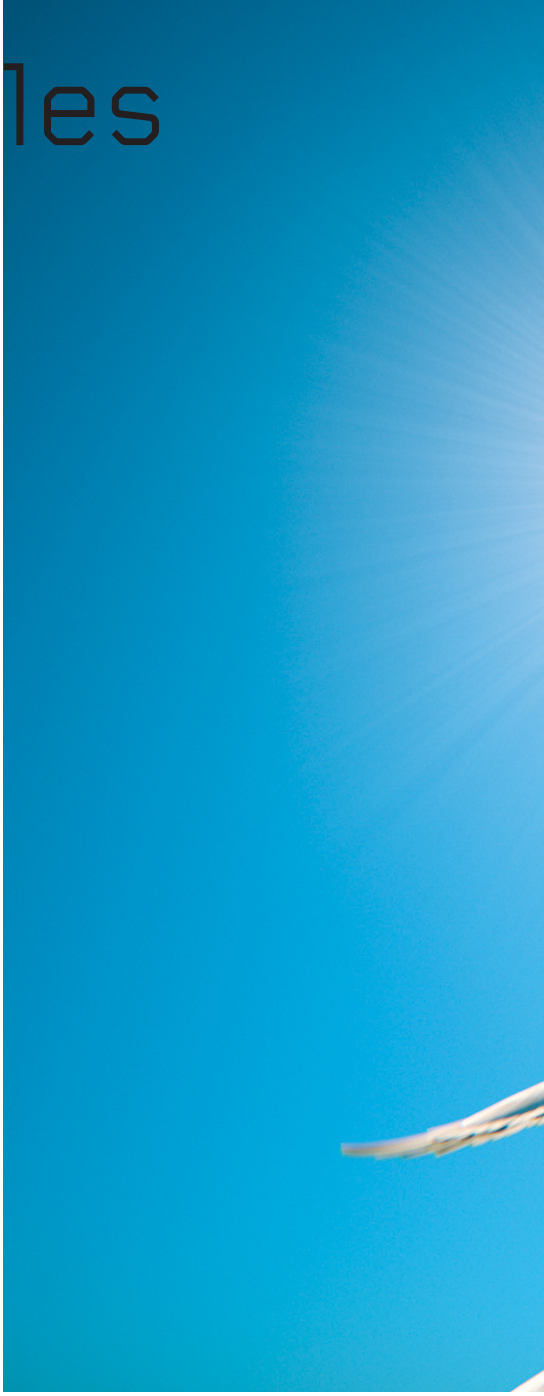

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Knowing where you are in space and time promises a deeper understanding of neighbors, ecosystems, and the environment.

BY SHASHI SHEKHAR, STEVEN K. FEINER, AND WALID G. AREF

Spatial Computing

SPATIAL COMPUTING ENCOMPASSES the ideas, solutions, tools, technologies, and systems that transform our lives by creating a new understanding of locations—how we know, communicate, and visualize our relationship to locations and how we navigate through them. Pervasive GPS allows hikers in national parks, boaters on lakes, children visiting new places, and taxis (or Uber drivers or self-driving cars) and unmanned aerial vehicles to know their locations, nearby facilities, and routes to reach places of interest.[a]

Large organizations use spatial computing for site selection, asset tracking, facility management,

a Participants in the Computing Community Consortium's 2012 workshop used the term "spatial computing" as a generalization for spatial data structures,[46] spatial databases,[50] spatial data mining,[10] spatial statistics,[12] spatial cognition,[8] and other computational issues related to geographic and non-geographic spaces (such as sky catalogs, indoors, and VLSI design). Within geographic spaces, the term focuses on computational aspects of a multidisciplinary area, variously referred to as geoinformatics, geomatics, geocomputation, geoinformation science, geographical information science, and computational geography. More broadly, spatial computing refers to the study of computing in spatial, temporal, spatiotemporal spaces across both geographic and nongeographic domains.

» key insights

- **Starting with the public availability of GPS, spatial computing has enriched our lives through location-based services (such as Google Maps, Uber, geotagging, and geotargeted, including Amber, alerts).**
- **It has also advanced computer science through ideas like spatial databases (such as R-tree and OGIS simple features library), spatial statistics (such as point process theory and Kriging), and spatial data mining (such as robust hotspot detection).**
- **Future potentially transformative opportunities include ubiquitous indoor location-based services, the location-aware Internet of Physical Things, continuous global monitoring, visualization, forecast, alerts, and warnings to address societal challenges like climate change and how to provide adequate food, energy, and water.**

