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Discrete and continuous conceptualizations of science: Implications for knowledge domain visualization

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ABSTRACT

Visual depiction of the structure and evolution of science has been proposed as a key strategy for dealing with the large, complex, and increasingly interdisciplinary records of scientific communication. While every such visualization assumes the existence of spatial structures within the system of science, new methods and tools are rarely linked to thorough reflection on the underlying spatial concepts. Meanwhile, geographic information science has adopted a view of geographic space as conceptualized through the duality of discrete objects and continuous fields. This paper argues that conceptualization of science has been dominated by a view of its constituent elements (e.g., authors, articles, journals, disciplines) as discrete objects. It is proposed that, like in geographic information science, alternative concepts could be used for the same phenomenon. For example, one could view an author as either a discrete object at a specific location or as a continuous field occupying all of a discipline. It is further proposed that this duality of spatial concepts can extend to the methods by which low-dimensional geometric models of high-dimensional scientific spaces are created and used. This can result in new methods revealing different kinds of insights. This is demonstrated by a juxtaposition of two visualizations of an author's intellectual evolution on the basis of either a discrete or continuous conceptualization.

1. Introduction

Visualization has been proposed as a key strategy for dealing with the rapidly evolving landscape of science. Visual approaches provide promising mechanisms for modeling and understanding ever-growing, ever-more-complex, ever-more-linked knowledge domains (Börner, Chen, & Boyack, 2003; Chen, 2003). This optimism and enthusiasm in regard to visual approaches for organizing and managing contemporary scientific research and communication resonates well with a rapid growth in the use of spatial concepts to explain phenomena that previously had been viewed in aspatial terms. The intersection of cognitive science and linguistics has been particularly fruitful in that regard, from work on spatial metaphors (Lakoff & Johnson, 1980) to Talmy's (1983) investigation of the spatial relationships encoded in prepositions. Recently, even more encompassing arguments regarding the possible spatial nature of human thought have been made, with Gärdenfors' conceptual spaces (Gärdenfors, 2000) as a prime example.

Sometimes, very specific spaces are being theoretically explored. An example is the recent attention paid to *geographic* space by such fields as anthropology, political science, and sociology. All these are symptoms of a broad movement that has become known as the "spatial turn" which is related to the "visual turn" of contemporary society. One indication of the fundamental changes occurring is the increased concern about *the visual* – note the switch from an adjective to a noun – that

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is frequently informed by postmodern and poststructuralist approaches (Rose, 2001). Those tend to be however somewhat separate from the discussion of *space* itself, where pragmatic needs tend to dominate, for example in the construction of ontologies of space.

One would expect that in-depth reflection on the nature of *space* itself and on the *visual* would be a central element in any attempt to *visualize* complex phenomena. That is because visualization always involves at least one type of space: a low-dimensional space presented to a viewer. In addition, if low-dimensional representations consisting of geometric elements and attached symbology are able to convey something meaningful about a phenomenon, then that phenomenon must be conceptualized in spatial terms. In other words, there also exists a conceptual space. For example, if users are able to extract meaningful relationships from a visualization showing scientific papers as point symbols and citations as line symbols that begin and end at point symbols, then scientific publications must have been conceptualized as existing in *some* space.

There is a growing body of empirical evidence that humans readily construct and apply such conceptual spaces. In one study, subjects were shown nothing but simple point symbols and were told that each point represented one text document. It turned out that subjects expected *closer* point symbols to represent more *similar* documents (Montello, Fabrikant, Ruocco, & Middleton, 2003). This may at the surface be quite surprising – since the point symbols look absolutely identical – unless there is an underlying conceptual space onto which the observed geometric distances are cognitively mapped. What is important about studies like these is that they point to the need to really think about space whenever visualization is employed as a knowledge construction mechanism.

Given this attention to geographic and map metaphors, one would expect that the corresponding source domains – geography and cartography – are carefully examined whenever metaphors referencing those domains are invoked. With respect to information visualization, Skupin (2000) argued that the use of map metaphors had suffered from insufficient engagement of existing cartographic literature and expertise. Since then, we have seen numerous visualizations, including those depicting scientific knowledge domains, that attempt to follow cartographic design principles more closely. However, while one encounters more examples that *look* like cartographic maps, an even more fundamental problem with existing approaches has come to the fore, namely a lack of awareness of how geographic space is *conceptualized* within geographic information science before it is ever visualized or undergoing other forms of spatial analysis. That has impact on the theory, practice, and overall vision of science mapping.

First, visualizations of science are in danger of obtaining the *look* of cartographic maps, but not their cognitive *function*. For example, consider the case of surface-type visualizations of science, which have become popular in the mapping of knowledge domains, but without consideration of the fundamental differences between interpolated and density surfaces. Interpolated surfaces assume that input locations are just samples from an actual continuum (e.g., elevation or temperature), which one then tries to reconstruct through such methods as surface interpolation. Once the continuum is represented as a surface, one can then ask meaningful questions about any location within it. Meanwhile, density surfaces are actually based on a discrete object conceptualization and the surface visualization is merely meant to allow an aggregate view of those discrete objects. That is reflected in the methods used to create them, which are completely different from those used for interpolated surfaces. The continuous look of density surfaces conflicts with the fact that they do not represent an actually continuous phenomenon. In fact, one can even claim that there is no such thing as density as such! All that exists is the density surface one computes for a given spatial denominator. For a single set of discrete objects there will be an infinite number of alternative surfaces derived from different denominators, all equally valid (Longley, Goodchild, & Maguire, 2005, p. 338). The problem is that viewers tend to be kept in the dark about that and are visually led to think that the surface space between mapped objects (e.g., authors) is occupied by something, when it actually remained an empty void all along.

Second, there has been a lack of systematic reflection on certain basic assumptions underlying scientometrics and science mapping. In the current paper, I focus on this aspect and hypothesize that a lack of reflection on conceptualizations of science has led to gaps in the methodological framework. That should then lead to blank spots in the list of available tools and, ultimately, gaps in our ability to model scientific knowledge domains. Though the literature provides limited explicit discussion of the nature of the conceptual spaces underlying knowledge domain visualizations, it is possible to examine the data and methods used and the visual outputs generated and to interpret them in the light of a conceptual framework.

The framework presented in this paper is formed around a fundamental distinction made among conceptualizations of geographic space, namely that between *discrete objects* and *continuous fields*. These represent fundamentally different ways of looking at spatial reality. One is based on the notion of discrete objects as existing in an otherwise empty, yet continuous, space (Figs. 2 and 4). Typical examples for phenomena typically conceptualized as discrete objects in the scientometric domain include journals, authors, individual journal articles, and scientific topics and disciplines (Fig. 2). Discrete objects can be distinguished in terms of their identity, their attributes, and the degree to which they occupy the space in question. For example, in a two-dimensional space one could distinguish between zero-dimensional, one-dimensional, and two-dimensional objects. Objects can further have relationships to other objects, such as when journal articles are linked by co-citations (Fig. 2c) or when authors are aggregated into clusters (Fig. 2b). One important aspect is that the conceptualization of the attributes, dimensionality, and relationships of objects may depend on the scope or scale of analysis. For example, a city may sometimes be conceptualized as a zero-dimensional object and at other times as a two-dimensional object, while maintaining its identity. Similarly, an author could sometimes be seen as an individual zero-dimensional object (Fig. 2b) and at other times as the aggregate of all of his/her publications (Fig. 2c) or even as a one-dimensional object, based on a trajectory traced through the knowledge domain (Fig. 4).

