GeoComputation in context

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Abstract

This paper considers GeoComputation in its disciplinary, epistemological, and societal contexts. It addresses three groups of questions: (a) the place of GeoComputation within geography, in particular in connection with GIS; (b) the epistemological legitimacy of GeoComputation as an approach to geographical research and problem solving; (c) GeoComputation's societal antecedents and implications. The paper examines the widely held view of GeoComputation as a collection of computational techniques and finds it unsatisfactory for several reasons, central among which is the neglect of any systematic connection with spatial theory and the theory of computation. The essay concludes with some of the challenges facing GeoComputation in this broader context of disciplinary, theoretical, and societal issues.

1 Introduction

The provisional working definition for GeoComputation adopted in this essay is the eclectic application of computational methods and techniques 'to portray spatial properties, to explain geographic phenomena, and to solve geographic problems'. This paraphrases Dobson's (1983) early attempt to define 'Automated Geography', a concept we would now readily identify with GeoComputation as formulated by the organizers of the first three conferences of that name. According to the prospectus of *GeoComputation 97*, the new term and conference series emerged in response to a growing need to bring together the diverse research efforts seeking to capitalise on the vastly expanded 'opportunities for taking a computational approach to the solution of complex geographical problems'. GeoComputation is understood to encompass a wide array of computer-based models and techniques, many of them derived from the field of artificial intelligence (AI) and the more recently defined area of computational intelligence (CI). These include expert systems, cellular automata, neural networks, fuzzy sets, genetic algorithms, fractal modelling, visualization and multimedia, exploratory data analysis and data mining, and so on. The announcement of *GeoComputation 98* goes further, stating that 'spatial computation represents the convergence of the disciplines of computer science, geography, geomatics, information science, mathematics, and statistics'. There is a suggestion here of something called 'spatial computation' that may go beyond the mere sharing of computational techniques, since no 'convergence of disciplines' has ever been achieved through the use of spreadsheets, statistical software, or graphics packages.

In considering GeoComputation in its broader context, the key question this essay addresses is whether GeoComputation is to be understood as a new perspective or paradigm in geography and related disciplines, or as a grab bag of useful computer-based tools. I will assume that the former is at least potentially the case, as there is little scope in talking about the broader context of grab bags or toolboxes. I have no quarrel with those to whom GeoComputation just means the universe of computational techniques applicable to spatial problems: this is probably quite accurate a characterisation of the current state of the art. The question is whether or not we are witnessing the rise of a distinct intellectual approach to the study of geographical space through computation, that is, whether the GeoComputation whole will ever be more than the sum of the computational parts.

This paper considers GeoComputation in its disciplinary, epistemological, and societal contexts. Accordingly, it addresses three groups of questions: (a) the place of GeoComputation within geography, in particular in connection with GIS; (b) the epistemological legitimacy of GeoComputation as a scientific approach to geographical research and problem-solving; (c) GeoComputation's societal, historical and institutional antecedents and implications. Many of these issues parallel those surrounding computation in general and more specifically, AI. Without neglecting some of the major points common to all aspects of the computational revolution, this essay will focus on the questions more specific to the spatial sciences and geography in particular. The essay concludes with some of the challenges facing GeoComputation in this broader context of disciplinary, societal, and philosophical issues.

