spatial information. The concept of a network captures binary relationships among arbitrary numbers of objects, called the nodes or vertices of the network. Any relation of interest can connect the nodes and be represented by edges (also known as links or arcs). The spatiality of a network results from positioning the nodes in some space. It may, furthermore, involve geometric properties of the edges, such as their length or shape. If the embedding space is a surface, networks can also be organized into thematic layers.

Network information answers questions about connectivity, such as *are nodes m and n connected?, what is the shortest path from m to n?, how central is m in the network?, where are the sources and sinks in the network?, how fast will something spread through the network?*, and many others.

The two main kinds of networks encountered in spatial information are link and path networks. *Link* networks capture logical or other abstract relationships between nodes, such as friendships, business relations, or treaties between social agents. *Path* or transportation networks model systems of paths along which matter, energy or information flows. Examples are roads, utilities, communication lines, synapses, blood vessels, or electric circuits.

Network applications benefit from the well-studied representations of networks as graphs and the correspondingly vast choice of algorithms. Partly due to this sound mathematical and computational basis, networks are the spatial concept that is most broadly recognized and applied across disciplines. One may speculate from this success story that a similar level of understanding and formalization of the other core concepts will encourage their use in transdisciplinary work. As the exposure here shows, such a level has not yet been reached in many cases.

Event

Events and processes are of central interest to science and society – capturing what is happening in the environment, in a human body, in cells or molecules, in machines, or in financial systems. Event information answers questions about *change*. Spatial events manifest themselves through changes of locations (i.e., motion), neighbourhoods, fields, objects, and networks, i.e., changes to instances of the previous core concepts.

Migration and embolism are examples of motion events; global warming is an example of an event manifesting itself in the change of temperature fields; growth can be change in neighbourhoods (e.g., a suburb), objects (e.g., vegetation) or networks (e.g., evolving professional networks).

Events can be seen as carved out of *processes* in the same way that physical objects are carved out of matter, i.e. by bounding the processes (Galton & Mizoguchi 2009). Languages make the same distinction through aspects of verbs, distinguishing perfective ("gone") and imperfective ("going") forms.

Events get related through temporal relations as well as through spatial relations among their participants. When tracing cholera transmission to drinking water, Dr. Snow reasoned that one event (drinking water from a contaminated pump) preceded another (contracting cholera) and that the participants of the events (patients and pumps) were in the same neighbourhood.

Granularity

Granularity is the first (and most spatial) concept of information on the list. It characterizes the size of the spatial, temporal, and thematic units about which information is reported. For example, satellite images have the spatial granularity of the distance on the ground corresponding to a pixel, the temporal granularity of the frequency at which they are taken, and the thematic granularity of the spectral bands recorded. Vote counts, on the other hand, have the spatial granularity of voting districts, the temporal granularity of voting cycles, and the two thematic granularity levels of parties and candidates.

Granularity information answers questions about the *precision* of spatial information. It matters most when taking and evaluating decisions based on that information. Granularity characterizes information about all concepts introduced so far: location is recorded at certain granularities, neighbourhoods can be identified at several levels, fields are recorded at certain spacings or sizes of cells, and the choice of the types of objects (say, buildings vs. cities) or nodes (say, transistors vs. people) determines the spatial granularities of object and network information. Events are defined and distinguished by choosing granularity levels in space, time, and theme.

The phenomena studied determine the choice of the spatial, temporal, and thematic granularities at which spatial information gets recorded. For example, migration, social networking, and the diffusion of technological innovations all involve people over months; embolism involves blood clots and vessels over hours; cancer involves cells and organs over months and years; climate change involves large air and water masses over decades; changing house prices involve land parcels and people over temporal granularities ranging from days to years.

Events are sometimes studied at multiple granularities (for example, erosion) or connected across granularities. To accommodate such studies, location descriptions are often hierarchical (for example, addresses); fields are often represented by nested raster data (called pyramids in the case of images); object hierarchies are expressed as part-whole relations between objects (for example, administrative subdivisions of countries); hierarchical network representations allow for more efficient reasoning (for example, in navigation), event models are connected across levels of detail (for example, in medicine).

Accuracy

Accuracy is a key property of spatial information, capturing how information relates to the world. Information about accuracy answers questions about the *correctness* of spatial information. The location of a building, given in the form of an address, coordinates, or driving instructions, can be more or less accurate in each case. The spatial, temporal, and thematic components of spatial information are all subject to (in)accuracy.

Assessing the accuracy of information requires two assumptions: that there is, at least in principle, correct information and that the results of repeated measurements or calculations distribute regularly around it. The first assumption requires an unambiguous specification of the reported phenomenon and of the procedure to measure it. For example, if temperatures are reported for different places, one may need to specify the level above ground at which they were measured. The second assumption requires an understanding of measurement as a random process.

Meaning

Understanding what producers meant by some spatial information is crucial to its adequate use. Producing meaningful results and making sense of them involves determining whether the same things are called the same and different things differently. The practical challenge is to capture what the producer means with some data or computations and to guide the user in interpreting them. For example, when navigation systems use road data, they make assumptions on what the data producer meant by an attribute like *road width* (paved or drivable?, number of lanes or meters or feet?). When producing and interpreting spatial analyses, operations such as distance need to be interpreted as well[10].