A very different conceptualization assumes the existence of a large number of fields, each spanning all of space continuously and without gaps. Space itself – instead of object identity – becomes what the representation is founded on (Peuquet, 2002). In order to accommodate making statements about particular locations, the space tends to be discretized, compared to the continuous space in which objects in the discrete object conceptualization are located. Objects may still be represented, though on the bases of attributes observed at particular locations, such as when information about a large number of term fields spanning a domain is used to chunk the knowledge continuum into cluster objects (Figs. 4 and 5).

One of the possible factors in missing methodological elements is *reverse ontology* (Peuquet, 2002), which is caused by and feeds into insufficiently thorough conceptualization and distinction between conceptual models and the logical data models used to represent a phenomenon. For example, someone mostly exposed to citation networks and respective network analysis tools is in danger of beginning to think that "a journal article *is* a node" or "a citation *is* a link" as opposed to recognizing that those are *chosen* representations and that quite different conceptualizations of journals and citations are possible.

What alternatives are there? First, this paper argues that the discrete object ontology has come to dominate the modeling of knowledge domains. This is due to a confluence of available data and methods (e.g., ISI data and network analysis tools), and the overall dominance of object-based ontologies within information science (as opposed to the broader notion of ontology used in philosophy). Second, it is proposed that the continuous field ontology is a natural complement to discrete object approaches in knowledge domain visualizations, in accordance with the acknowledged duality of objects and fields (Couclelis, 1993). For example, "a journal article is a field spanning a knowledge domain" could be a useful alternative conceptualization. Third, specific computational methods are discussed in the context of the object-field debate to arrive at a framework that allows identifying missing methodologies, including for the analysis of *change* (i.e., temporal dynamics) in knowledge domains. One such methodological gap is then explored as a proof-of-concept visualization, namely the conceptualization of an author as a continuous field occupying *all* of a knowledge domain, which then leads to the author being visualized *as* a two-dimensional landscape.

2. Conceptualizing spaces: the status quo

2.1. Spaces of geography

In order to understand the process by which geographic space becomes represented in a database, let us first consider the major steps typically involved in abstracting the infinitely complex geographic reality towards physical storage in a database (Fig. 1).

Physical storage and all further computing – including human–computer interaction – is based on the final, physical model stage, but is profoundly dependent on how geographic space was initially conceptualized. While the general process, unsurprisingly, mirrors the standard approach to database design, we will focus on aspects particularly pertinent to the representation of *space*. The most fundamental *decision* or *choice* made early on concerns the conceptualization of geographic space. Note that we are referring to this as a "decision" or "choice" in order to indicate that multiple conceptualizations of the same space and even of the same phenomenon in that space are possible and admissible. The first decision at the conceptual modeling stage is how to divide geographic space into certain chunks to which further modeling decisions are then applied. For example, we may choose to distinguish roads from lakes, temperature, elevation, military troop movements, or poverty levels.

The next step – and the one most pertinent to this article – is to decide how to conceptualize those chunks. The two main choices are between the *discrete object* and the *continuous field* conceptualizations.

In the discrete object view, we conceptualize a phenomenon as consisting of objects positioned in an otherwise empty space. Objects tend to have descriptive attributes associated with them and that can be the basis for aggregation and cate-

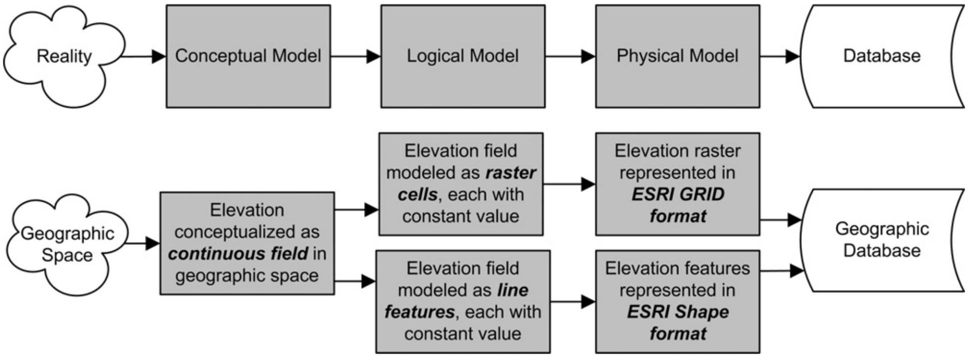


Fig. 1. Standard abstraction steps in database design and their application in the representation of elevation in a geographic database.

gorization. They are countable – related to this is the ability to determine object density – and their relationships to other objects can be explored and exploited. Those relationships can be explicit, such as connectivity in a network, or implicit, like the distances among point features. Prototypical examples to which the discrete object conceptualization is typically applied include roads, countries, and land parcels. Consider the legal implications if land ownership was *not* conceptualized in a discrete manner, i.e., if parcels were not clearly distinct from each other, but instead were overlapping or even exhibit sliding degrees of partial ownership.

When the continuous field conceptualization is used, the space in question is viewed as being completely covered by a large number of continuous fields, each corresponding to one particular descriptive aspect or attribute of that space. Typical applications of that conceptualization include surface temperature, humidity, and elevation (see also Fig. 1). Notice how one could never observe an actual *absence* of these phenomena; they can be observed at any geographic location. Income tax and land cover are other phenomena that are typically conceptualized as continuous fields, assuming that extraterritorial and “no-tax” areas are understood as having a tax rate of zero and open water and bare rock and ice are valid land cover categories.

Compared to those examples, choosing a suitable conceptualization is in practice often more difficult, since it may be reasonable to conceptualize the same phenomenon in either discrete or continuous terms. The choice will depend on the questions that need answering and on how far one wants to push that pursuit. Longley et al. (2005) give such a compelling example for this, and with such relevance for the core arguments put forth in this paper, that it is well worth to cite it in some detail:

> “Suppose you were hired for the summer to count the number of lakes in Minnesota . . . The task sounds simple and you were happy to get the job. But on the first day you started to run into difficulty. What about small ponds, do they count as lakes? What about wide stretches of rivers? What about swamps that dry up in the summer? What about a lake with a narrow section connecting two wider parts, is it one lake or two?” (Longley et al., 2005, p. 72)

In this particular scenario, an alternative approach, based on a continuously distributed phenomenon, might look as follows:

> “Instead of counting, our strategy would be to lay a grid over the map, and assign each grid cell a score on the lakeness scale. The size of the grid cell would determine how accurately the result approximated the value we could theoretically obtain by visiting one of the infinite number of points in the state [Minnesota, A.S.]. At the end, we could tabulate the resulting scores, counting the number of cells having each value of lakeness, or averaging the lakeness score.” (Longley et al., 2005, p. 72)

Notice how the differences in how actual data are transformed *begin* here with different conceptualizations. Specific data models, such as the choice between raster and vector models and between specific physical formats, such as Shape files versus TIFF files, derive from that, not the other way around (Fig. 1). Now ask yourself whether mappings of science are typically likewise driven by how elements of science are conceptualized, or whether a bottom-up, data-driven conceptualization is the norm. I would argue that knowledge domain visualizations are too often characterized by a type of reverse ontology, where knowledge domain ontology and ultimately the end user’s view of the reality of science is driven by the source data’s schemas.

