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Geography and computational social science

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Abstract The emergence of computational social science has had a transformative influence on the geographical sciences, integrating diverse themes of scholarship and allying it with the pursuit of grand challenges in the physical, natural, and life sciences. Geography has benefitted from many of these developments and has, in turn, catalyzed significant advances and innovation in computational social science. In this paper, I explore the relationship between geography, computing, and the social sciences by examining the evolution of some central themes in the computational social sciences: complexity, informatics, modeling and simulation, information visualization, cyberspace, socio-technical systems, and semantic computing.

Keywords Computational social science · Geographic Information Science · Complexity · Agent-based models · Cyberspace · Cyber-infrastructure · Social computing

Introduction

Computational social science makes use of computing and informatics in exploring the mechanisms that drive complex social, behavioral, and economic systems. Although it concerns itself with questions of physical and natural science, geography is also intricately connected to the social sciences. Almost all social science phenomena are, in some respect, spatial in nature and for many social science problems, geography acts as a unifying theme in exploring potential answers. Recently, advances in computing have allied geography and the social sciences further. For some time, the development of computing in the geographical sciences and in social science lagged behind advances in computer science and informatics. Delays were often apparent, in which methods and tools from computing trickled-down to the social sciences. More recently, the relationship has begun to change and social science has begun to have a reciprocal influence upon computing, pioneering new areas of scholarship and innovation, owing in large part to the development of computational social science. The relationship between geography and computing has shifted even more dramatically: geographic information technologies are now a core part of informatics and spatial thinking is beginning to spread broadly throughout computing.

In this paper, I study the motives responsible for the these changes and I trace their consequences. I examine the relationship between geography,

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computing, and social science, with the intent of exploring the exchange of ideas and methods and of charting potential avenues for future development at their confluence. These issues are considered with attention to the core components of computational social science: complexity studies, informatics, computer modeling and simulation, information visualization, cyberspace, socio-technical systems, and semantic computing. In each case, it is evident that geography has benefitted from a close association with computational social science and has, in many areas, contributed substantially to furthering innovation and novelty in computational social science. These developments are in a state of relative infancy and the potential for mutual growth in the future is considerable. Several bottlenecks and challenges do remain, however, in relating computational social science to theory, safeguarding privacy in socio-technical systems, and in the potential erosion of disciplinary identity as diverse areas of scholarship mix. The topic of social network analysis, which is central to computational social science, is largely overlooked by geographers and geographical forays into this area have largely been missed in computational social science.

The paper is organized as follows. Background material is presented in the next section, charting the origins of computational social science and geographers' experimentation with computing during the quantitative revolution, and tracing the development of spatially-integrated social science around geographic information technologies. Discussion then moves to the core areas of computational social science, their genesis, their influence on the geographical sciences, and the contributions by geographers to their development. The paper concludes with an examination of remaining challenges in advancing both computational social science and computing in the geographical sciences, as well as a discussion of remaining opportunities.

Background

The discipline of geography has traditionally evolved closely with (and within) the social sciences. In many instances the relationship has been one of dependency; advances in other social sciences had often filtered into geography, where they were "spatialized" by adding a geographical context to an idea or method that had originally been developed without space as a central concern. Geographically weighted regression analysis (Fotheringham et al. 2004), spatial econometrics (Anselin 1988), and spatial mismatch approaches to social justice (Mclafferty and Preston 1992) are examples of very useful instances of this practice.

A tradition of borrowed methodology dates to a general shift toward quantitative modes of scholarship in the 1960s and 1970s (Burton 1963), which for geography meant that empirical methods were adopted from related endeavors in economics and sociology and that within the discipline, aspects of inquiry in human geography (particularly in behavioral geography, economic geography, and transport geography) drew inspiration from quantitative methods more commonly employed in physical geography research (Golledge and Stimson 1997). The "quantification" of elements of geographical scholarship at this time was significant because it aligned geography with important developments at the forefront of the quantitative social sciences of the day (King 1994), particularly in data analysis (Haggett et al. 1977), network approaches in studying relationships in systems (Haggett and Chorley 1969), statistical estimation and testing (Cliff and Ord 1973), and mathematical modeling (Chorley and Haggett 1967). Indeed, for many branches of geographical inquiry, the scientific method shifted from a concern with area studies to the development of a uniquely spatial science (Goodchild et al. 2000). This had the effect, arguably, of furthering the level of interdisciplinary work by geographers.

