Next-generation Digital Earth

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A speech of then-Vice President Al Gore in 1998 created a vision for a Digital Earth, and played a role in stimulating the development of a first generation of virtual globes, typified by Google Earth, that achieved many but not all the elements of this vision. The technical achievements of Google Earth, and the functionality of this first generation of virtual globes, are reviewed against the Gore vision. Meanwhile, developments in technology continue, the era of "big data" has arrived, the general public is more and more engaged with technology through citizen science and crowd-sourcing, and advances have been made in our scientific understanding of the Earth system. However, although Google Earth stimulated progress in communicating the results of science, there continue to be substantial barriers in the public's access to science. All these factors prompt a reexamination of the initial vision of Digital Earth, and a discussion of the major elements that should be part of a next generation.

scientific communication | visualization

Digital replicas of complex entities and systems are now routine in many fields—in the design and testing stages of aerospace engineering, in digital reconstructions of ancient cities, or even in physiology, in which digital cadavers can replace real ones in the training of medical students. The concept of a Digital Earth, a digital replica of the entire planet, occurs in Al Gore's 1992 book *Earth in the Balance* (1), and was developed further in a speech written for delivery by Gore at the opening of the California Science Center in January 1998 (portal.opengeospatial.org/files/?artifact_id=6210). By the turn of the century, support for advanced 3D graphics had become standard on personal computers, allowing real-time manipulation of complex objects. Following the speech, the Clinton Administration directed NASA to form a Digital Earth office, a number of prototype projects were begun, and, with the 2005 launch of the Google Earth service, a fine-resolution, digital replica of the planet, or at least of its surface, was within reach of anyone with a broadband Internet connection.

The effect on the scientific community was immediate and palpable (2). Here was a readily accessible technology that could be used to present scientific data and results (scientific applications of Google Earth were recently reviewed in ref. 3) in easily digestible, visual form to collaborators and a general public that perceived it as free, fast, and fun. Digital Earth had relevance to any science dealing with the surface and near-surface of the Earth, and could be used to illustrate and even address a host of problems facing humanity, from climate change and natural disasters to warfare, hunger, and poverty (see, for example, the 2009 Beijing Declaration on Digital Earth; 159.226.224.4/isde6en/hykx11.html). The Chinese Academy of Sciences responded by organizing the first International Symposium on Digital Earth in Beijing in 1999; the symposium became a biennial event, and has been held in Canada, the Czech Republic, Japan, the United States, China, and Australia. In 2006, the International Society for Digital Earth (ISDE) was established, and biennial Digital Earth Summits have been convened in New Zealand, Germany, and Bulgaria. In 2008, ISDE's official publication, the *International Journal of Digital Earth*, was inaugurated.

In this concept of Digital Earth, sharing of scientific information about the planet could extend well beyond the scientific community, to people with very limited technical skills and computing resources—the vision of an information food chain extending all the way from science to public policy seemed almost within reach. Google's own Earth Engine project exemplifies this vision by making available Gore's "vast quantities of geo-referenced information." Unlike geographic information systems (GISs), which have a reputation for being difficult to learn, and force users to confront the intuitively difficult spatial concepts of scale and map projections, Digital Earth implementations such as Google Earth avoided projections entirely by showing the Earth as seen from space (technically a perspective orthographic projection onto the 2D plane of the screen), measured distance by using the length of the shortest path over the curved surface, and reduced scale to the simple metaphor of raising or lowering the user's viewpoint. A fly-by, the "magic carpet ride" of the Gore speech, the capstone achievement for generations of undergraduate GIS students, could be created by a child of age 10 in 10 minutes by using nothing more than a home computer and a downloaded Google Earth client.

There will always be a need for flattening the Earth, to see the entire surface at once, albeit distorted, or to present information on paper. However, there is no doubt that virtual globes had enormous advantages over traditional maps as a means of communicating data, information, and knowledge about the surface and near-surface of the planet. Here for the first time were software environments that could overlay layers of information by using geographic location as a common key, show buildings and vegetation as complex 3D structures, pan and zoom at the click of a mouse, and visualize extracts from petabytes of rapidly

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accumulating georeferenced information in fractions of a second.

It is now 7 years since the launch of Google Earth, and a similar period has elapsed since the release of the earliest of what is now a long list of comparable virtual globes, including NASA's open-source WorldWind (worldwind.arc.nasa.gov), Wuhan University's GeoGlobe, the Chinese Academy of Sciences Digital Earth Prototype System, Microsoft's Bing Maps (www.bing.com/maps), Esri's ArcGIS Explorer (www.esri.com/software/arcgis/explorer/), Unidata's Integrated Data Viewer (www.unidata.ucar.edu/software/idv/), and Digitnext's VirtualGeo (virtual-geo.diginext.fr/EN/). It is also more than a decade since the Gore speech and the vision that did much to motivate these efforts, which, in some cases, have extended well beyond the Gore vision. This seems an appropriate time, therefore, to examine what this first generation has achieved, and to envision what might be achievable and desirable in the future, another 6 or 7 years from now (an earlier and now somewhat dated analysis is provided in ref. 4). At the same time, these virtual globes, especially Google Earth, are examined from a critical scientific perspective to draw out some of the issues that lie at the intersection of commercial software and the scientific enterprise.