2 GeoComputation and geography

A first group of issues concerns the place of GeoComputation within a geographical research and applications environment that is by now widely computerized and data-oriented. Even disregarding pervasive but clearly non-geographical applications (word processing still being by far the most common use of the computers on most geographers' desk), there are very few areas within geography that have no use for - say - a computer-generated map, graphic, or table. More significantly, there are fewer and fewer areas (and not just within geography) that have not been touched by GIS. In some sense we have been doing GeoComputation for many years without knowing it. Less trivially, however, it is fair to say that GeoComputation has thus far found only limited acceptance within the discipline. More surprisingly, it even has an uneasy relation with mainstream quantitative geography, as evidenced by the relative dearth of GeoComputation-orientated articles and topics in the main quantitative geography journals and texts. These statements must be qualified by the ambiguity of what really counts as GeoComputation work, this being a fuzzy set rather than a Boolean category. Still, in my mind, there are clear instances of the set as well as marginal ones, and it is the more (proto)typical ones that tend to find the least recognition. My remarks in this essay concern primarily these more representative cases. There is not much point in trying to specify what is 'core GeoComputation' and what is not, but let us agree that the core does not include most traditional computer-supported spatial modelling and analysis of spatial data. In particular, it does not include routine GIS research and applications. Indeed, GIS is in many ways the antagonistic big brother who is robbing GeoComputation of the recognition it deserves.

Contrasting the development of GeoComputation with that of GIS is instructive. While part of GeoComputation broadly defined, GIS has enjoyed tremendous popularity and commercial success for nearly two decades, whereas GeoComputation is still waiting to take off both as a concept and as actual practice. Novelty is not the explanation, since neither the individual techniques that are part of it, nor the notion of GeoComputation in itself are very new, as may be seen from Dobson's (1983) 'Automated Geography' article and the ensuing discussion forum in the August 1983 issue of the *Professional Geographer*. This section examines the reasons for this discrepancy and the very different roles of GeoComputation and GIS within the disciplinary matrix.

The phenomenal success and rapid spread of GIS both within geography and well beyond have been amply documented (Foresman 1998; Goodchild 1998). GIS courses in universities cannot keep up with student demand. The GIS specialty group is by far the largest within the US Association of American Geographers (AAG), and there are few academic job advertisements in geography that do not require at least some GIS skills. There are dozens of GIS texts, and it seems, a new GIS-orientated journal is being launched every few months. GIS conferences abound, some of them drawing thousands of participants. The GIS industry has been booming for the past fifteen years and its products can be found all over the globe in both rich and poor countries. In the late eighties the US National Science Foundation (NSF) deemed GIS important enough to become the focus of a national research priority, funding the National Center for Geographic Information and Analysis (NCGIA). Shortly thereafter, the European Science Foundation (ESF) followed suit, supporting the five-year GISDATA programme across European countries.

The reasons for the success of GIS are many, among them of course luck and serendipity, but some of these stand out as defining everything GeoComputation has not yet been. These include the early beginnings in a large-scale, very visible, and eminently practical application (Tomlinson 1998); the major institutional and commercial interest that these applied origins attracted; the compatibility with the highly respected cartographic tradition in geography; the strong visual orientation; and the intuitive appeal of the overlay model of GIS operation, a time-honoured principle that could be explained in a few words (or pictures) to anyone not already familiar with mylar overlay techniques. In many ways GIS was geography's 'horseless carriage', a technological advance that would allow applied geographers and others to do faster, more comfortably, and better what they had always done. That the horseless carriage would eventually change the structure of the disciplinary landscape was not foreseen at the time, and certainly most GIS pioneers did not make any such claims. Contrast this reassuring background with that of GeoComputation: no major applied demonstration project; no significant institutional or commercial interest in its further development and diffusion; no obvious affinity with any of the major intellectual themes in geography and related fields; no characteristic visual or other easily accessible mode of presentation; no unifying, simple to grasp underlying principle; instead, rumbles about a revolution *ante portas*, that are not substantiated either by the past record nor by some coherent vision of things to come (Dobson 1983, 1993; Openshaw and Openshaw 1997).