To be sure, users of geographic information systems (GIS) frequently suffer from that same problem. In fact, the move from the data-driven ontological duality of rasters and vectors towards the cognition-driven duality of fields and objects has been a hallmark in the emergence of geographic information science (GIScience). Being too familiar with the core computational techniques and being positioned too close to the subject matter and the “task-at-hand” certainly makes critical perspective more difficult. It is not surprising then that some important insights relevant to GIScience had to come from outside of its core practitioners. Philosophy was a prime candidate for this, as exemplified by the work of Barry Smith on geographic ontology. Questions like “Do mountains exist?” (Smith & Mark, 2003) are as crucial to geographic information science as questions like “Do authors exist?” are to the science of science.

As for the object/field issue, Couclelis (1993) successfully argues that it denotes a fundamental distinction among conceptualizations of geography and that it complements the duality of atomic and plenum views of quantum theory presented by Hooker (1973). Since fields and objects form a domain-independent, *cognitively* oriented duality, it stands to reason that they can also be employed in mappings of science.

This *cognitive* orientation of basic conceptual approaches constrasts with an increasing *computational* orientation as we move from the conceptual model stage to the logical and eventually the physical model stage (Fig. 1). The logical modeling stage can be a particularly tempting source of reverse ontology in visualization, since during graphic design there is a close association between graphic symbols and the geometric elements prescribed by a given logical model. Correct reading of many visualizations is then dependent on seeing through the logical model to the correct conceptual model. For an example, consider the use of contour lines to depict elevation (Fig. 1, bottom). Novice users of topographic maps sometimes think that contour line symbols correspond to actual features found in the physical space, a curious example of reverse ontology. In reality, these lines – driven by a choice made at the logical modeling stage – simply mark boundaries between rigidly defined zones within the elevation continuum. Like with many semiotic systems, with practice this one too promotes its own oblivion, and experienced users have no trouble seeing *through* the limits imposed by the logical model and recognize the conceptualization of elevation as a continuous field.

2.2. Spaces of science

Armed with an understanding of broad strategies underlying the conceptualization of geographic space, we can now attempt the metaphorical transfer of those same notions to the conceptualization of science, with particular concern for how science is or could be visualized. "All" it takes is to imagine science as an *n*-dimensional landscape in a space defined by the multitude of scientific ideas, topics, and methodologies. Thinking back to the attempt at counting lakes in Minnesota, instead of such a geographic entity type as lake we might be dealing with a scientific entity type like *author* or *publication*, and instead of Minnesota we might be using a particular knowledge domain within the space of science.

We are then ready to ask certain questions. What is an *author* in that space? What is a *publication* in that space? What is a *citation* in that space? How many authors, publications, and citations are there really, when delineating them is driven first and foremost not by the available data bases – a possible sign of reverse ontology – but by how we conceptualize authors, publications, and citations? Are authors like land parcels, discrete, with clear-cut boundaries between them? Or are they more like street intersections, discrete, but with no right to exist on their own, always depending on the existence of other entities. Intersections depend in their existence on the meeting of at least two street objects. Similarly, does an author exist, even if the database contains no article published by him? Or are authors like surface temperature, existing everywhere in a knowledge domain, continuously, but with different intensities in different scientific locales, and sometimes reacting to conditions in those locales by the physical manifestation of a publication? Plenty of questions emerge, all of which imply making choices among concepts.

Just as every geographic map is a conceptual model (Hsu, 1979), so is every map of science a conceptual model. Thus, we can look at knowledge domain visualizations for clues regarding the conceptualizations of science involved, even if explicit statements regarding conceptualization are mostly absent. Through that process, one can identify examples from scientometrics and science mapping for which metaphorical mapping between the source domain of geography and the target domain of general science can be performed. To be more precise, we will identify metaphorical mappings that already are commonly encountered as well as those that have apparently been missed by a lacking conceptualization-based framework.

Where actual graphic examples are missing, one can look for other evidence in the literature. First of all, it becomes apparent that visions involving geographic and map metaphors have been associated with information science for a long time. According to Rayward (1994), Paul Otlet, generally seen as the father of information science, had a vision that looks similar to contemporary science mapping:

> He wanted to 'winnow' documents of their best grain and continuously 'to map' all of the intellectual domains. 'Mapping' assists exploration by reducing unnecessary voyages over already discovered terrain (Rayward, 1994, p. 248).

Note though that Otlet thought of individual documents as *containing* but not *being* the elements from which a survey of intellectual domains could be constructed. Mapping of individual books, articles, or authors would not have served that vision well. While Otlet envisioned an intense process of *transformation* applied to those raw data, that was mostly a question of extracting and cross-referencing of more atomic 'facts'. Half a century after Otlet, Eugene Garfield's vision regarding construction and use of citation models likewise indicate a view of science as occupied by discrete objects, possibly hierarchically organized:

> If one considers the book as the macro unit of thought and the periodical article the micro unit of thought, then the citation index in some respect deals in the submicro or molecular unit of thought (Garfield, 1955).

It thus seems that the discrete object view has been at the foundation of scientometrics from the very beginning. De Solla Price's arguments regarding the "growth of science" (Price, 1963) on the basis of the *numbers* of journals, abstracts, and authors *growing* over time only make sense when each journal, abstract, or author is viewed as a discrete entity. Such publication counts have been the cornerstone of scientometric notions of literature growth ever since (Tabah, 2001). Keep in mind that the conceptualization of a space and the definition of growth with respect to that space are inherently related. If the space of science is thought to be *consisting of* or be *made up of* bibliometric entities – in other words, if those entities are thought to form the substance of science – then a growth in the number of entities is identical to the growth of science. If, on the other hand, those bibliometric entities are merely *situated in* the space of science, then counting them generates far less inference regarding the growth of science itself. Growth *within* a space is something quite different from growth *of* that space. One author might spend a lifetime in the same subject area, producing a great number of publications. Another author continuously reinvents herself, switching interests every couple of years, and produces fewer publications. If measured by publication counts, does the latter author thus contribute less to the growth of science? Or, by acting as a bee carrying intellectual pollen between different sub-domains, does the second author actually contribute more? A view *solely* based on a conceptualizing of authors as discrete entities makes it harder to answer those questions.

Just like two lakes in Minnesota touching each other begs the question of whether we are looking at two lakes or just one, we need to ask whether a paper that has two different names listed as authors really has two authors (i.e., co-authors). If so, where in that paper runs the boundary between them? And if we cannot delineate such a boundary, do we assume that both authors have equal command over all aspects of the paper, i.e., do they truly co-own *all* those smaller building blocks of the article, the very pieces Otlet was thinking about? It seems that a question like "how many authors have published