ILLUSTRATION BY PETER CROWTHER ASSOCIATES

navigation, and logistics. Scientists use Global Navigation Satellite Systems, or GNSS[24] (such as the global positioning system, or GPS), to track endangered species and better understand animal behavior, while farmers use these technologies to support precision agriculture to increase crop yields and reduce costs. Virtual globes[14] (such as Google Earth and NASA World Wind) help teach schoolchildren about their local neighborhoods and the world beyond (such as the Wini Seamount near Hawaii, extraterrestrial landscapes on Mars and the Moon, and the Sloan Digital Sky Survey) in an engaging and interactive way. In the wake of recent natural disasters (such as Hurricane Sandy in 2012), Google Earth has allowed millions of people to access imagery to help disaster-response-and recovery services.[26] Within days of the 2010 Haiti earthquake, post-disaster roadmaps had been created thanks to citizen volunteers submitting timely local information to the popular volunteered geographic information[13] website OpenStreetMaps.[44]

In the coming decade, spatial computing promises an array of transformative capabilities; for example, where route finding today is based on shortest travel time or distance, companies are experimenting with eco-routing, finding routes that minimize fuel consumption and greenhouse-gas emissions. Smart routing that avoids left turns saves delivery company UPS more than three million gallons of fuel annually.[20] Such savings can be multiplied many times over when eco-routing services are available for consumers, as well as fleet owners, including public transportation.

The ubiquity of mobile phones represents an opportunity for gathering information about all aspects of our world and the people in it.[17] Research has shown the potential for mobile phones with built-in motion detectors carried by everyday users to detect earthquakes seconds after they begin.[11] Navigation companies (such as Waze; https://www.waze.com/) increasingly use mobile phone records to estimate traffic levels on busy highways. There is a growing need for a cyberinfrastructure (such as the Earth Cube initiative from the National Science Foundation, http://www.nsf.gov/geo/earthcube/) to facilitate our understanding of the Earth as a complex system. Technological advances have greatly facilitated the collection of data from the field and the laboratory and simulation of Earth systems. This has resulted in exponential growth of geoscience data and the dramatic increase in our ability to accommodate diverse phenomena in models of Earth systems. Such advances may be crucial for understanding our changing planet and its physics (such as in oceans, atmosphere, and land), biology (such as plants, animals, and ecology), and society (such as climate change,[19] sustainable economic development, understanding interactions among food, energy, and water systems,[36] and connected and autonomous cars[1]).

Work in spatial computing has been extensive in recent decades, particularly in the geographic context. It is difficult to convey the breadth and depth of this large interdisciplinary body of work to the broad computing community in a magazine article. Our goal here is thus twofold: share a broad perspective on spatial computing based on discussions at the 2012 Computing Community Consortium workshop (http://cra.org/ccc/events/spatial-computing-workshop/) and start a broader discussion on the role the larger computing community can play in this interdisciplinary area. We do this by describing a few examples from the workshop without trying to either prioritize or be comprehensive; more examples are covered in the Appendix and in Shekhar et al.[52] Finally, we advocate support for the interdisciplinary field beyond the examples presented here. We include several figures to illustrate societal stories and visions from the workshop.

Transformative Accomplishments

Spatial computing initially aimed to support computational representation and analysis of maps and other geographic data. Its influence was concentrated in highly specialized disciplines (as represented by the professional organizations listed in Table 1). Since

Table 1. Representative spatial computing organizations.

ACM SIGSPATIAL
International Society of Photogrammetry and Remote Sensing
International Geographical Union
IEEE Geoscience and Remote Sensing Society
Institute of Navigation
Society of Photo-optics Instrumentation Engineers

then, a number of transformative spatial computing technologies have become deeply integrated into society at large, helping answer many kinds of questions humans have always asked. Here, we briefly describe a few applications and research results of high significance and broad interest; for a deeper exploration of spatial computing, see various textbooks,[3,5,6,47,50] monographs,[45,48] encyclopedias,[16,53] and journals.[4]

Global Positioning System. Where am I on the surface of the Earth? In the 18th century, "the longitude problem"[55] was among the most challenging in science. Lacking the ability to measure their longitude, sailors in the great ages of exploration were literally lost at sea as soon as land was out of sight. Eventually, with the combined help of compasses, maps, star positions, and the chronometer (a clock that worked on moving ships), it became possible to position oneself with some level of precision, even in the middle of the ocean with no landmarks. With the 1978 launch of GPS and subsequent availability for civilian use, it is now possible to quickly and precisely locate oneself anywhere on the surface of the Earth. GPS is an example of the space-based GNSS,[24,27] which provides location and time information anywhere on Earth where there is an unobstructed line of sight to four or more navigation satellites (out of a few dozen).[39] GNSS-based accurate timekeeping facilitates everyday activities (such as clock synchronization in computer networks, including the Internet), geographic distributed sensor grids to monitor moving objects (such as missiles, planes, vehicles, and tectonic plates), and electric power distribution grids. Its localization capabilities have made possible a number of location-based services for end users (such as turn-by-turn navigation, local search, and geocoding). GNSS and related location-based services are today widely deployed and useful for commerce, science, tracking, and surveillance. Widespread proliferation of GPS systems was made possible by its low-cost very-large-scale integrated (VLSI) circuits implementations that could easily be integrated into mobile phones and tablets.