Adding insult to injury, many of the original proponents of the notion of GeoComputation ended up identifying it with GIS a decade down the road. In 1993, the tenth anniversary of the 'Automated Geography' discussions, the *Professional Geographer* invited most of the original and some new contributors to comment on how the emerging perspective had fared since it was first debated in the journal in 1983. It is instructive to read these more recent contributions written after the GIS revolution had become part of the mainstream. In most of them the terms Automated Geography and GIS are used interchangeably (Cromley 1993; Goodchild 1993; Pickles 1993; Sheppard 1993). Even Dobson himself capitulates under the assault of the GIS steamroller: in his words, “today GIS is often used implicitly as a covering term for the collective technologies… that I listed as components of Automated Geography.” (Dobson 1993: 434). A perusal of the two earlier volumes of GeoComputation conference proceedings confirms that this is indeed a fairly common view. Most supporters of GeoComputation will agree however that GIS, widely regarded to be ‘geography’s piece of the computer revolution’, is only a part of a much broader project that has yet to be fully spelled out.

In my view a critical part of the definition of GeoComputation is the distinction, routinely overlooked even by experts, between **computation** and **computing**. As a first approximation this is the difference between approaching the computer as an integral component of the modelling of complex systems and processes, *versus* treating it as an equation-solving and data-handling device. While there may be no clear demarcation line between these two views, most practitioners will agree that a difference exists and that it is important. The following section explores further the significance of that distinction. But even granting that computation in geography goes beyond the mere use of computing, it is not immediately evident why all the disparate research and application areas that make use of certain kinds of computational technique(s) deserve to be pulled together under a new fancy designation (Kellerman 1983). The ‘quantitative revolution’ in geography earned its name precisely because it went well beyond the introduction of mathematical and statistical techniques to provide a truly new angle to the conceptualization of geographical space, problems, and phenomena. Will GeoComputation ever be able to claim as much?

3 The epistemology of GeoComputation

Consideration of the reasons for the slow diffusion of GeoComputation relative to GIS and other computer-based methods and tools quickly leads to epistemological questions. A presentation of GeoComputation by some of its proponents as theory-free and philosophy-free has not only deterred many potential adopters but is also factually incorrect. Indeed, it is precisely the fact that GeoComputation is loaded with unfamiliar and unclarified epistemological underpinnings that accounts for much of the skepticism with which the approach has been received. This section begins by contrasting the apparent epistemological poverty of GeoComputation with the rich philosophical and theoretical roots of quantitative geography. It then proceeds to explore the epistemological background of computation, this being the natural area to search for the basis of a theory of geo-**computation**. Last, the significance of the ‘**geo-**‘ prefix is questioned in a brief discussion of whether GeoComputation may mean something more than merely the use of computational techniques in geography and related fields.

While contrasting GeoComputation with GIS helps clarify mostly the practical reasons for the relatively slow development of the former, a comparison with quantitative geography sheds light on the theoretical side of the issue. The comparison is apposite because of the strong affinities between the two perspectives: both make heavy use of geographical data, both emphasize modelling, both involve extensive use of computers, and most proponents of GeoComputation have intellectual roots in mainstream quantitative geography. As every undergraduate knows, geography's quantitative revolution was heavily influenced by the tenets of positivist philosophies and the physicalist model of science. The quantitative movement soon coalesced around the set of research objectives and practices deriving from the positivist formulation of the scientific method: observation and measurement, experimental design, hypothesis testing, mathematical modelling and theory development, and the standards of objectivity, replicability, and analytic thinking (Harvey 1969). What held this intellectual culture together however were not the methods themselves but the underlying belief that the world studied by human geography, no less than that of physical geography, is amenable to the same kinds of approaches to description and explanation, if not prediction, as the world of physical science. Moreover, positivist geographers were able to define the whole discipline on the basis of one of the most fundamental notions in physics - space. Geometry, the formal science of space, provided the theoretical foundation on which quantitative geography was built, and cemented the identity of a substantial part of the discipline as the **spatial science**.