Recently, the relationship between geography and other social sciences has shifted: geography now enjoys a more pioneering position in the genesis of ideas for the social sciences. The permeation of tools for spatial analysis, particularly those based around Geographic Information Systems, and the recent widespread adoption of cartography as a visualization medium (Butler 2006) have catalyzed these trends. Developments in geographic information science, particularly in spatial databases, database access, spatial analysis, positioning technologies, remote sensing, and geo-visualization, were critical in advancing efforts to craft a "spatially integrated social science" in the 1990s (Goodchild et al. 2000), centered around the development of "dataware" for spatial analysis of information. Uptake of these tools in the social sciences has been remarkable and the percolation of geographic information technology through the social sciences has been influential in promoting the unique benefits of a spatial approach in answering social science questions. Geographic information technology is now commonly used in criminology and law (Chainey and Ratcliffe 2005), archaeology (Wheatley and Gillings 2002), public health (Kurland and Gorr 2006), anthropology (Aldenderfer and Maschner 1996), economics (Bateman et al. 2005), and demography (Peters and Macdonald 2005).

More significant, perhaps, is the slow but steady infusion of spatial thinking into social sciences (Goodchild et al. 2000; Gieryn 2000), perhaps as a by-product of popular use of geographic tools. Consideration of geography is now evident in many of the central themes of social science. The relationship between mobility, accessibility to the built environment, and obesity is a significant point of inquiry in public health research (Hill et al. 2003). The spatial mechanics of diffusion and spatial interaction are opening new avenues of inquiry in epidemiology research of human (Ferguson 2007) and animal populations (Highfield et al. 2008). Examination of human activity patterns and their relationships to time geography is of great currency in transportation research (Kwan et al. 2003). Ideas about the elasticity of distance and distance-decay over space and time (Sui 2004) are popularly reproduced in studies of globalization (Friedman 2005). Economists have rediscovered the value of economic geography in explaining agglomerated markets, spatial spillovers, neighborhood effects, spatial externalities, and the flow of global trade (Fujita et al. 2001; Krugman 1992).

In the remaining sections, I will explore how geography, computing, and social science have evolved beyond these foundations and I will discuss the potential for future growth. Exploring the development of computational social science's core themes is perhaps a useful guideline for this.

Complexity studies

Complexity studies are a core component of computational social science. Social scientists' interests in complexity have led them to integrate novel methods from computing in their scholarship. This has been beneficial to the field, aligning social science with many "big science" questions and helping to translate the work of social scientists into the language of the natural, physical, and life sciences. For geography, the relationship between complexity and social science is crucial: many of the signature themes of complexity science are geographical in nature, as are many classic exemplars and much of the novelty in integrating complexity, computation, and social science has come from geography.

The main tenet of complexity is the exploration of the collective dynamics of intricate systems and phenomena composed of many working parts. Complex systems are characterized by massively interactive connections, often tempered by non-linear relationships (positive and negative feedback, phase shifts, bifurcation) between system elements. Emergence is a hallmark of complexity, encapsulating the propensity for components of complex systems to self-organize and for information to propagate back and forth across scales. These signatures of complex systems characterize many significant social science phenomena: shifts in economic markets (Krugman 1996), the evolution of societies (Epstein and Axtell 1996), and the cognitive functioning of the mind (Logan 2007). Indeed, much of the appeal of complexity studies lies in the commonality of these signatures across diverse systems and academic disciplines. Social scientists' forays into complexity studies have allied them with scholars pursuing similar themes in the natural, physical, and earth sciences, where similar signatures are observed (Kauffman 1996).

Many complex phenomena are geographic. The classic Schelling (1971) and Sakoda (1971) models of segregation, which demonstrate that small biases in residential preference can—through emergence in a complex system—lead to widespread polarization of communities, are almost entirely geographic in foundation. Segregation dynamics relate directly to how people mediate the geography of their location decisions and how they balance their behavioral geography with opportunities in the built environment; this has been a long-standing topic of interest in human geography (Clark and Cadwaller 1973; Sui and Wu 2006). Flocking, herding, and swarming behavior is another benchmark of complex systems in which individual behavior can lead to aggregate outcomes that are qualitatively distinct in form and scale. Ideas about the formation of flocking has been used to explain the sociological behavior of insects (Theraulaz et al. 1998), seemingly irrational swings in economic markets (Arthur 1990), and the genesis of panic in collective behavior (Vicsek 2003). Flocking behavior is fundamentally geographic, involving the examination of neighborhood and edge effects (O'sullivan 2009), which may be animated by processes of diffusion and spatial interaction through social and physical environments (Wilson 2000; Batty 2005; Benenson and Torrens 2004). Feedback relationships between elements of complex systems are often codetermined by geographical inertia and spatial hierarchy (Christaller 1933), which can explain rank-size relationships (Batty 2008), fractality and self-similarity across scales (Batty and Longley 1994), and self-organization (Portugali 2000).

The affinity between spatial dynamics and complexity has been influential in connecting geography to computational social science and related developments in the physical, life, and natural sciences, which share a curiosity about many of the same phenomena and processes of interest to geographers. This has helped to align geography with many "big science" questions. These are questions of vital public interest that transcend disciplines and academic silos: the genesis of resilience amid catastrophe (Cutter 2003), engineering sustainable complex systems (Wilbanks 1994), curing disease and promoting health (Gatrell 2005), exploring human origins (Lake 2000), uncovering the mechanics of the mind and cognition (Kitchin et al. 1997), resolving global inequalities (Krugman 2005), and understanding human-environment interaction (Manson and Evans 2007).