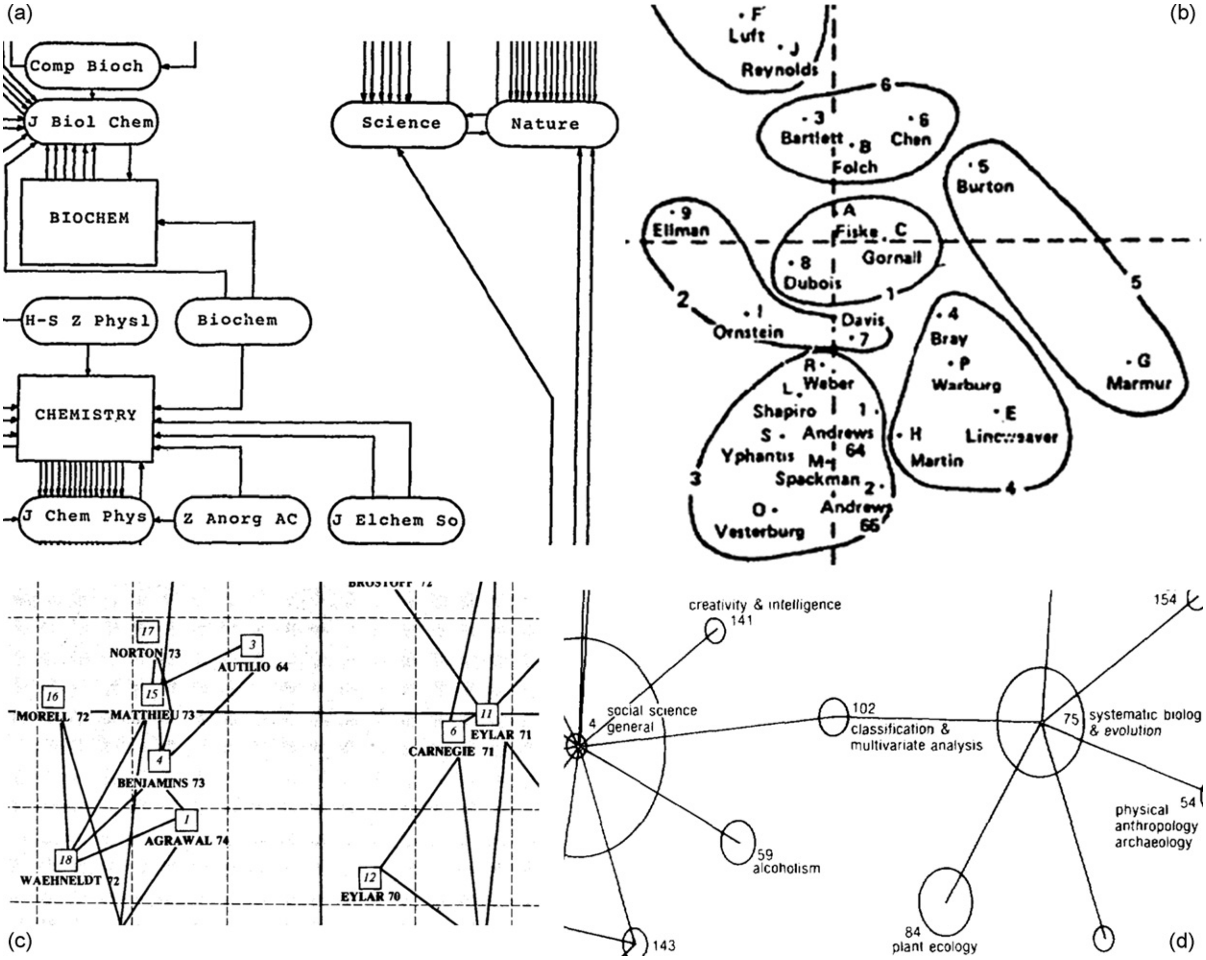


Fig. 2. Dominance of discrete object conceptualization in early science mapping: (a) journals and disciplines (Narin, Mark, & Berlt, 1972), (b) authors (Griffith, Small, Stonehill, & Dey, 1974), (c) journal articles (Institute for Scientific Information, 1981), (d) disciplines and research subjects (Small & Garfield, 1985). (Fig. 2a by permission of Francis Narin, Fig. 2b–d by permission of Henry Small.)

in this journal?" is therefore quite meaningless, because a conceptualization of authors solely as discrete objects is not sufficient. More meaningful questions would be "how much authorship is there?" or "how is authorship changing in this journal?"

One approach *around* this problem has been to link zero-dimensional discrete objects with one-dimensional elements to form networks, such as co-author networks for authors and co-citation networks for citations. Conceptually, linking authors and publications to form networks may indeed allow us to better observe growth *within* and *of* the space of science. This has been the dominant proposed solution to the problem that discrete counts of science entities tell us little about the *substantive* growth of science. In that sense, citation modeling along the lines of Eugene Garfield's ideas was indeed a major advance. However, conceptually, it addresses the problem by adding yet another *discrete* element to the mix! Citation, co-citation, co-authorship – the scientometric literature invariably treats these as discrete objects themselves. This manifests itself in the visualizations – remember that each of those is a conceptual model – generated in science mapping, as they almost exclusively consist of point symbols (for authors, papers, journals) that are sometimes connected by lines (for citations, co-citations, co-authorship) to form networks (Institute for Scientific Information, 1981). When journals are the subject of a study then each journal is represented as a single point symbol, possibly linked to other journals; ditto for authors, individual articles, and disciplines (Fig. 2).

What are the reasons for the dominance of the discrete object view in the mapping of science? Three dominant reasons can be pointed out: (1) the driving influence of the information retrieval tradition, (2) conceptualizations inherent in the dominant data transformation methods, and (3) a certain degree of reverse ontology where source data drive the conceptualization of science.

First, as has been pointed out elsewhere (Börner et al., 2003; White & McCain, 1997), researchers working on methods for science mapping have mostly been emerging out of the information retrieval tradition. In information retrieval there is a natural emphasis on ultimately providing access to the original data items. *Search* as the dominant paradigm and *recall* and *precision* as the main validation mechanisms in information retrieval lend themselves to a discrete object view. Remember that recall and precision rely on the ability to count items.

Second, the methods traditionally used to transform science communications into visual depictions enforce a discrete object view. Consider the case of multidimensional scaling (MDS) and its various derivative methods used for dimensionality reduction (see Fig. 2b–d). Distances between input vectors are computed to generate a distance matrix. Then an attempt is made to preserve relative distances as much as possible in two dimensions. With *m* input vectors we will always end up with exactly *m* point locations in the output. Interestingly, the space between those features remains an undefined void, both in high-dimensional input space and low-dimensional display space (Skupin, 2002). Meanwhile, the planar enforcement attempted by network layout algorithms (e.g., Kamada & Kawai, 1989) likewise implies a discrete object view.

Third, the capture and distribution of data about science – such as citation databases – is so consistently based on clearly delineated objects, that it becomes difficult to *think* about articles, authors, journals, or citations in any other way. This is akin to the reverse ontology trap encountered when "a forester who is an experienced user of a GIS for analysis such as ArcInfo . . . will begin to think of forest stands in an analytical context more as 'polygons' than as complex areal entities with often ill-defined boundaries" (Peuquet, 2002, p. 268). The very term 'polygon' derives from the on-the-ground surveying tradition (polygons = many angles), where detailed measurement of discrete entities is essential. Compare this to the emergence of remote sensing, where a single, continuous snapshot of the ground is taken. Unless an application specifically calls for it, many environmental models that use remote sensing and other continuous coverage data (such as from high-density sensor networks) never involve discrete features at all! Arguably, fulfilling such aspirations as science prediction will require moving towards richer conceptualizations of science translated into specific computational methods. For example we will have to be able to express the relation between two articles as their "citationness" instead of only the binary citation value currently used, where a citation or co-citation link either exists or is absent. We will also need to be able to ask "what is this person's 'authorness' in this subject area?" instead of "has this person published on this?" Incidentally, note the difference between the more fuzzy notion of *authority* versus the crispness of *author*.