Whatever one may think of the positivist worldview as an epistemological position (and goodness knows the critics have not left unchallenged a iota of it), it did provide its followers with a strong sense of identity and purpose as well as non-negligible amounts of professional pride. Mainstream quantitative geography, like it or not, is a complete intellectual programme: it has a philosophy, a set of accepted research practices, techniques that draw their credibility from being derived from those of hard science, and a widely accepted conceptual framework based on the abstract properties of space. It did not accomplish everything it had set out to do, but it was a mighty good try (Macmillan 1989). Contrast that with GeoComputation: no philosophy (and proud of it!), no set of approved practices to help define the standards of acceptable work, a haphazard collection of techniques developed for all sorts of different purposes in a variety of areas with sometimes unproven intellectual credentials, and last but not least, no obvious conceptual framework to define some alternative vision of what geography may be about, or where it might go. While these traits may appeal to our postmodern longings for deconstruction, it is no wonder that most quantitative geographers - who, incidentally, took to comput-**ing** (and GIS) like ducks to water - continue to hold GeoComput-**ation** at arm's length.

It does not have to be that way, for GeoComputation is a stepchild with quite distinguished hidden parentage. Computation is the name of a theory - the highly formal **theory of computation** (Minsky 1967, Lewis and Papadimitriou 1981). In contrast with the computer revolution, which made computers part of everyday life, the computational revolution was a conceptual one the effects of which were felt primarily within the domains of mathematics, theoretical computer science, cognitive science, and some areas in modern physics. Much better known both within other sciences and among the educated public were the widely popularised developments in chaos theory and complex systems (Waldrop 1992), though few people are aware of the close links between these ideas and the formal theory of computation.

The theory of computation is the theory of **effective procedures**. According to Minsky, one of the pioneers of the theory of computation, the notion of effective procedure

> "already promises to be as important to the practical culture of modern scientific life as were the ideas of geometry, calculus, or atoms. It is a vital intellectual tool for working with or trying to build models of intricate, complicated systems – be they minds or engineering systems. … I believe it is equally valuable for clear thinking about biological, psychological, mathematical, **and (especially) philosophical questions**." (Minsky 1967:viii, emphasis added).

In a nutshell, an effective procedure is a step-by-step description of a process that is sufficiently well specified to be carried out by a dumb machine that can follow instructions. The notion is closely related to that of algorithm but has some additional theoretical connotations. This innocuous-looking idea provides the theory of computation with some very profound questions that may be tackled with the tools of modern mathematics and logic as well as philosophy: What processes in the world can be described in such precise manner? What is the appropriate language for describing specific processes? Could any one fixed language deal with all describable processes? Could any one type of machine deal with all possible effective procedures? Can there be well-defined processes that cannot be expressed as effective procedures? Is the operation of the mind an effective procedure? (Minsky 1967:104). And so on. Thus at the core of the theory of computation is an unlikely combination of concepts that include, in addition to effective procedure, the notions of machine, language, and process. Each one of these is addressed by one of the three main branches of the theory of computation: **automata theory** deals with the sequence of increasingly powerful abstract machines, of which the Turing machine is by far the most important; **formal grammar theory** deals with the hierarchy of languages that can be 'understood' by the hierarchy of abstract machines; and the **theory of recursive functions** uses number theory to represent the computation performed by a Turing machine as a numerical encoding. These three perspectives on computation are formally equivalent in the sense that any results obtained in one of them can be translated into corresponding results in the others, even though the different angles yield different kinds of insights and one or the other may be more suitable for specific purposes (Lewis and Papadimitriou 1981; Hopcroft and Ullman 1979). Adherents of GeoComputation are familiar with at least one direct application from each of the first two branches: cellular automata from automata theory, and shape grammars from formal grammar theory. I am not aware of any equally obvious example from the theory of recursive functions, although the programming language LISP that was developed specifically for the needs of AI is based on that theory.