Remote sensing.[3] What fraction of the terrestrial surface is covered by forest? How has the forest cover changed in recent decades in the face of climate change, urbanization, and population growth? Traditionally, these questions were answered through manual land surveys, which are labor-intensive and thus often limited to small areas. Modern remote sensing satellites (such as MODIS; http://modis-land.gsfc.nasa.gov/, and Landsat, http://landsat.usgs.gov/) have made it possible to monitor land cover changes continuously[31] on a global scale. Moreover, specialized instruments can sense subsurface resources (such as aquifers and an underground ocean on Jupiter's largest moon Ganymede). Due to the large data volume, computing technologies are crucial in storing, querying, and analyzing remote sensing datasets. These datasets have also inspired computing innovations like Google Earth Engines.[43]

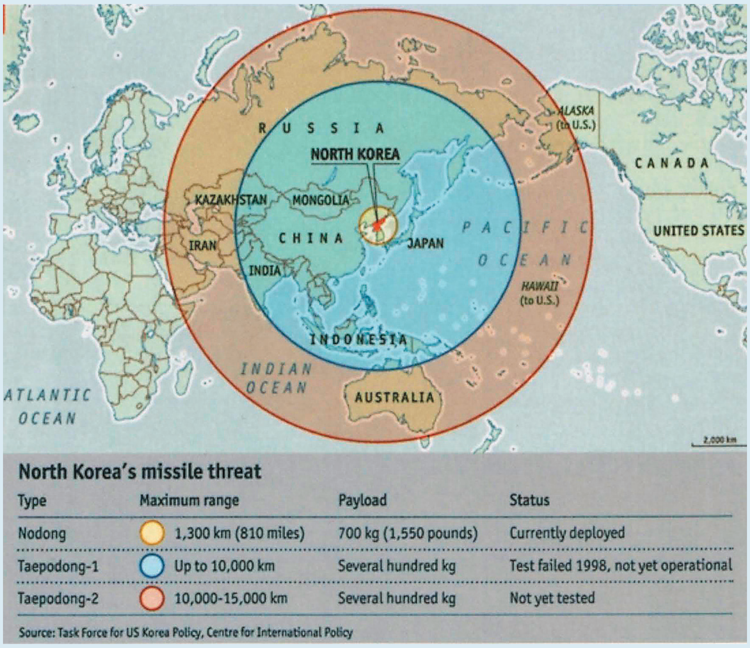
Geographic information system. Which countries can be reached by North Korea's missiles? Figure 1 is a well-known example of erroneous distance information computed on a planar map using circular distance, a mistake easily made without the help of GIS supporting spherical measurements. GIS understands a large number of map projections used by common geographic data producers and aids in fusing map data from diverse sources. As the Earth is not a perfect sphere, GIS also understands more accurate representations of the Earth, including ellipsoid representations and non-parametric representations that use land-based geodetic reference points for localization. GIS captures, stores, analyzes, manages, and visualizes spatial data;[22,53] for example, a map of the Earth is a representation of a curved surface on a plane. While map projections largely retain topological properties (except at map boundaries), retention of metric properties (such as distance and area) depends on the projection being used. GIS has a number of unique capabilities (such as cartography, geodetic data, and map layers). GIS can also join tables based on geometry to support spatial querying and statistical analysis, as explored in the next two paragraphs. GIS has greatly benefited from computing advances (such as algorithms like plane-sweep) and data structures (such as triangulated irregular networks related to map rendering and map overlay).

Spatial database management systems. Within the Sloan Digital Sky Survey, find galaxy pairs that are within 30 arc-seconds of each other. Which houses are most likely to be flooded by global warming-induced sea-level rise or cloud bursts or spring snow melt? Before development of spatial databases, such spatial queries required extensive programming and suffered from long computation times due to the mismatch between 2D spatial data and 1D datatypes (such as number) and indexes used by traditional database systems (such as B+ Tree). In addition, a naive collection of spatial data types is inadequate for multistage queries since the result of some queries (such as the union of disjoint polygons) cannot naturally be represented as a point, line, or polygon. Spatial databases[50] (such as Oracle Spatial and PostGIS) introduced spatial data types (such as OGIS simple features[38]), operations (such as inside and distance), spatial data structures (such as R-trees and Voronoi diagrams), and algorithms (such as shortest-path, nearest-neighbor, and range query) to represent and efficiently answer multistage concurrent spatial queries. The reduced programming effort resulted in more compact code and quicker response times.