Big data

The development of a computational approach to understanding complex systems is also associated with changes in the nature and availability of data regarding the phenomena that interest social scientists. The growth of computational social science has paralleled the growth of an ecology of "big data" (Nature Publishing Group 2008) in society. Data regarding entire populations are now accessible, in digital form, and data-sets can often be reliably cross-indexed across populations and themes to produce a relatively holistic picture of some social phenomena (Benenson and Omer 2003). Moreover, an expanding suite of "dataware" products are available to mine those data for meaning and to assist in their translation to knowledge, allowing digital data to be associated with hypotheses, ideas, and policies. In a sense, digital information of this kind acts as the substrate for computational social science. In particular, geography and geographic information technologies have been influential in relating big data to social science scholarship, serving as a means by which data can be meaningfully indexed, organized, contextualized, and related across disciplines and applications.

Social science has perhaps always been a data-intensive endeavor: surveys and censuses are important media throughout the field. The digitization of existing analog records has expanded the availability of primary and secondary data and publication of these resources through Online clearing houses has increased the accessibility of data to the extent that there now exists a relatively huge silo of financial, legal, health, economic, preference, and demographic resources to "feed" computational social science.

Many data are now generated automatically: digital transactions by credit card are indexed by name and type; communications by landline and cellular telephony can be associated uniquely to individuals; store purchases can be registered to customer loyalty cards, even if they are paid by cash; and many health records are accessible across information systems. Collectively, these data form a "cloud" of digital resources that can be indexed to individuals, groups, times, and activities (often stored across many computer systems, but centrally accessible through search engines or browser software). In many instances, they may be cross-referenced across sources, as is commonly performed by actuaries to assess investment risk, for example.

The aforementioned records involve active participation by the individual for which records are obtained: they must swipe a card or report physically for a diagnosis. Other data are obtained passively, by remote sensing. This may involve imaging at-a-distance, when for example aerial photography is used to estimate population density from night-time lights (Sutton 1997), or when closed-circuit televisions are used match license plates to congestion pricing schemes on roads (Chang et al. 2004) or to check faces against lists of unwelcome guests in casinos (Bowyer 2004). Increasingly, remote sensing technologies have been embedded in inanimate objects, with the byproduct that people may be indentified with the things that they interact with, by browsing, handling, or sharing. In some instances the objects themselves may even network with the ability to automatically triangulate their position (Sterling 2004).

In this ecology of information, humans are increasingly shadowed by a continuously-fed corpus of digital information regarding their activities, actions, and interactions (Dodge and Kitchin 2005). The involvement of computational social science in this scheme is in generating meaning from data by relating data to substantive ideas and structures, by tying together diverse threads of information across themes, and by situating information in the bigger picture that society, culture, and politics convey.

Transactional data can (to some extent) serve as an indicator of social behavior and interaction, providing valuable information about attitudes, valences, and preferences that would previously have had to be acquired through interview and direct observation. The adaptation of machine-learning techniques for social science research is an important consideration in developing these inferences. Theories and hypotheses from social science are often used to construct the algorithms and heuristics that automate knowledge discovery and data-mining (KDD) (Fayyad et al. 1997) in large databases. Signatures of social behavior in databases (common trends, deviations from normal patterns, principal components of behavior) can be distilled to "eigenbehaviors" (Eagle et al. 2009) that may serve as the templates for structured queries to large databases or as foundations for the meaningful extraction of information from raw data. Researchers have already begun to use these techniques to extract social signals from cellular telephony records by "reality mining" (Eagle and Pentland 2006), i.e., deriving indicators of human behavior in data. Other efforts are underway to extract meaning such as sentiment from media by means of natural language processing (Nasukawa and Yi 2003).

The contribution of geography to these developments is considerable. Place, space, and location are common indices that transcend many databases and can be used as a unique key to integrate data across information systems or variables within a given database. Data may also be organized geographically into thematic layers. Many large-scale data collection efforts, such as censuses of population, housing, and economic activity, are place-based for this reason. A variety of geographic data structures and data access methods have been developed to organize big data spatially. These include geo-relational models that store geometries alongside data attributes (Morehouse 1985); bounding volumes that encapsulate data within spatial divisions and related tessellation and parsing techniques such as quadtrees, octrees, and binary space partitions (Rigaux et al. 2002); nearest-neighbor structures that allow data to be indexed quickly in attribute space (Shekhar and Chawla 2003); and moving object databases that relate entities to their trajectories in space and time (Wolfson et al. 1998). The scheme popularly used by search engines and webcrawlers to archive and access data on the World Wide Web (which is among the world's largest databases)—MapReduce (Dean and Ghemawat 2008)—is based, fundamentally on using the geography of relationships in attribute space to distill massive amounts of information into manageable form.