There are two potential contributions of the theory of computation to GeoComputation as a theoretical project, which I shall call syntactic and semantic. Here I summarize the more detailed argument developed in Couclelis (1986) regarding the theoretical credentials of AI in particular. The syntactic contribution stems from the hierarchy of formal structures illustrated in Figure 1. Set theory and logic begot modern algebra. Aspects of modern algebra are specialized in the mathematics of discrete structures, which include graphs, lattices, Boolean algebras, and combinatorics. At the next level down, there are general theories of modelling such as Zeigler's (1976) which systematise the formal principles of modelling and simulation in any field. These provide a framework for an integrated representation of the three branches of the theory of computation one level down. Below that we have the more familiar specialisations of the theory of computation such as AI, computer architectures, parallel distributed computing, and the different programming languages. There are unbroken chains of structure-preserving relations or structural equivalences connecting the theory of computation with set theory and logic at one end, and with concrete computer programs at the other. Thus, in principle, any valid computational method or algorithm corresponds to a sequence of valid formalisms at higher levels. While the transformation from model to algorithm is generally well understood, the reverse route is only rarely possible. Still, one level up from the computational technique, automata theory or formal grammar theory can help clarify its properties, perhaps turn a messy 'black box' into concise sets of interpretable statements, and detect logical inconsistencies and other problems (Dijkstra 1976). Work along these lines would contribute welcome analytic rigor to some of these techniques, reveal unsuspected affinities among disparate problem-solving approaches, and may help bring about a rapprochement with mainstream quantitative geography with potential major benefits for both sides.

[Fig.1 here]

The semantic or conceptual contributions of the theory of computation to a theory of GeoComputation would stem from three main sources: the ability to manipulate symbols representing arbitrary entities (e.g., shapes or 'objects') rather than just numbers; the possibility, reflected in the assignment statement of programming languages, to express qualitative change from one category of things to some other category of things; and the possibility to explore phenomena so complex that there is no better model of them than their full step-by-step description (Couclelis 1986). The logical manipulation of symbols corresponding to arbitrary concepts, the representation of qualitative change, and the simulation of highly complex systems are three areas where the superiority of computational over traditional mathematical and statistical techniques is indisputable. Again here there may be much to be gained from systematic work that would establish these comparative advantages within the context of GeoComputation through both theoretical development and practical demonstration. By expanding the realm of modellable phenomena beyond the strictly quantitative there may even be a chance to connect with those who find numbers and measurement in the social domain too limiting a language.

Last but not by no means least in a future theory of GeoCompuation would be the question of the connection of computation with **space**. The theory of computation is the theory of abstract machines that transform information instead of energy. Adopting computation as a paradigm implies that the underlying notion of machine is appropriate as a fundamental metaphor for the domain in question. Thus AI was built on the premise that the mind operates like an information-processing machine, so that cognitive processes can be modelled as computational processes. More recently the field of artificial life was established on a similar assumption that the processes characterizing life, once abstracted from their carbon-and-water realizations, are also analogous to the operation of abstract information-processing machines (Levy 1992). The theoretical challenge for GeoComputation is to formulate a model based on the computational notion of machine that justifies the 'geo' prefix. That this may be the case is not at all obvious. The key characteristic of the computational machine model is that it specifies the time-dependent notion of **process**, whereas the theory of scientific geography (and most of the other 'geo'-sciences) is predicated upon the static spatial framework of geometry. In a companion paper I speculate a little further on what the theoretical connection between geography and abstract machines might be, and distinguish two different varieties of GeoComputation, 'hard' and 'soft', in analogy with hard and soft AI. I then suggest that hard GeoComputation is the computational theory of spatial processes (Couclelis 1998). This sounds like a nice idea, but we are not there yet.

4 GeoComputation and society

Societal and institutional issues raised by GeoComputation include its place within a post-modern, globalised information society as well as its status within academia. Just as GIS has had major impacts well beyond geography, GeoComputation has the potential to influence a number of other spatial sciences, disciplines, and application areas with a spatial component, but also to be noticed beyond the walls of universities and research centers. This potential is based on the fact that GeoComputation blends well with several major trends in contemporary society. It is obviously in tune with the computer revolution, and capitalises on the continuing dramatic expansion in computing power and the ubiquity of user-friendly, versatile machines. It has a better chance than stodgy quantitative geography to attract the interest of the coming generation of researchers, who grew up running (and sometimes programming) software as complex as anything we build. It certainly agrees with the strong applications- and data orientation of our age, and can help people make better use of information now widely available on the World Wide Web and numerous other easily accessible sources. It fits nicely into the growing push for multidisciplinary work, borrowing techniques from areas far removed from those to which they are applied. Busy researchers appreciate the ability to pick and choose just what they need out of the GeoComputation toolbox, and most of us don't seem to miss the steep learning curve associated with more systematic approaches. Eclecticist, iconoclastic, computer-minded, and theoretically agnostic, GeoComputation is also very much a postmodern intellectual product.