3. Conceptualizing science: beyond discrete objects

The purpose of this paper is to draw attention to the fundamental duality of discrete and continuous phenomena as a cognitively informed starting point for the conceptualization and visualization of science. While this is for the first time explicitly voiced in this paper, the differences and relative advantages/disadvantages of the two perspectives are fundamental enough that it is not surprising that some researchers have begun to work towards a continuous field perspective. The emergence of landscape-type visualizations of science is a good example. However, the lack of a thorough, cognitively informed framework makes itself felt even then. Landscape visualization involving mountains and valleys may *look* similar, even if they are based on fundamentally different concepts. Examples are the terrain-like landscapes seen in ThemeScapes (Wise, 1999), VxInsight (Davidson, Hendrickson, Johnson, Meyers, & Wylie, 1998), and term dominance landscapes (Skupin, 2004).

In the case of VxInsight, the surface constructed from text documents actually represents an aggregate view of *discrete objects*, "with the height of each mountain being proportional to the number of objects beneath it" (Boyack, Wylie, Davidson, & Johnson, 2000). On a conceptual level, such a density surface is fundamentally different from a surface representing a continuous phenomenon, like temperature. A continuous phenomenon could actually be observed at arbitrarily chosen zero-dimensional locations anywhere within the space, but that is not the case for a density surface. Two surfaces – one constructed through interpolation, the other through density computation – may obtain the same look, but their cognitive plausibility (Fabrikant & Skupin, 2005) arguably differs, since one represents a continuous field and the other a set of discrete objects.

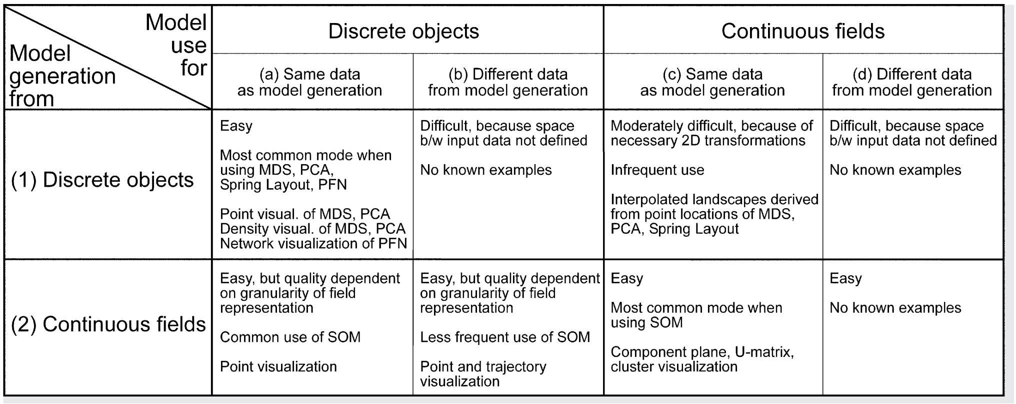
Things are a bit more complicated with Themescapes, where the final surface is built up as the local sum of multiple term surfaces. However, each of those term surfaces is actually a smoothed density surface depicting the density of documents with which that term is locally associated (Wise, 1999). Therefore, like VxInsight, we are again dealing with a view of textual reality as consisting of discrete objects.

What is the missing link here? Why is it that the understandable drive towards richer visualization involving both discrete and continuous concepts – such as in the creation of surface visualizations – has not yet led to sufficiently coherent results? One answer may be that the deliberate application of spatial concepts must be directed not only at the building blocks of the system of science communication (authors, articles, etc.), but also at how those building blocks are manipulated in the course of visualization. As argued by Skupin (2002), most traditional dimensionality reduction techniques have been implicitly wed to the object view, as when MDS-based visualizations almost always consist of point displays. One approach to break out of this is to apply further transformations to the raw two-dimensional geometry. The landscapes generated in Themescapes and VxInsight are an examples for that. While Wise (1999) explicitly acknowledges the adoption of techniques derived from GIS within Themescapes, we must move beyond that towards adopting fundamental spatial concepts used in GIScience.

One useful distinction one can make is in terms of:

(a) how the data from which a spatial model of science is *generated* are conceptualized,
(b) whether the data to which a model is applied is the same as the data from which the model was generated, and
(c) how the data to which a spatial model of science is *applied* are conceptualized.

Table 1
Consequences of different conceptualizations underlying model creation versus model use.



Model use for / Model generation from	Discrete objects		Continuous fields	
	(a) Same data as model generation	(b) Different data from model generation	(c) Same data as model generation	(d) Different data from model generation
(1) Discrete objects	Easy Most common mode when using MDS, PCA, Spring Layout, PFN Point visual. of MDS, PCA Density visual. of MDS, PCA Network visualization of PFN	Difficult, because space b/w input data not defined No known examples	Moderately difficult, because of necessary 2D transformations Infrequent use Interpolated landscapes derived from point locations of MDS, PCA, Spring Layout	Difficult, because space b/w input data not defined No known examples
(2) Continuous fields	Easy, but quality dependent on granularity of field representation Common use of SOM Point visualization	Easy, but quality dependent on granularity of field representation Less frequent use of SOM Point and trajectory visualization	Easy Most common mode when using SOM Component plane, U-matrix, cluster visualization	Easy No known examples

Specific visualizations reflect an intersection of those three aspects (Table 1). It becomes clear that most existing visualizations of science fall into a single segment (1a in Table 1), where a model is generated from discrete objects and is applied to discrete objects, which actually are the very same data set as those used in model generation. Visualizations based on the self-organizing map (SOM) method (2a–d in Table 1) are among the few where model generation is based on a conceptualization of source data as representing a continuous field (Skupin, 2002). Current methods can be categorized in that manner, but one can also identify methods that do not yet exist. For example, I would characterize the application of a science model generated from continuous fields to science data likewise reflecting a continuous field view (2d in Table 1) as quite straightforward, yet I am not aware of any examples for it.

4. Visualizing science based on different conceptualizations

Guided by a conceptualization-based framework for visualizing science, we can now proceed to demonstrate what the effect would be if only a few aspects of a knowledge domain visualization were to change. In this case, we will dedicate ourselves to the notion of the “author.” The only change will be to conceptualize an author as a single discrete entity in a knowledge domain versus conceptualizing the same author as a continuous field that permeates all of the knowledge domain. In addition, the source data on the basis of which we will map that author onto the knowledge domain will not be part of the data set from which the knowledge domain model was created. We are thus demonstrating visualizations set in segments 2b and 2d of Table 1. Finally, we will also illustrate how temporal change in an author’s intellectual output can likewise be visualized on the basis of the discrete versus continuous view.

4.1. *What is an author?*

One major reason for using the concept of an author to illustrate implications of different conceptualization is that the concept is not at all contested within visual or computational approaches to science modeling. There is no explicit indication in the scientometrics literature that authors are anything other than discrete entities, clearly distinct and delineated from each other. On the other hand, as mentioned earlier, such methods as co-author network analysis represent an implicit acknowledgement that the author concept is a bit more complicated. One has to turn to critical theory, largely of French origin, to find explicit discussion of related issues. Michel Foucault and his famous essay “What is an author?” is a prime example (Foucault, 1979), as is Roland Barthes’ radical “Death of the Author” (Barthes, 1977). Unless scientific literature is sufficiently different from other literatures – a point that itself is under debate – constructive engagement of postmodern literary theory by scientometrics remains a crucial endeavor, but is outside the scope of this paper.