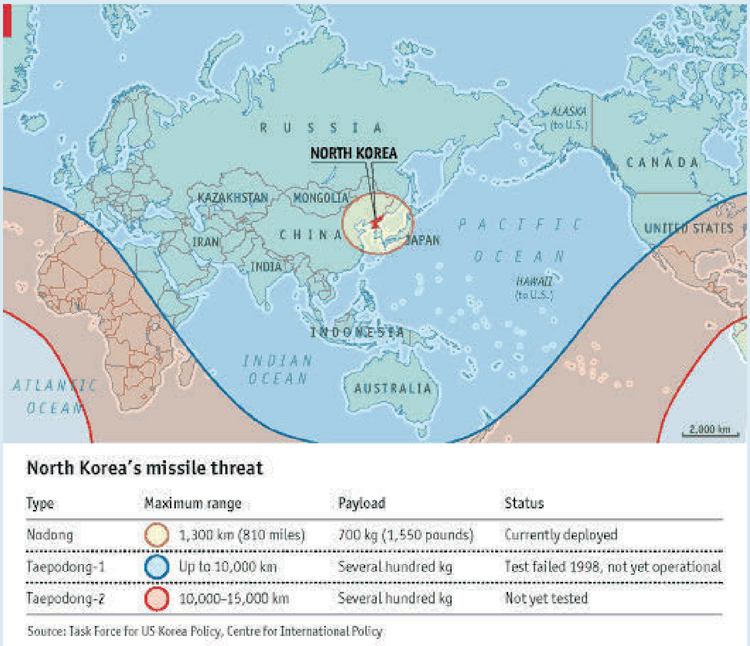
Spatial statistics. Which areas of a silicon wafer have an unusually high concentration of defects? Has there been an outbreak of disease? Where? In 1854, Dr. John Snow manually plotted Cholera locations on a street map of London to visually identify the outbreak hotspot around the Broad Street water pump (see Figure 2a). It took several days to perform this analysis for even a single disease over a small geographic area. Today, public-health agencies monitor scores of infectious diseases over very large geographic areas through spatial statistical tests (Figure 2b) designed to detect outbreaks (such as scan statistics) and hotspots, as well as distinguish these events from natural variations. Spatial statistical techniques are also routinely used in public safety (such as hotspots of crime reports), VLSI circuit design (such as defect hotspots on silicon wafers), weather forecasting (such as data assimilation), transportation (such as accident hotspots), mining (such as

Figure 1. Geographic information system. A 2003 article in *The Economist* significantly underestimated the distance North Korean missiles could travel because its map did not account for the spherical shape of the Earth; the correct version is below.[9]

(a) Flat Earth



(a) Spherical Earth



Kriging), public health (such as cancer cluster detection), and agriculture (such as designing management zones for precision agriculture and sample design for agriculture census). Spatial statistical theories (such as point processes, spatial autocorrelation, and geostatistics) address unique challenges (such as violation of independent identical distribution assumption) in applying traditional statistical models (such as linear regression, pearson correlation coefficient) to geographic data. Although spatial statistical techniques are an order of magnitude more computational and data intensive than traditional statistical techniques, the increased availability in recent decades of inexpensive high-performance computing and data technologies (such as sensors, the spatial database management system, and GIS) has facilitated wider interest in and adoption of spatial statistical methods.[12]

Where am I on the surface of the Earth?

Recent Change

In the late 20th century, most maps were produced by a small group of highly trained people in government agencies and surveying companies. Organizations (such as the U.S. Department of Defense and oil exploration companies) used highly specialized software (such as Esri ArcGIS and Oracle Spatial) for editing and analyzing geographic information. As summarized in Table 2, recent advances in spatial computing have changed this situation dramatically. Users with cellphones and access to the Internet number in the billions, meaning virtually the entire planet uses spatial technologies. Their very success has raised users' expectations of spatial computing. At the same time, users increasingly worry about the potential misuse of location data.

Billions using location-based services and updating actual maps. The proliferation of Web-based technologies, cellphones, smartwatches, consumer GPS-devices, and location-based social media facilitates widespread use of location-based services,[48] and Internet services (such as Google Earth and OpenStreetMap) bring GIS to the masses. With cellphones and consumer GPS devices, services (such as Enhanced 911 and navigation applications) are used by billions of people. Uber, Waze, Google Maps, Facebook check-in and other location-based social media are also used by more than one billion people worldwide.

Billions functioning as mapmakers, and many phenomena being observable. The source of geodata is increasingly smartphone users who may actively or even passively contribute their own geographic information. The immediate effect is wider coverage and increased numbers of surveyors for all sorts of spatial data. More phenomena are becoming observable because sensors are getting richer for 3D mapping, while broader spectrums at finer resolutions are being captured.