To realise its potential for greater recognition and influence GeoComputation must get out of the conference theatre and onto the streets. Here again the histories of the three cognate fields discussed in this essay - GIS, mainstream quantitative geography, and computation yield useful insights. The credibility of these fields within academia went hand in hand with (in the case of GIS, followed) their practical successes, as – to varying degrees - all three proved to be eminently **useful** in real-world applications. GIS was born to meet concrete institutional needs and continued to grow responding to diverse demands from wide segments of society. At a more modest but still significant scale, land use and transportation planners, public service providers, policy makers, and numerous interests in the private sector have quantitative geography to thank for spatial interaction and location-allocation models and several other techniques derived from spatial analysis. The theory of computation is at the basis of applied computer science with its myriad of contributions to all aspects of the economy, society, and everyday life. More specifically, AI, which started out as a speculation on the function of the mind, has helped improve the performance of a wide array of products of modern technology, from domestic appliances and medical devices to guided missiles. For better or for worse, depending on one's viewpoint, these practical successes have carved a place in society for the corresponding approaches, a place that ensures their continued vitality, both material and intellectual. It is too early to say if GeoComputation will ever have a measurable practical impact of that sort, but if it does, we can expect an accelerating mutual reinforcement between technical and societal interests.

5 Challenges for GeoComputation

Looking ahead there seem to be two kinds of future scenarios for GeoComputation, some more likely and evolutionary, others less likely but revolutionary. The former promise a steady modest to moderate expansion of the current trend, whereby GeoComputation continues to be viewed as a collection of powerful computational techniques borrowed from a variety of different fields and applicable to diverse geographical problems. There are more researchers experimenting with such techniques, more computational alternatives to traditional methods, more useful algorithms being promoted and improved, more papers appearing in mainstream journals, more GeoComputation-oriented sessions at conferences attracting larger academic crowds. There is nothing wrong with that picture except that it is less than what some of us would like to see. It is hard to be content with more of the same when we can glimpse the ‘revolutionary’ scenarios. However, a GeoComputation revolution would need to overcome considerable challenges on several different fronts - practical, theoretical, institutional and societal. Throughout this essay I hinted at what I believe these to be. In place of a conclusion, here is my personal list of GeoComputation’s five major challenges.

(a) GeoComputation must develop a few major demonstration projects of obvious practical interest, and persuade commercial companies to invest in and market applications-oriented GeoComputation-based products. The positive feedback loop between the worth of an innovation and the interest of the private sector in it is well known. In principle, the more marketable an idea appears, the more commercial interest there is in polishing, packaging, and selling it, which in turn provides more motivation and resources for further basic research and development, which leads to wider demand and more and improved supply. This is the dynamic version of the ‘better mousetrap’ story. Of course in our less than perfect world many a good mousetrap often goes undiscovered but people by and large can tell what works for them. GeoComputation *qua* academic pursuit could certainly benefit from a fraction of the commercial spotlight GIS has been enjoying, with all the infusion of talent, research moneys and institutional support that kind of attention brings. A few GeoComputation applications have already drawn a fair amount of public attention (Openshaw et al. 1983, Openshaw et al. 1988) but a couple of isolated projects are not enough to launch the feed-forward loop of commercial development and more research. We need to identify appropriate application niches where GeoComputation techniques can be shown to have a competitive edge, and find the entrepreneurial savvy to get the private sector to notice.