Remotely-sensed data are often generated by location-aware hardware and the geography of the location and spatial context in which data were acquired is used to attribute meaning to those data (Sui 2007). For this reason, Geographic Positioning Systems (GPS) are embedded in many devices that people use to communicate, travel, and authenticate their identities. Other, alternative positioning systems can be used to triangulate the location of actions and interactions in social systems. Radio Frequency Identity (RFID) or ultrasonic tags can be affixed to surgeons, patients, and supplies in hospitals, for example, to trace behaviors and routines during surgical procedures (Izumi and Nara 2009). Wireless Internet access points can be used to triangulate the movement of laptop users in urban environments (Torrens 2008). Behavior can also be inferred from movements detected in video using pattern-matching (Viola et al. 2005). The geography of these patterns and behaviors is also being used to develop location-based services (Schiller and Voisard 2004) that make use of information regarding where people are, where they have been, and what they have done (or what other people with similar geographical history have done), to deliver information to mobile, location-aware devices carried in pockets and handbags (portable music players, cellphones, handheld computers, cameras) or embedded in objects (vehicles, assets, casino chips).

Agent-based modeling

Classic (mostly statistical) methods from quantitative social science are often unsuitable for characterizing the signature traits of complex systems. Statistical analysis in the social sciences, for example, often focuses on static examination of cross-sections, commonly performed at a single scale. This may be useful for benchmarking properties of complex systems for a snapshot in time, but it does little to describe the continuum of dynamics and interactivity that determine emergence and self-organization in complex systems. In search of schemes for infusing complexity into their models, social scientists have been drawn to automata methods from computer science and many social scientists have used automata to construct entirely synthetic replicas of social systems, in silico, for the purposes of experimenting with phenomena that they cannot access on the ground. Once again, the contribution of geography to these developments has been substantial.

Automata date to the origins of digital computing and the pioneering work by Alan Turing (1936, 1938) on the computability of numbers and by John von Neumann (1951) and Stanislaw Ulam (1969) in building digital computers. Automata are machines—either of mathematical or physical form (robots, switches, central processing units)—that process information input to them and relate that information to state descriptors that characterize their condition in an array of finite or infinite states. State information may be garnered internally, or it may be exchanged with other automata or entities. An automaton uses this information to determine its actions using a set of transition rules that establish what state it should adopt (or not) in a future moment. In essence, this scheme affords automata the ability to be proactive, sensitive, and communicative: key ingredients for social behavior. When automata are ascribed agency (economic motives, political will, cognitive dissonance), they are referred to as agent-based models. When designed to model individual behavior, they are commonly referred to as individual-based models. When used to describe interactions between many entities in some interactive system or environment, they are termed multi-agent models. When bounded in space, they are often built as cellular automata.

Just as automata are used as the building-blocks for machines—sensors, control systems, processors—social scientists have used them to generate social systems in computer simulation. The idea, in doing so, is to generate social systems from the bottom-up (Epstein 2006): in piecing systems together from individual components, focusing on the interactions that generate system dynamics, it is hoped that the complexity of the system can be fully understood in a way that is missing in top-down (reductionist) models that explain systems by dissection. This approach is something of a natural fit for computational social science concerned with complexity and operating in an era of big data. Societies can be modeled based on the collective agency of individual citizens (Epstein and Axtell 1996); artificial economies can be built through the interplay of conflict and cooperation among synthetic agents (Axelrod 1997); and model cities can be constructed and grown using computerized agent settlers and developers (Torrens 2006). All of these concepts can be adjusted in simulation, parameterized for different spaces and populations, run backwards and forwards in time, and updated as new data suggest alternative hypotheses or theories.

The automata approach—with its emphasis on information exchange—is inherently social; it is also inherently geographical. Interaction in space and time is at the core of information exchange in automata and the diffusion of information over space and time is central to agent-based models in their variant forms. The coupled relationship between states and transitions rules echoes the relationship between patterns and processes that form the foundation of most geographical phenomena. The object-oriented programming paradigm upon which many agent-based models are developed has a natural affinity with social hierarchy, but also with spatial hierarchy: models of cities can be easily abstracted using spatial logic (megalopolises to city-systems to metropolises to cities to districts to neighborhoods to streets), for example. The methods (routines) of object-oriented programming are easily related to processes that fit within these hierarchies: streets are bundled as neighborhoods so that services can efficiently administered over a given area; districts of distinct character emerge in cities because of spatial separation or agglomeration among land-uses; metropolises coalesce as city-systems when their adjaceny confers some spatial advantage; and megalopolises form because of economies of scale (Hall 1988). When relating their simulations to the real-world, many builders of automata models in social science draw on techniques from spatial analysis for calibration, validation, and verification: map comparison, measures of spatial structure and composition, image processing, and fractal measures (Manson 2007).