Multiple location-aware platforms. Spatial computing support was traditionally limited to application software layers (such as ArcGIS), Web services (such as Google Maps and MapQuest), and database management (such as SQL3/ OGIS). In the past decade, spatial computing support has emerged at several levels of the computing stack, including HTML5, social media check-ins, Internet Protocol Version 6, and open location services.

Rising expectations due to vast potential and risk. Location-based services, navigation aids, and interactive maps arguably exceed user expectations. Their intuitive basis and ease of use have earned them a solid reputation. Consumers see the potential of spatial computing for reducing greenhouse-gas emissions, strengthening cybersecurity, improving consumer confidence, and otherwise addressing many other societal problems. However, the very success of spatial computing technologies also raises red flags among users. Geoprivacy concerns must thus be addressed to avoid spooking citizens, exposing economic entities to liability, and undermining public trust.

Short-Term Opportunities

The profound changes outlined here reflect emerging avenues of research in spatial computing and give rise to a number of exciting new opportunities.

Augmented reality systems. Augmented reality enriches our perception of the real world by overlaying spatially aligned media in real time; for example, it can alter a user's view of the environment by adding computer graphics to convey past, present, or future information about a place or object, as in

Figure 3 and Figure 4. It is already used in head-up displays in aircraft cockpits and has become a popular feature in smartphone applications. As lightweight, but powerful, computer-driven eyewear becomes more commonplace, augmented reality will play a more central role in medicine, architecture, tourism, commerce, engineering, civil/urban planning, and assembly and maintenance, as well as in general day-to-day intelligence amplification. New spatial computing research challenges in this area stem from the need for new algorithms, as well as cooperation between users and the cloud, full 3D position and orientation (pose) estimation of people and devices, and registration of physical and virtual things. What natural interfaces can be adapted to leverage all human senses (such as vision, hearing, and touch) and controls (such as thumbs, fingers, hands, legs, eyes, head, and torso) to interact with augmented reality across multiple tasks? How can technology capture human bodies with full degrees of freedom and represent them in virtual space?

Spatial predictive analytics. Progress in spatial statistics[45] and spatial data mining[51] over the past decade has the potential to improve the accuracy and timeliness of predictions about the future path of hurricanes, spread of infectious diseases, and traffic congestion. Such questions have confounded classical prediction methods[32,35] due to challenges like spatial autocorrelation, nonstationarity, and edge effects. Spatial models can be invaluable when making spatiotemporal predictions about a broad range of issues, including the location of probable tumor growth in a human body or the spread of cracks in aircraft wings or highway bridges. Questions that need to be answered in this research area include: How might machine-learning techniques[30] be generalized to address spatiotemporal challenges of autocorrelation, nonstationarity, heterogeneity, and multiscale? How can frequent spatiotemporal patterns be mined despite transaction-induced distortions (such as loss or double-counting of neighborhood relationships)? What scalable and numerically robust methods are available for computing the determinants of very large sparse (but not banded) matrices in the context

Figure 2. Analysis of water pump sites and deaths from cholera in London in 1854:[54] (a) pump sites and deaths; and (b) output of spatial statistical test.