The approach presented here is far more pragmatic. We ask whether a choice between conceptualizing an author as a discrete object or as a continuous field can have specific consequences for visualization. This can be answered in the affirmative, as will be demonstrated next. The sequence of data modeling steps introduced in Fig. 1 provides a good basis for understanding the consequences of choices made at the conceptual stage (Fig. 3). Those two choices ultimately lead to the two different visualizations presented in Figs. 4 and 5.

Note how despite the choices made, all data generated in the process end up in the same database. This is meant to highlight that visualizations derived from different conceptualizations can in fact occupy the same space, thereby enabling overlay operations. The notion of a *base map* is central to operationalizing this. Specifically, a data set of 22,000+ abstracts submitted to the Annual Meeting of the Association of American Geographers (AAG) between 1993 and 2002 was used to first construct a base map representing the knowledge domain of geography. The core methodology consists of a representation of each abstract as an n-dimensional document vector ($n = 2{,}586$), followed by the construction of a two-dimensional model of the document space as a SOM, and visualization in GIS software (Skupin, 2004).

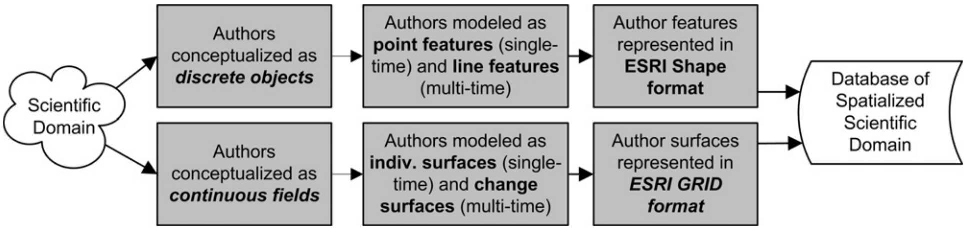


Fig. 3. The effect of different conceptualizations of *authors* on subsequent data modeling steps.

The self-organizing map used here consists of a two-dimensional lattice of nodes that are arranged in a regular hexagonal pattern, with each node having six neighbors. Each of these nodes, also known as neurons, has associated with it a vector of *n* weights. Within each neuron vector, there is one weight value for each of the *n* terms of the input vocabulary. These weights are initially given random values. During training, one input document vector at a time is presented to the SOM, prompting the computation of document-neuron similarities, which is made possible by the fact that document vectors and neuron vectors have the same length *n*. Once the most similar neuron vector to a particular document vector is found, the weights of that best-matching neuron are updated in the direction of an even better match. Neighboring neurons in the two-dimensional lattice are likewise updated, up to a certain distance from the best-matching neuron. Then, the next document is compared to now-current set of neurons, the best-matching neuron is found, and so forth. Over the course of thousands of these training cycles, the SOM will slowly come to represent major topological structures existing in the *n*-dimensional input space (Kohonen, 2001; Skupin & Agarwal, 2008). Due to the large number of 10,000 neurons, the SOM method here functions as a dimensionality reduction technique, with each neuron representing a small portion of the *n*-dimensional input space.

Use of the SOM method implies that AAG abstracts are interpreted as samples from a science continuum and that the result does not represent the input vectors themselves but that instead a true *model* is constructed from the vectors. The model itself (i.e., the two-dimensional arrangement of neurons) can be visualized, for example through clustering (top center of Figs. 4 and 5). Note that these clusters are constructed from the raster-like, space-filling model of the document space itself (Skupin, 2004), not from the input documents, as compared to density-based approaches previously mentioned. The labeled cluster solution will serve as backdrop to all further visualizations, providing a stable visual reference.

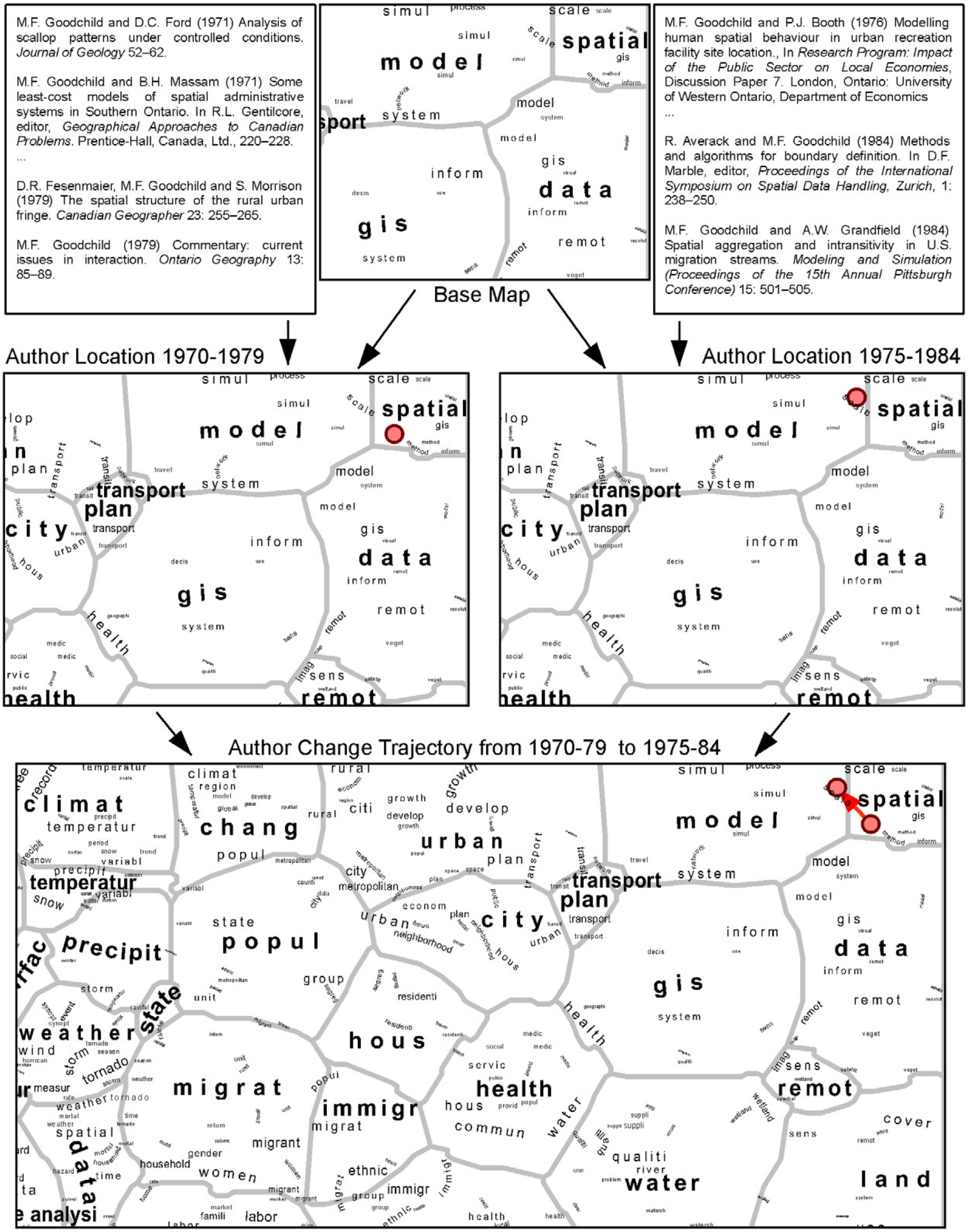
That model can now be applied to *other* data that are conceptualized either as discrete objects or continuous fields (2b and 2d in Table 1). With a goal of visualizing author dynamics, two sets of publications were extracted from the curriculum vita of Michael Goodchild, the most well-known GIScience researcher. One consists of a list of 27 papers published between 1970 and 1979. The other set contains 45 papers published between 1975 and 1984. The 5-year overlap was chosen to make the source data less susceptible to minor temporal variation. Each of the two time slices is extracted by simply copying the according section of Goodchild's CV (upper left and upper right in Figs. 4 and 5). Each slice containing a 10-year range of publications is then processed as though it was a single document, including stop word removal, stemming, and finally indexing against the same dictionary of *n* terms as the original abstracts used to train the SOM. The two *n*-dimensional term vectors with which Goodchild becomes represented can be thought of along the lines of Howard White's author CAMEOs, specifically the natural language type (White, 2001). Since each neuron in the SOM likewise consists of a vector with length *n*, one can perform similarity computations between the time slice vectors and the 10,000 neuron vectors. Similarity/dissimilarity between time slices and neurons is at the heart of how authors are mapped onto the knowledge domain model.