Many of the landmark agent-based models advertised in social science as being illustrative of the approach are fundamentally geographic in nature. This includes the segregation models developed by Schelling and Sakoda that were already discussed, the sugarscape models of societal emergence built by Joshua Epstein and Robert Axtell (Epstein and Axtell 1996), the TRANSIMS model of driving behavior (Nagel et al. 1998) and the related EPISIMS model of epidemiology (Eubank et al. 2004), Krugman and Fujita's automata models of agglomeration economies (Krugman 1996), and models of insect social behavior built around stigmergy and swarming (Bonabeau et al. 1999). Other, explicitly geographical agent-based models enjoy popular followings in social science research, and many open-source models are used as "plug-ins" to drive dynamics in larger social science simulations (Clarke et al. 2007; Waddell 2002; Reynolds 1999).

In many instances, the agency for agent-based models is developed as artificial intelligence, a field also pioneered by Alan Turing (1950). In artificial intelligence approaches, computer algorithms and heuristics that mimic the myriad of ways in which humans organize thoughts, perceive their surroundings, act on impulses, and use memories (Minsky 1967) are used as the basis for information processing. Many agent-based models in the social sciences rely on spatial intelligence: spatial cognition (Mallota and Basten 2008), mental maps (Sperb and Cabral 2004), visual perception (Turner and Penn 2002), and navigation and way-finding (Raubal 2001). This is particularly true in robotics, where much of the artificial intelligence and agency afforded social robots is derived from spatial behavior (Latombe 1991).

Information visualization

The interaction between humans and computers is a significant consideration in computational social science, relating directly to the sociology of computer use, the psychology of visual, tactile, and auditory perception of computer interfaces, social behavior using computers, and the mediation of human activity through computing. Much of the scholarship by computational social scientists in this area is focused on information visualization (Gershon and Eick 1997): the design of visual information as a medium for human perception. Computational social scientists also make use of information visualization in their own work, as a mechanism for reducing complexity in their models and data. Geography, with its strong tradition in cartography, has had a major influence in fusing concepts from information visualization with computational social science.

In some instances, computational social science is used to explore social aspects of human-computer interaction. In these examples, information visualization is studied as a medium for collaboration and communication and issues regarding the effective design of visual information for different public or scientific audiences is examined (Tufte 2001). In other cases, the focus is on cognitive aspects of effective information visualization, such as perception, concerns with color and stereoscopic vision, and the use texture (Ware 2000). Much attention has been paid to tasks, such as intelligence analysis (Kapler and Wright 2005), control systems (Azuma et al. 2000), and navigation aids (Levine 1982), where ad hoc designs for conveying information may be required. Increased attention is also being paid to visually-impaired users, and to schemes for converting visual information into tactile (Osawa 2006) or auditory form (Wall and Brewster 2006).

Because of the complexity of many computational social science applications, their consumption of large amounts of data, and the often voluminous output of results and data points that related analysis generates, information visualization is often used to reduce complexity and to minimize information overloading. This can be achieved by reducing dimensionality in data, using techniques such as parallel coordinate plotting, for example (Edsall 2003) or by visualizing structure and network pathways, as is often done to chart commonalities in academic citation across diverse disciplines (Small 1999). Other schemes use information visualization to convey uncertainty and precision (Deitrick and Edsall 2006). In some instances, visualization is used to make data more complex, by using animation to add dimensionality, for example (Börner and Penumarthy 2003).

Geography is often central to information visualization for computational social science. Many visualizations manifest as maps—either as fully-fledged cartographic media or as abstract visual indices to data. Others are displayed, queried, and managed as Geographic Information Systems. Spatial thinking also features prominently in the effective design of information visualization. Schemes for creating effective color palettes that were developed in computer cartography (Harrower and Brewer 2003) are commonly used in information visualization, as are methods of classification and aggregation designed for choropleth mapping (Andrienko and Andrienko 2006). Cartograms, which project geometries based on variable information, are also popularly used in information visualization (Tobler 2004).

Spatial cognition is often a central concern in assessing the perceptibility of information visualizations. Behavioral geographers have examined this issue in depth, exploring the recall of visual information (Montello 2002), spatial cognition of shapes and dimensions (Klippel et al. 2009), the relationship between the formation of thoughts and eye movements when interacting with visual information on-screen (Ltekin et al. 2009), as well as relationships between spatial behaviors as manifest in virtual reality and on the ground (Portugali 2006).

Cyberspace

Cyberspace is a virtual medium: software, data, and protocols for information-sharing (the World Wide Web) that are conveyed on and by a tangible domain of networked client and server machines, routers, switches, and cables (the Internet). Large parts of cyberspace are designed for machines to use, and other portions exist to enable communication between humans. In this sense, cyberspace perhaps represents the quintessential confluence of computation with social science: humans use it to share information and, individually or collectively, they engage with it perceptually to create replicas of or diversions from the real-world (Baudrillard 1994). Cyberspace is also a space, and the geography of the technological backbone that underpins its networks and the imagined world often created within its software is of significant interest.