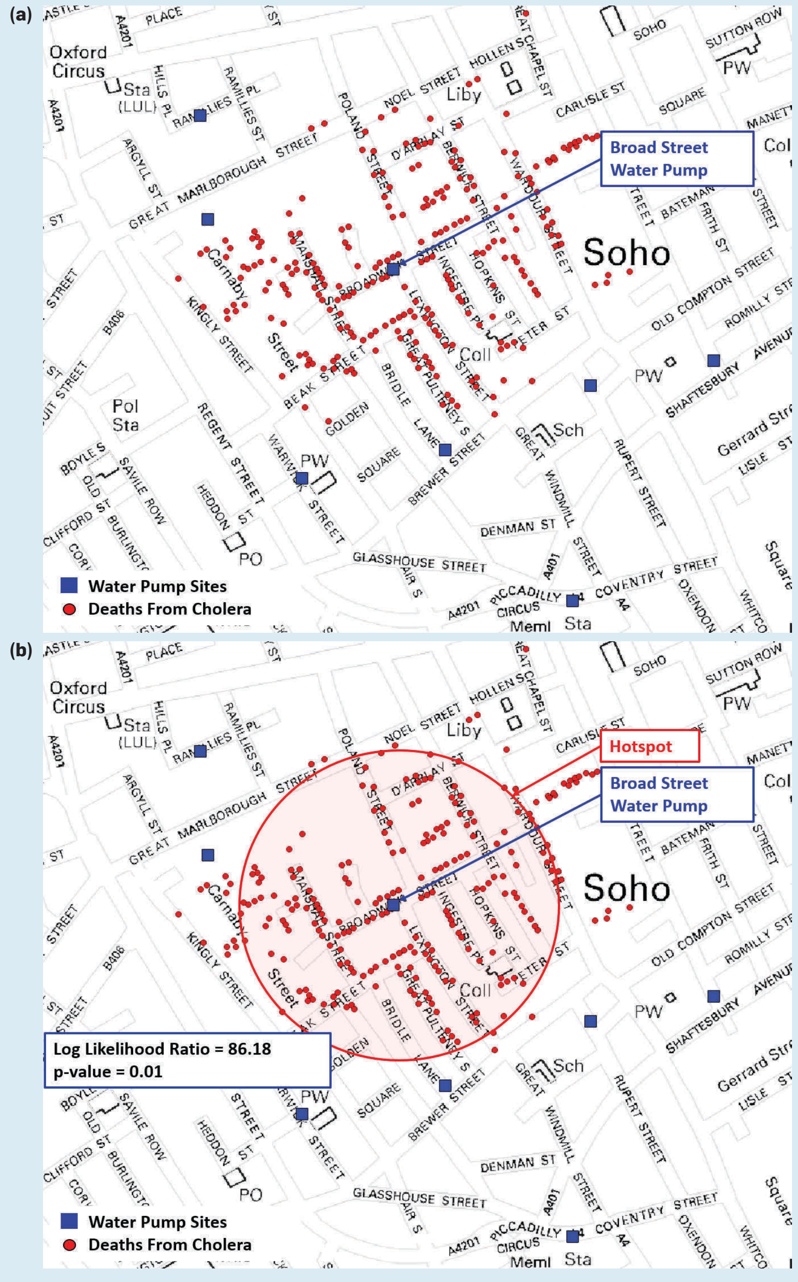


Table 2. Recent changes in spatial computing.

Late 20th Century	21st Century and Beyond
Sophisticated groups (such as the Department of Defense and oil-exploration companies) used GIS technologies.	Billions of people use location-based services and update actual maps.
Highly trained people in government agencies and surveying companies produce maps.	Billions of people are mapmakers, and many phenomena are observable.
Only specialized software (such as ArcGIS and Oracle Spatial) could edit or analyze geographic information.	More and more platforms are becoming location aware.
User expectations were modest (such as to assist in producing and distributing paper maps and their electronic counterparts).	User expectations are increasing due to vast potential and risk.

of maximum likelihood parameter estimation for spatial autoregression modeling?

Geocollaborative systems, fleets, and crowds. Spatial computing promises to take the Internet beyond cyberspace to the location-aware Internet of Everything, enabling connections among fixed structures and moving objects (such as cars, pedestrians, and bicycles), helping coordinate movement and understand patterns of mobility in cities and beyond; for example, the city of Los Angeles in April 2013 interconnected all of its 4,500 traffic signals to improve traffic flow during rush hour. Spatial computing enables smartmobs (groups of people) to come together quickly for a common cause, reducing the need for any one person to lead; drivers, smartcars, and infrastructure may cooperate in the future to reduce congestion, speed evacuation, and enhance safety. This cooperation raises the challenge of "trust" while using a group of spatial agents for computation and decision making. How might geographically distributed agents (such as smart signals and cars) cooperate in a trustworthy manner, even in the face of GPS spoofing?

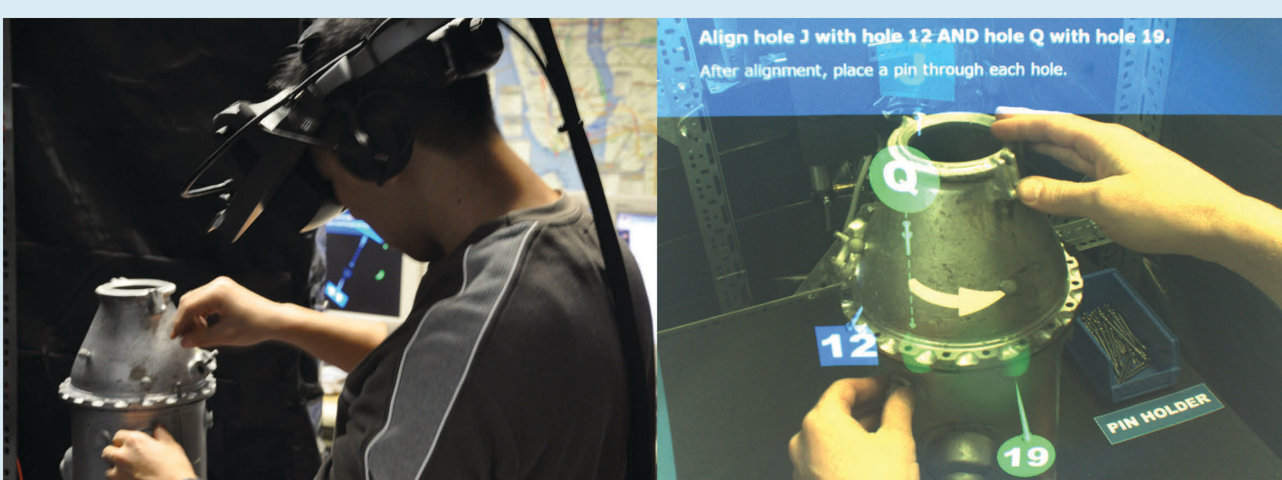
Moving spatial computing indoors, underwater, and underground. Despite worldwide availability, GPS signals are largely unavailable indoors, where we human beings spend 80% to 90% of our time.[56] Location-based services (such as route navigation) currently fill 10% to 20% of our time, but with emerging technologies like indoor localization, routing, and navigation (available in major airports and hospitals), the new expectation in the 21st century is our spatial context will be available essentially all the time, leveraging localization indoors and underground (such as mines and tunnels) through cellphone towers, Wi-Fi transmitters, and other indoor infrastructure. Indoor localization raises several new research questions, including: What scalable algorithms can create navigable maps for indoor space from CAD drawings? What about buildings where CAD drawings are not available? How can we perform reliable localization in indoor spaces where GPS signals might be attenuated or denied?