Information about meaning (a.k.a. *semantic* information) answers the question *how to interpret* the terms used in spatial information. It concerns the spatial, temporal, and thematic components. Data and computations do not have a well-defined meaning by themselves, but are used by somebody to mean something in some context. Therefore, it is impossible to fix the meaning of terms in information. However, one can make the conditions for using and interpreting a term explicit. This is what *ontologies* do: they state constraints on the use and interpretation of terms.

But language use is flexible and does not always follow rules, even for technical terms. An empirical account of how some terms are actually used can therefore provide additional insights on intended meaning and actual interpretation. This is what *folksonomies* deliver: they list and group the terms with which information resources have been tagged.

Value

The final concept proposed as core is that of value. Information about values attached to or affected by spatial information answers questions about the *roles played by spatial information in society*. The prototypical value is economic, but the valuation of spatial information as a good in society goes far beyond monetary considerations. It includes assessing the relation of spatial information to other important values in society, such as privacy, trust, infrastructure, or heritage.

Establishing access policies for spatial information is a pressing societal need requiring a better understanding of all values involved. It is complicated by the fact that information about indoor and geographic spaces gets collected and shared by almost

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[10] http://www.economist.com/node/1788311

everybody. This phenomenon of crowd-sourced or Volunteered Geographic Information (VGI, (Goodchild 2007)) is profoundly altering the values related to spatial information, from economic as well as institutional, ethical, and legal perspectives.

Given these wide ranging aspects of spatial information values, no coherent theoretical framework for them can be expected any time soon. Even theories about the economic value of spatial information remain sketchy and difficult to apply, because they involve parameters that are hard to generalize, control, and measure. The cost of spatial information is no reliable guide to its economic value, because it often reflects the expenses for collecting the information, rather than the value of the result. The values of information, economic and otherwise, tend to accrue holistically and unpredictably, by new questions that can be asked and answered.

Also-ran

It may be useful to consider some arguments against core status for some other concepts. Earlier lists of concept candidates contained the notions of spatial relation, layer, motion, path, uncertainty, and scale. Typical reasons to exclude these from the list were that they were too broad or too narrow. In particular:

- *spatial relations* serve to specify location and are covered there;
- *distance*, the most important spatial relation, occurs in several other concepts (location, neighbourhood, network, granularity, accuracy); introducing it as a core concept would call for *direction* and possibly other spatial relations as well;
- *layers* structure the representations of several concepts (fields, objects, networks) and are dealt with there, together with *overlay*, as one of the fundamental GIS operations;
- *motion* is only one spatial event, though arguably the most important one;

- *paths* are covered as parts of networks;
- *uncertainty* covers the concepts of granularity, accuracy, and meaning;
- *scale* is an ill-defined catch-all for several concepts, of which granularity is on the list, extent (of a study area) can be seen as a field or object, and support is a more specialized concept (belonging to measurement ontology).

Conclusions

Geographic information techniques and technologies (for example, geographic information systems, location-based services, location-based information retrieval, geo-processing, and geo-visualization) have matured to the point where they need transdisciplinary challenges to grow. As an alternative to the letter soup used in technical talk about spatial information (consider GML, WMS, WFS, SVG), this article has proposed a small set of core concepts of spatial information, expected to be intelligible to non-specialists and conducive to transdisciplinary research.

The selection of concepts is now being analysed and described in more detail[11]. The main research challenge, in the context of supporting transdisciplinary work, is the need to map the concepts across disciplines. Having identified common concepts does not imply that they are used *in the same way* across domains. For example, one domain's idea of a neighbourhood may be quite different from that of another. To map between different uses of the concepts, they could be formalized into an ontology (Guarino 1995), complementing and benefiting from existing ontologies of spatial information with slightly different purposes (Frank 2003; Couclelis 2010). Yet, abstracting further from the concepts in order to place them into the hierarchy of a foundational ontology, while useful for conceptual clarity, would not necessarily solve

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[11] See http://ifgi.uni-muenster.de/services/ojs/index.php/ccsi/article/view/4 for a continuing discussion.

the mapping problem. For example, specifying that a neighbourhood is a spatial region does not help to map between two neighbourhood definitions based on different processes.

Designing ontology patterns (Gangemi et al. 2005) for the concepts, using top level distinctions without forcing the concepts into a complete hierarchy or fixed definition may be a more promising approach for mapping purposes. Linking ontology patterns for the concepts to actual data and software through annotation would support information retrieval and reasoning, as well as cross-domain mappings, grounded in the practice of spatial information and analysis.

An overall theoretical analysis of why the concepts are what they are is tempting and may become feasible and productive at some point. If done too early, however, it may constrain the conceptual view of geographic information through a theoretical stance rather than through grounding in data and demonstrated benefits in applications.

Transdisciplinary research typically asks for *theories of change* (Câmara et al. 2009). One of the main benefits to be expected from a list of core concepts of spatial information is that they establish the conceptual foundations for such theories. If the domain theories can be formulated in terms of the proposed concepts, as indicated in the discussion of events, their choice will be corroborated; if not, other concepts will have to join or replace them.

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Spatial Concepts	Location	Neighbourhood	Field	Object	Network	Event
Information Concepts	Granularity	Accuracy	Meaning	Value		

Table 1. The proposed core concepts of spatial information.