Social scientists may examine cyberspace from the outside looking in, by studying usage patterns by demography, socio-economic status, and occupation; the use of cyberspace in education and training; and the economics of e-commerce. People's use of cyberspace is also explored, for example, the diffusion of information and memes, the nature of gender and identity in Online forums, and cyber-crime and related issues of legal jurisdiction (Castells 2001).

Much of the interest of computational social scientists in cyberspace is focused on the creation of societies, populations, and cultures within the cyberspace itself. Networked games are an exemplar of this approach. Massively Multiplayer Online Role-Playing Games (MMORPGs), for example, are related to many aspects of computational social science: modeling and simulation, big data, and information visualization. Many MMORPGs contain large populations of users and well-defined landscapes, customs, cultures, and sub-cultures (Schroeder 2002), which can only be analyzed by social science once the computation used to create them is fully understood. Virtual worlds are another example. They are commonly employed in Web-based representations of social phenomena to convey features of the real world in digital form, under the constraints of network bandwidth and the limits of two-dimensional computer screens. They are also used as computational laboratories for social science, for ethnographic studies, market research, and collaboration (Bainbridge 2007; Hudson-Smith 2002).

To a large degree, cyberspaces and virtual worlds are best understood geographically: they exist to map the "meat-space" (or "meet-space") of the real-world to the "cyberspace" of the world that exists within the wires that network computers (Kitchin 1998) or within the minds of the people that use them (Gibson 1984). They also map digital information stored on computers to well-known concepts from the real-world, to better enable user interaction with data. As such, the social science of digital and virtual worlds is intricately bound to human geography and geographic information. Geography is equally relevant in explaining the infrastructure that drives cyberspace: the spatial distribution of computers and networks and their relationship to population centers and hubs of economic and cultural activity (Townsend 2001); the sites of production for Online media and the physical location of e-commerce

(Zook 2002); and the geography of the digital divide in access to Internet technology and related opportunities (Dodge and Kitchin 2000).

Spatial concepts are also significant in understanding the conceptual foundations for cyberspace (as in Gibson's (1984) original idea of cyberspace as a consensual hallucination). Cyberspace is replete with spatial imagery and ontology: Web *sites* and site *maps*, cyber*space*, chat *rooms*, Web *portals*, *browsing* and *surfing*, *home* pages, the implied directionality in *up*loading and *down*loading and topology of hyper*links*. The field of cybergeography is concerned with the translation of geography from the real-world to cyberspace and with the creation of entirely new spaces Online (Dodge 2001; Kwan 2001). Much of this work makes use of maps and mapping as a template for analysis and as comparative media (Dodge and Kitchin 2001).

Virtual worlds are commonly developed as synthetic representations of real spaces, or as imagined alternatives of the real-world geographies. Whether geographic actions and norms hold in those settings can be meaningful in studying social and behavioral geography: trespassing on virtual representations of national monuments may be disregarded by visitors to virtual worlds, but "walking" through somebody's avatar might be socially unacceptable. Many virtual worlds are designed as cities (Shiode 2001), with densely populated or built sites and accessible locations (near entrance portals or along mirrored coordinates) often enjoying prestige over less well-occupied areas of the world, in much the same way that central cities are desirable in real urban areas. Other, collaboratively-built virtual cities resemble suburban sprawl, raising questions regarding consumers' preferences for housing in the urban marketplace and attitudes about urban planning (Shiode and Torrens 2008). Virtual worlds commonly manifest as globes and many virtual globes are run as Geographic Information Systems that interface users with the World Wide Web (Butler 2006). Again, this raises interesting questions about the nature of human perception of scale.

Socio-technical systems

Computational social science is also inextricably associated with socio-technical systems: phenomena in which social processes interact seamlessly (even symbiotically) with technology. This characterization describes many significant systems of interest to social scientists: transportation systems, currency exchanges and equities markets, and virtual organizations. Geography—particularly distance and the spacing and timing of activity—is a critical component of these systems and the technology that underpins them and, in some cases, geography forms the foundation upon which such systems are generated.

Many of these ideas are encapsulated in the notion of social computing. Operationally, the term describes the generation and use of social media [so-called Web 2.0 technologies (O'Reilly 2007)]: instant messaging, Tweeting, Web-logging (blogging), and the use of social networking portals on the World Wide Web. It also relates to crowd-sourced media (often based around a culture of open-source technology), such as Wikis (user-updated reference media), collaborative filtering of Websites and bulletin boards, distributed trust and reputation systems, and collective tagging of Online content in bookmark repositories and Web-based notebooks. Related topics such as the dynamics of cooperation, the evolution of norms, division of labor, and the emergence of culture are of obvious relevance to social science. Entirely new forms of social and economic behavior are also being created using social media. Howard Rheingold (2002) has documented the emergence of smart mobs, for example, and the collective behavior that is enabled and tempered by social computing.