Figure 3. Augmented reality applications are becoming commonplace for smartphones.

Long-Term Research Needs

Spatial computing provides society tremendous value, but significant challenges are also emerging from those successes. Meeting them indeed requires expertise beyond the realm of spatial computing itself. First, overcoming the challenges of the public being de facto mapmakers and most phenomena being observable requires moving from the fusion of data from a few trusted sources to the synergy of data across a multitude of volunteers. Second, surmounting the challenge of

Figure 4. Experimental augmented reality assistance in aircraft-engine assembly. Henderson, S. and Feiner, S. Augmented reality in the psychomotor phase of a procedural task. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality* (2011).



equipping multiple platforms to be location aware will move spatial computing from a few platforms (such as cellphones) to almost all platforms (such as sensors, PCs, and clouds). Third, a greater understanding of human cognition is needed to ensure all members of society benefit from location-based services. And finally, spatial computing will have to address users' trust in and worry over privacy.

From fusion to synergetics. Historically, popular GIS software products (such as Esri's Arc family, PCI Geomatica, and ERDAS IMAGINE) were designed for geometric data (such as point, lines, and polygons) and raster data (such as satellite imagery). However, an ever-increasing volume of geographic data comes from volunteer citizens through check-ins, tweets, geotags, georeports from Ushahidi, and donated GPS tracks. Volunteered geographic information raises challenges related to data error, trustworthiness, and bias. The political and legal consequences of errors in spatial computing technology may be high; for example, after Hurricane Katrina in 2005, there was considerable concern in the U.S. Congress about the fact that the delays in releasing federal maps of New Orleans's most flood-prone neighborhoods had slowed rebuilding while yielding uncertainty.[15] Such political/legal complications could worsen in the future. Addressing such challenges requires a shift from traditional data-fusion ideas to a broader paradigm of data synergetics, raising yet more issues; for example, volunteers often use place names (such as Silicon Valley) and prepositions (such as near, in, at, and along) instead of numerical coordinates (such as latitude and longitude). Methods are thus needed for porting the current numerical-coordinate based data structures and algorithms to spatial data with place names and spatial prepositions. In addition, spatial and spatiotemporal computing standards are needed to more effectively use volunteered geographic information through quality-improvement processes (such as peer review and testing for recency) and documentation of quality measures (such as positional accuracy).

From sensors to clouds. In the 20th century, the public face of spatial computing was represented by software (such as ArcGIS and Oracle Spatial Databases). Today, all levels of the computing stack in spatial systems are influenced by the fact that more and more platforms are location-aware due to the widespread use of smartphones and Web-based virtual globes. New infrastructure is needed to support spatial computing at lower layers of the computing stack so spatial data types and operations are appropriately allocated across hardware, assembly languages, operating system kernels, runtime systems, network stacks, database management systems, geographic information systems, and application programs. Augmented reality capabilities are needed to accommodate such devices as eyeglass displays and smartphones for automated, accurate, and scalable retrieval, recognition, and presentation of information. Sensing opportunities involve providing pervasive infrastructure for real-time centimeter-scale localization for emergency response, health management, and real-time situation awareness for water and energy distribution. Computational issues[5] raised by spatial big data mean new research opportunities for cloud computing addressing the size, variety, and update rate of spatial datasets that exceed the capacity of commonly used spatial computing technologies to learn, manage, and process data with reasonable effort.