(b) GeoComputation must develop scientific standards that will make it fully acceptable to the quantitative side of geography and to other geosciences. Reliability, transparency, robustness, and quality control in GeoComputation techniques will greatly enhance the ease of use required to spark commercial and institutional interest in GeoComputation applications. At the same time, these are also the qualities that will make such techniques more acceptable to the vast majority of academics working with spatial data who are trained in, and evaluated by, the traditional principles of proper scientific work. Right now quality control is left to the motivation and abilities of individual researchers, many of whom may lack a deeper understanding of the assumptions and limitations of particular techniques. It is necessary to organise, document and clean up the GeoComputation toolbox, stick up the warning labels where such are needed, and provide user manuals that people can rely on. This is non-trivial research agenda considering that the practical logic of computation is very different from that of mathematical and statistical techniques, and much less likely to have been acquired in quantitative methods classes. This methodological challenge is closely related to the next, theoretical one.

(c) GeoComputation must overcome the current lack of epistemological definition, which makes it appear like little more than a grab bag of problem-solving techniques of varying degrees of practical utility. The epistemological agnosticism of GeoComputation may seem liberating to some, but if there appears to be no theory or philosophy it is only because we have not been looking. Approaches and perspectives reflect beliefs about how the world is; techniques and methodologies, about how the world works, and how we may find out about it. The theory and epistemology of computation are both well defined. The former is a demanding mathematical field; the latter reflects a view of the world as complex process and raises profound and original philosophical questions regarding determinism, predictability, the nature of thought, and the limits of the knowable. Not everyone interested in GeoComputation can or need to delve in this domain, but at least some of us should do so from time to time. Applying borrowed techniques professionally is one thing; constructing a new field requires a deeper level of understanding.

(d) GeoComputation must develop a coherent perspective on geographical space - that is, justify the 'Geo' prefix. Computational techniques are used widely today in a wide range of disciplines: how is GeoComputation different from econo-, chemo-, or oceano-computation? Or is it more like psycho-computation and bio-computation, which gave rise to highly original and intellectually exciting new fields better known under the name of artificial intelligence and artificial life? In a companion paper I speculate at length on this theme (Couclelis 1998) but the issue must be raised again here: What does GeoComputation have to say about geographical space - conversely, what difference does space make to the formal and interpreted properties of computational approaches? There is room here for some full-blooded GeoComputational theory, or, more practically, for computational models and languages that are genuinely spatial. We will know that we have established a new approach once we move beyond the piecemeal substitution of computational techniques for more established ones, and begin to formulate truly innovative geographical questions and solutions.

(e) GeoComputation must move in directions that parallel the most intellectually and socially exciting computational developments of the information age. The context of GeoComputation begins and ends with society, and thus the last of the five challenges rejoins the first one. Revolutions, even modest ones, affect not just our ways of doing things but also our ways of thinking. Here again we can learn from the example of GIS. Originally a piece of software for 'doing' land management, it has in recent years provoked both hopes and anxieties relating to a wide array of fundamental societal issues. As an object of reflection and critique, it has attracted the interest of even those geographers who would not normally make use of data-oriented tools or quantitative methods (Pickles 1995). The power of that technology to stimulate thought and debate well beyond the technical is a measure of the success of the GIS revolution (Goodchild 1993). So too GeoComputation's growing practical utility may some day find itself engaged in an unanticipated discourse with the societal questions it raises: questions about the wider implications of its forthcoming coupling with the evolving information infrastructure as well as with GIS, questions about the policy uses to which it is put, questions about the kinds of geographies entailed by the computational assumption. We shall then remember fondly the first few GeoComputation conferences, and smile at how crisp and technical things had looked back then.

Can GeoComputation meet these challenges? Is this all asking too much?… It may well be, but we would-be revolutionaries need to keep on dreaming.

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Fig. 1 The discrete-structure hierarchy of formalisms (adapted from Couclelis 1986:4)