Comingling of social and technical systems have also led to the development of virtual organizations, which use Internet and communications technologies as the conduits for commerce, handling transactions digitally and even generating and distributing digital products Online. This is particularly common for software developers, but it is also prevalent for clerical services such as transcription and accounting, and even for secretarial services (Ferriss 2007). Other companies—particularly those that deal in the design of products or in retailing easily shipped goods—have developed business models that combine traditional bricks-and-mortar operations with virtual organizations (Castells 2001; Mitchell 1995).

In each of these cases, geography and computational social science are of relevance. Many socio-technical systems manifest as cyber-places: a hybridization of cyberspace and the tangible world. In some cases, these are literal hybrids: intelligent highways and smart buildings are examples (McCullough 2004). In other instances, computing extends the functionality of the tangible place, by providing contextually-aware functionality, access to digital information, or by becoming so ubiquitously available as to seem pervasive (Weiser 1991). The role of geography in mediating the relationship between technology, sociality, and place is a key concern in these instances. Many socio-technical systems function—computationally and socially—as code-spaces (Dodge and Kitchin 2005). Information is coded based on location, movement, transferability, proximity and authenticity; authority, rights, and privileges are bestowed upon people and things based on these codes. Often, this information is tangibly affixed to objects and people, stored in badges, cards, or buttons for use in airports, hospitals, and secure workplaces (Dodge and Kitchin 2004). This has led to the burgeoning emergence of cyber-places that are automatically generated, monitored, and mediated by software (Thrift and French 2002; Batty 1997; Graham 2005).

Socio-technical systems are often associated with the decline (or death) of distance and its relationship to sites of activity, action, and interaction (Cairncross 1997; The Economist 2003). The rise of telecommuting in the workplace and outsourcing of business operations are examples in which Internet and digital communications technologies facilitate action-at-a-distance with sufficient fidelity that technology can be substituted for physical interaction. In other instances, however, socio-technical systems enable new forums for interaction-by-proximity: for example, Anthony Townsend has documented how the provision of wireless Internet access in New York's Bryant Park fostered social interaction in that space (Schmidt and Townsend 2003); other scholars have detailed the effect that Wi-Fi technology has had in reinforcing civic urban spaces (Torrens 2008).

Geography is also central to the development of Wiki-resources. Online, community-distributed computing projects (such as the SETI@home initiative (Korpela et al. 2001), which processes large volumes of astronomical observations for signs of extraterrestrial communications) leverage the distribution of computer processing power over vast spaces to engage in high-performance computing tasks that would be largely unfeasible to attempt in a central location (because of cost, power consumption, and cooling requirements). Some of the most popular Wiki projects are wholly geographical. The *OpenStreetMap* initiative (http://www.openstreetmap.org/) launched by Steve Coast provides a platform for users to upload location traces of their movement over the landscape; these traces are then automatically assembled as street maps and pathways to be compiled as digital atlases (Haklay and Weber 2008). A related system also allows users to collectively filter the content for quality control. These resources provide significant sources of volunteered geographic information (Goodchild 2007) for computational social science, partially because it is free of pricing and usage restrictions (many maps are not) and because it is steadily updated.

Semantic computing on the Web

The semantic Web (Berners-Lee et al. 2001) exists in nascent form. It is an additional layer atop the World Wide Web, based on inference engines (Web services) that can automatically catalog the semantic meaning of information on the Web, in addition to documenting the presence of its underlying data. The same inference engines can also mediate the relationships between Web users and that information, semantically contextualizing requests initiated by humans, using procedures close to natural language processing.

This is an incredibly significant development for computational social science. It places computational social science at the heart of developments in Internet and communications technology—the semantics required to broker relationships between human agents and Web service agents would undoubtedly have their genesis in computational social science. The semantic Web could also unify the varied research threads pursued in computational social science: complexity, big data, agent-based modeling, socio-technical systems, and cyberspace, offering unique potential to translate computational social science into actionable semantics for the Web. Following developments in geographic information science, many aspects of geographic information technology have already shifted to the semantic Web (Egenhofer 2002). The potential for further integration of spatial thinking is profound.

Geographic information systems have continually followed development in information technology. When databases moved to the Web, so too did geographic information systems. Initially, Web-based GIS were developed as fairly straightforward Online maps (gazetteers) which mediated user queries for information on networks, usually to dedicated repositories of spatial data (Smith and Frew 1995). As the number of such resources grew, a "GeoWeb" of spatial data and metadata began to form, later adding information from location-aware hardware (Elwood 2010). Those technologies evolved further, initially to adopt structured database querying technologies native to Web technologies and eventually to evolve as fully-fledged Web services capable of semantically processing user queries for Online spatial data, across a variety of resources (Zhang and Tsou 2009).