4.2. Author as discrete object

In the discrete object view, a given author is conceptualized as existing at certain locations in the knowledge domain, but not at others. For two different time slices, an author is conceptualized as having occupied two different locations. Computationally, one can determine the position of each time slice vector with respect to the neural model by finding the most similar neuron vector and assigning its two-dimensional location to the time slice (Fig. 4, middle). If at a single moment in time an author is conceptualized as a single discrete object, then over multiple time periods a cognitively plausible conceptualization is that of a trajectory (Fabrikant & Skupin, 2005), which becomes represent by a line symbol in the visualization (Fig. 4, bottom). One interesting aspect of this discrete approach is its efficient, compact use of the available display space. The graphic footprint of the trajectory is so small that there would be enough space left to overlay other discrete elements. For example, one could add the trajectories of additional authors. That would enable us to explicitly invoke additional metaphors that have traditionally been associated with discrete objects, such as proximity, parallelism, convergence, and divergence.

4.3. Author as continuous field

How can we justify conceptualizing an author as a continuous field? Imagine you had to map Eugene Garfield onto a map of the field of scientometrics. If all you had available was a single point symbol to represent Garfield, where would you position it? Thinking this through conceptually, wouldn't this mean that Eugene Garfield could be "found" there and *only* there in scientometrics? Given the influence of Eugene Garfield on the field, shouldn't he occupy a much larger *area*? And,



M.F. Goodchild and D.C. Ford (1971) Analysis of scallop patterns under controlled conditions. *Journal of Geology* 52–62.

M.F. Goodchild and B.H. Massam (1971) Some least-cost models of spatial administrative systems in Southern Ontario. In R.L. Gentilcore, editor, *Geographical Approaches to Canadian Problems*. Prentice-Hall, Canada, Ltd., 220–228.

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D.R. Fesenmaier, M.F. Goodchild and S. Morrison (1979) The spatial structure of the rural urban fringe. *Canadian Geographer* 23: 255–265.

M.F. Goodchild (1979) Commentary: current issues in interaction. *Ontario Geography* 13: 85–89.

M.F. Goodchild and P.J. Booth (1976) Modelling human spatial behaviour in urban recreation facility site location., In *Research Program: Impact of the Public Sector on Local Economies*, Discussion Paper 7. London, Ontario: University of Western Ontario, Department of Economics

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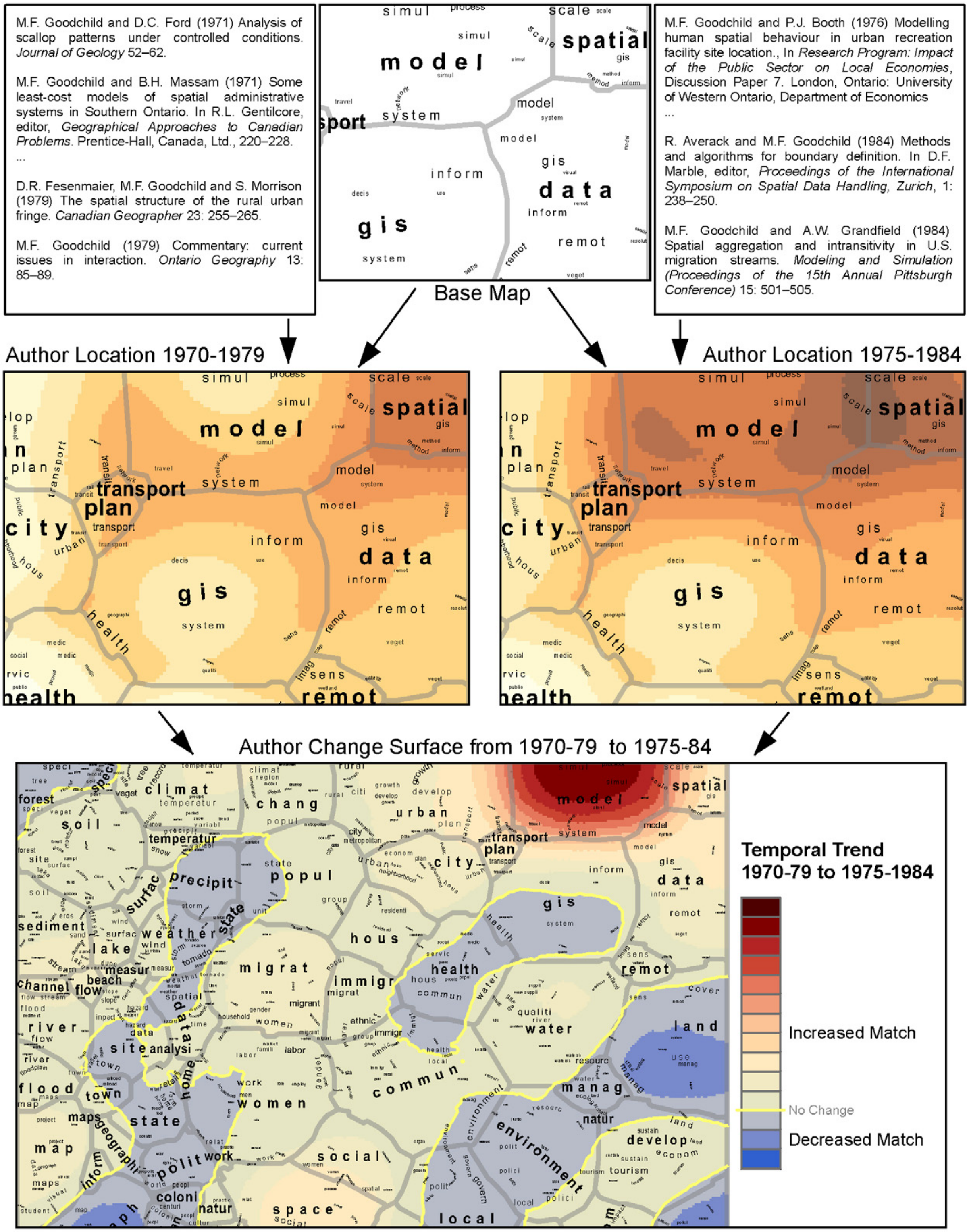
R. Averack and M.F. Goodchild (1984) Methods and algorithms for boundary definition. In D.F. Marble, editor, *Proceedings of the International Symposium on Spatial Data Handling, Zurich*, 1: 238–250.