Spatial cognition first. Spatial computing services were previously defined for only a small number of GIS-trained professionals who shared a specialized technical language not readily understood by the general public. With everyday citizens using location-based services while becoming the equivalent of mapmakers themselves, today there is an urgent need to understand the psychology of spatial cognition. Such understanding will improve the use and design of maps and other geographic information products by a large fraction of society. Further research on spatial cognitive assistance is needed to explore such ideas as landmark-based routing for individuals who cannot read maps or for navigating inside a new space (such as a building or campus) where not all areas (such as walkways) have

How do we serve societal needs (such as tracking infectious disease) while protecting individual geoprivacy?

names. Understanding group behavior in terms of participative planning (such as collaboration on landscape, bridge, and building design) or smart mobs for coordinating location movement will enhance spatial computing services for groups of people, as opposed to individuals. Context (such as who is tweeting, where they are, and physical features in the situation) should also be brought into these scenarios to investigate new opportunities for tweet interpretation for warning alerts during emergencies (such as natural disasters like Hurricane Sandy). New ways to understand our spatial abilities (such as navigation, learning spatial layouts, and reading maps) and the way different groups (such as drivers and pedestrians) think about space must be further investigated to leverage some of these opportunities: How do humans represent and learn cognitive maps? How could spatial-cognition concepts improve usability of spatial-computing services? How can we create user interfaces that bridge the gap between spatial computing "in the small," typically on indoor desktop systems with stereo displays and precise 3D tracking, and spatial computing "in the large," typically outdoors through coarse GNSS on mobile/wearable devices?

Geoprivacy. While location information (such as GPS in phones and cars) delivers great value to emergency-response personnel, consumers, and industry, streams of such data also introduce serious privacy and trustworthiness questions related to the use of geolocation and geosurveillance to monitor and control citizens, or sometimes called stalking, geo-slavery,[7] and geoprivacy;[18,34,41,42] for example, the European Union accused Google Street View (https://www.google.com/maps/streetview/) of privacy violations, leading it to suffer temporary bans in a number of countries. Striking a balance between utility and privacy remains a difficult challenge. Computer science efforts to obfuscate location information have largely yielded negative results to date. Many individuals thus hesitate to indulge in mobile commerce due to concern about privacy of their locations, trajectories, and other spatiotemporal personal information.[18] Computer scientists need to join forces with policymakers and other advocates to win consumer confidence. New legal principles must be devised to align with "fair information practices,"[42] especially those related to notice, transparency, consent, integrity, and accountability. However, such alignment also raises questions, including: What would be considered "adequate notice" for collecting spatial data? How should consent be requested? What information should be stored, and for how long? More broadly, when does localization (such as GPS tracking) lead to a privacy violation? Is reducing spatiotemporal resolution sufficient to discourage stalking and other forms of geoslavery? How do we serve societal needs (such as tracking infectious disease) while protecting individual geoprivacy?

Conclusion

Spatial computing promises an impressive array of opportunities for researchers and entrepreneurs alike in the coming decades. Successfully harnessing this potential will require significant intellectual investment and related funding of spatial computing research topics, including, but not limited to, the examples we explored here. Many spatial-computing projects today are too limited to achieve the critical mass needed for major steps forward. Benefactors must strongly consider funding larger and more adventurous efforts involving a dozen or more faculty groups across multiple universities. Some exemplary initiatives include the U.S. National Center of Geographic Information and Analysis, GEOmatics for Informed Decisions network in Canada, RGE in the Netherlands, and the Cooperative Research Centre for Spatial Information in Australia. Another barrier to progress in research has been the fact grant proposals are often reviewed by panels with few or no spatial-computing experts, sometimes resulting in a lack of champions. Funding agencies should thus consider special review panels and specialized requests for proposals.

A number of agencies have research initiatives in spatial computing,[23,25,26,28,29] including the National Cancer Institute's Spatial Uncertainty: Data, Modeling, and Communication initiative, the National Geospatial-Intelligence Agency's Academic Research Program, and the Chorochronos project[49] funded by the European Union. Given its cross-cutting reach, benefactors should aim to establish computer science leadership in this emerging area by creating a dedicated and enduring research program for spatial computing. Multiagency coordination to reduce competing projects and facilitate interdisciplinary, interagency research would benefit the entire field, as well as the agencies themselves.

Finally, spatial-computing scientists need more institutional support on their home campuses. Beyond large one-time grants, a few research universities have established GIS centers (akin to computer centers in the 1960s), as well as campuswide spatial initiatives (such as the Center for Spatial Studies at the University of California, Santa Barbara; http://spatial.ucsb.edu/, and U-Spatial at the University of Minnesota) that serve research endeavors across a range of disciplines, including climate change and public health. More research universities should follow their lead.

Spatial computing has proved itself a major economic opportunity for society, and further support for spatial computing research will ensure even more revolutionary advances to come.

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