The power of a geographical semantic Web could grow further if it became widely interoperable across varied sets of semantics and ontologies (Kuhn 2005) and particularly if it could relate to semantic concepts that span the social sciences. Indeed, developments in geographic agent-based modeling, cybergeography, and understanding of spatial complexity could potentially translate into process models that would form the foundation for semantic geographic information systems by mimicking spatial intelligence and behavior (Torrens 2009). Such systems are already beginning to be realized in prototypical form, as predestination routines that estimate future trajectories for moving objects based on location histories (Krumm and Horvitz 2007). Developments in GeoWeb semantics could also advance interactions between geography (especially human geography) and efforts to develop large cyber-infrastructures of analytical systems, mechanical systems, built systems, and natural systems (National Science Foundation 2007; Oden et al. 2006; Zhang and Tsou 2009).

Epilog

In this paper, I have charted the development of the geographical sciences and computational social science through complexity studies, the informatics of big data, agent-based modeling and generative simulation, information visualization, cyberspace and virtual worlds, socio-technical systems and social computing, and semantic computing on the Web. In each case, it is readily apparent that geography has played a significant role in the development of technologies and ideas that have advanced the explanatory power of computational social science.

My treatment of these topics has been optimistic. The consociation between geography, computing, and the social sciences has been, in many senses, extremely beneficial and even natural. To some extent, they are now inseparable. The co-evolution of the fields has not been without controversy, however. Shifts toward computing in social science and the geographical sciences have resulted, in some cases, in a dramatic change in the mode of scientific inquiry. For the geographical sciences, this has generated some tensions between computational geography and critical geography (Schuurman 1999). Although there are many examples of work that transcends both fields with fantastic results (Kwan and Schwanen 2009), these tensions remain to some extent.

Many social scientists (and computer scientists) are critical of the widespread automation of data collection and analysis and question whether access to the driving mechanics of socio-technical systems will be equitable or just (Smith et al. 2005; Dodge and Kitchin 2004). This is particularly troublesome for the geographical sciences, where developments in the precision of positioning systems and potency of contextual analysis could potentially erode location privacy for individuals in their workplaces, homes, and recreation spaces (Dobson and Fisher 2003; Monmonier 2002; Armstrong and Ruggles 2005). It is also problematic that location information is not easily excised or masked in these applications without loss of fidelity (Kwan et al. 2004).

Within the social sciences, awareness of the significance of geography (and the malleability of space and time under social influence) has also generated debate about its relevance (Cairncross 1997; Kolko 2000), although it is safe to say that geography still exists and remains as pertinent as ever, if not more so (Malecki and Gorman 2001; The Economist 2003; Olson and Olson 2000; Wang et al. 2003; Day 2007). In a similar sense, the widespread acceptance of geographic information technologies, catalyzed by computational social science, has eroded some of the mystery surrounding geographic information systems. This has been apparent in the recent development of Web mapping and the mashing-up of digital maps and social media, characterized as "neogeography" pioneered by hackers and citizen scientists without "formal" cartographic or geography training (Haklay et al. 2008). While many regard this as a positive development for geography, extending its reach to a more diverse audience, others are less sure of the usefulness of the trend (Goodchild 2007; Treves 2007).

I have glossed over some significant bottlenecks in the development of computational social science and geography. Moving development of agent-based models away from simple, abstract representations of socio-spatial processes, and toward richer, more detailed treatments of individual and collective behavior is a significant challenge. Many computational social scientists feel that agent models should be developed simply, so that an indelible path from model parameters to outcomes can be easily traced (Epstein 2006). Others decry the lack of realism in agent-based models and argue against their usefulness in supporting social science theory (Torrens and O'Sullivan 2001). The appropriateness of limiting assumptions (rational actors, utility-driven preference, tendencies toward equilibrium) beyond their disciplinary confines is a related concern. In some cases, agent-based models are developed in an absence of social science theory (because the systems of interest defy description or observation by traditional means, or because the purpose of the exercise is to generate theory that can then be explored) and turn, instead, to tools built for other (related) disciplines. Often, methods are borrowed from physics and economics (Benenson and Torrens 2004), because of the tractability of their approaches, but these schemes may not always transfer easily to other disciplines and may be difficult to calibrate, validate, and verify in their new contexts.

Social networks are a glaring omission from my description of computational social science, but for good reasons. For many scholars, social network analysis is the main method of computational social science (Lazer et al. 2009; Macy and Willer 2002; Watts 2007), but the technique is problematic for geographers because much of the research in social network analysis and sociometrics is developed without consideration of space. This is beginning to change (Butts 2009; Liben-Nowell et al. 2005), but even though investigation of networks by geographers has been ongoing for some time (Haggett and Chorley 1969), efforts to merge *social* network analysis and geography have, for the most part, been only recently realized (Singleton and Longley 2009; Ter Wal and Boschma 2009; Sorenson 2003).

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