M.F. Goodchild and A.W. Grandfield (1984) Spatial aggregation and intransitivity in U.S. migration streams. *Modeling and Simulation (Proceedings of the 15th Annual Pittsburgh Conference)* 15: 501–505.

Fig. 4. A scientist conceptualized as a multi-temporal discrete object becomes represented as a trajectory. Michael F. Goodchild is visualized on a base map constructed from 22,000+ abstracts submitted to the Annual Meetings of the Association of American Geographers (AAG).



M.F. Goodchild and D.C. Ford (1971) Analysis of scallop patterns under controlled conditions. *Journal of Geology* 52–62.

M.F. Goodchild and B.H. Massam (1971) Some least-cost models of spatial administrative systems in Southern Ontario. In R.L. Gentilcore, editor, *Geographical Approaches to Canadian Problems*. Prentice-Hall, Canada, Ltd., 220–228.

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D.R. Fesenmaier, M.F. Goodchild and S. Morrison (1979) The spatial structure of the rural urban fringe. *Canadian Geographer* 23: 255–265.

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M.F. Goodchild and P.J. Booth (1976) Modelling human spatial behaviour in urban recreation facility site location., In *Research Program: Impact of the Public Sector on Local Economies*, Discussion Paper 7. London, Ontario: University of Western Ontario, Department of Economics

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R. Averack and M.F. Goodchild (1984) Methods and algorithms for boundary definition. In D.F. Marble, editor, *Proceedings of the International Symposium on Spatial Data Handling, Zurich*, 1: 238–250.

M.F. Goodchild and A.W. Grandfield (1984) Spatial aggregation and intransitivity in U.S. migration streams. *Modeling and Simulation (Proceedings of the 15th Annual Pittsburgh Conference)* 15: 501–505.

Fig. 5. A scientist conceptualized as a continuous field for a given time slice (darker shading indicates stronger match) becomes represented as a change surface, when the earlier time surface is substracted from the later surface. Michael F. Goodchild is visualized on a base map constructed from 22,000+ abstracts submitted to the Annual Meetings of the AAG.

to take this thought further, wouldn't that area extend over all of scientometrics? Doesn't Garfield occupy in some sense *all* of scientometrics?

More generally speaking, what does it really mean to call someone a "geographer," "information scientist," or "philosopher" if a single author is conceptualized as a single discrete object? Some might answer that a knowledge domain is simply the aggregation of all individual authors engaged in it. However, even at the level of the individual author that is not quite satisfying. Consider the location of Michael Goodchild in Fig. 4, according to which his interests had a singular focus at each moment in time. Did he never deal with any other topics in the geographic knowledge domain? We might learn something about his primary interests, those most persistently coming through in his publications, but we learn nothing about secondary and tertiary interests and how those might have changed over time.

Alternatively, one could argue that, like Eugene Garfield in scientometrics, the geographer Michael Goodchild does occupy all of the knowledge domain of geography. However, in reflection of the hierarchy of his interests, not all parts of geography would be equally well matched. Goodchild will have a stronger response in some regions than in others. We could recognize this by conceptualizing him as a field that continuously occupies all of geography.

To implement this for the map of geography, one would have to map a continuous field onto a continuous model and using data that played no role in that model's creation (Table 1, section 2d). With the trained SOM as a starting point, that is not difficult. The approach taken here is to compute for each neuron its similarity to Goodchild's CV extract, by comparing the *n*-dimensional neuron vector to the *n*-dimensional CV vector. This computation is the same as in the case of the discrete conceptualization described earlier. However, instead of discarding all but the *most* similar neuron, *each* neuron's similarity to a given time slice is kept. This results in a continuous field of *n*-dimensional similarity values, which can be mapped onto the SOM by virtue of the known two-dimensional neuron locations, with similarity values providing elevations for a landscape. Each 10-year time slice of Goodchild's publications can thus be visualized as a continuous surface (Fig. 5, middle).

Since each temporal landscape is completely space-filling, change over time can not be visualized as a simple trajectory. Instead, change itself is conceptualized and implemented as continuous as the two time slices. Computationally, one can use raster algebra to subtract the earlier surface from the later one. This is here done in off-the-shelf GIS software (ArcGIS), which was used for all other two-dimensional processing as well. The result is a change surface, with some regions showing a stronger match to the author's interest and others showing a decreasing match over time (Fig. 5, bottom). Notice how explicit and expressive change is depicted. The region labeled "model" shows by far the strongest growth and this corresponds to the direction the trajectory in the discrete object view points to (Fig. 4, bottom). The more interesting aspect is the emergence of secondary regions of increase (e.g., "space") and decrease (e.g., "land use"). The price one pays for all the additional information conveyed through this visualization derived from a conceptualization of an author as continuous field is that much more space is occupied.

One could demonstrate this kind of juxtaposition of the effects of discrete versus continuous concepts for many more circumstances. For example, as already mentioned, in the discrete mode the trajectories of different authors could be visually compared. Meanwhile, in continuous mode, one could subtract the change surfaces of different authors from each other to arrive at a continuous landscape of author difference.

5. Conclusions

As argued in this paper, science mapping has not yet sufficiently connected with thorough reflection on the conceptualization of science. While the spatializations generated in the course of science mapping presume the existence of a high-dimensional spatial reality within which science is situated, the *nature* of that space remains largely unexplored. We have contrasted that with how geographic space has been actively engaged by geographic information science. Specifically, the two main conceptual approaches were discussed: the discrete object view and the continuous field view.

Conversely to these two principal approaches taken in dealing with geography, it appears that the elements of science are almost exclusively conceptualized as discrete objects, from articles to authors, journals, and citations. One may wonder to what degree this is driven by the data collected about science – such as citation databases – as opposed to deliberate reflection on the subject matter.

An unnecessarily narrow perspective on how science is conceptualized – based only on discrete objects – impedes the development of methods not just for visualization. In GIScience, visualization is only one of a broad range of modeling applications, all of which can be linked to how geographic space is conceptualized. From monitoring to prediction, science modeling will similarly depend on a richer set of concepts than is currently employed. Adding a continuous field perspective to the conceptualization of science can have consequences for scientometrics and its wide-ranging applications, from the academic workplace to science policy. Fortunately, some core concepts have been questioned by the information science community for some time, as in the case of "the document" (Briet, 2006) or "the work" (Smiraglia, 2001). The distinction between intellectual content and physical form promoted by Smiraglia seems a particularly helpful bridge towards being able to *see* existing concepts in a new light/space, but there is little evidence so far that those insights have connected with visualizations of science. There is a need to trace geographic metaphors (e.g., landscape) back to their source domain – geography – and likewise to link methods for implementing geographic metaphors (e.g., MDS) to principles developed in geographic information science.

The point of this paper was not to extol the virtues of the continuous field view versus the discrete object view. Each of the examples discussed, from MDS-based mappings to Themescapes, VxInsight, and the SOM-based overlay, has its place in a yet to be expounded conceptualization-based methodological framework for science mapping. Beyond the duality discussed here, one will want to consider transitory stages. This applies not only to the degree of discreteness or continuity, but also to the abrupt or smooth character of change across space (MacEachren, 1992). The ultimate goal must be to *combine* these perspectives in a multimodal manner while adapting to different questions being asked under different circumstances. A view of the conceptualizations of science inspired by the multifaceted views of the geographic space will hopefully be a useful step towards that goal.

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