Achievements of Virtual Globes to Date

A common reaction to the Gore speech in 1998 centered on data volume: with approximately 5×10^{14} sq m of surface, as little as a single byte allocated to each square meter results in half a petabyte of data before compression. Zooming down to 1 m resolution and panning across the surface requires some clever algorithms and data structures if it is to be achievable with a standard personal computer at the end of a typical broadband connection, with limited capacity for local caching of data. Virtual globes use a variety of hierarchical tiling structures known as discrete global grids (and reminiscent of Buckminster Fuller's geodesic domes) to enable rapid zoom (reviewed in ref. 5), precompute tiles on the server to avoid extensive local computation, and use sophisticated level-of-detail management to allow the field of view to be refreshed at video rates (6).

One of the most attractive features of the virtual globes for the scientific user has been their capacity for extension and adaptation to individual needs. Google's Keyhole Markup Language allows the user's 2D and 3D data to be readily superimposed on the virtual globe in a variety of formats, opening the door to the vast number of "mashups" that have been constructed recently in every area of science. Open-source packages such as NASA's World Wind can be extended with new code, and Google's Application Programming Interface allows Google Earth functions to be embedded within the user's own application.

Virtual globes that are able to capture and display elevation above or below the surface have obvious applications in oceanography, atmospheric science, and geomorphology. Since its initial launch, Google has also enhanced the temporal dimensions of Google Earth, allowing the display of time series and the use of historic base maps. Unidata's Thematic Realtime Environmental Distributed Data Services project (www.unidata.ucar.edu/projects/THREDDS/) aims to facilitate sharing of data among Earth scientists using the Integrated Data Viewer platform, and includes a full range of 3D and temporal support.

Nevertheless, this first generation of virtual globes has several limitations, each with implications for potential uses. For a scientist, issues of accuracy, replicability, and documentation are likely to be of special concern, although they may be of less concern for the general public. Some of the more technical limitations are discussed in this section, and the following section asks what new developments might characterize a second, more powerful generation of Digital Earth.

Accuracy, Replicability, and Documentation. The Earth does not conform to any simple mathematical shape. The geoid or isopotential surface, best understood as the surface formed by sea level and its imaginary extension under the continents, must be approximated by a mathematical shape to define latitude and longitude and thus to measure location. Google Earth uses the specific oblate spheroid known as WGS84, an international standard World Geodetic System, and, in principle, measures made on the surface of this implementation of Digital Earth should conform to this standard. Lines of latitude should grow further apart away from the equator, whereas lines of longitude will, of course, converge on the poles.

Google Earth allows the user to add several types of figures to the Earth's surface, and in some cases to drag them freely over the surface. Dragging a circle, for example, produces several expected behaviors [these experiments were conducted with Google Earth Pro-6.0.1.2032 (beta); build date, December 10, 2010]: its radius remains constant, but its circumference grows longer toward the poles as the local curvature becomes less. However, some behaviors are unexpected, including a stepwise change of circle area as it is dragged toward the poles. Behavior becomes almost chaotic when the circle is dragged to contain the pole itself, or to intersect with 180° longitude. The mathematics of the spheroid are difficult, and perhaps shortcuts are being taken, for example, by resorting to calculations on the sphere or on a planar projection when the spheroid becomes less tractable.

Problems of dealing with uncertainty may have broader implications. Positions on the Earth are the result of measurement, and thus have accuracies that are limited by the measuring device. It is a long-established principle of science that measurements should be reported with a numerical precision that matches their accuracy, and the principle provides easy access to estimates of inherent uncertainty. However, latitudes and longitudes are routinely reported by Google Earth to as many as six decimal places of degrees (corresponding, in the case of latitude, or longitude at the equator, to ~10 cm) irrespective of the spatial resolution of the display. Distances, for example, between Los Angeles and New York, can be reported to hundredths of centimeters, an absurd precision given the lack of an accepted definition of the distance between two extended objects. Clearly the designers of this software lost track of an important scientific principle, preferring, instead, to exploit the full numerical precision of the computing system.

Readily accessible virtual globes are attractive bases for rapid determination of latitude and longitude. It is easy, for example, to find the location of a feature such as a road intersection by identifying it on the virtual globe's already georegistered image and capturing its coordinates. Any misregistration of imagery (by tying an image to the Earth's surface inaccurately) is inherited by any locations captured by using it, and when new imagery is inserted in the virtual globe, any previously registered feature will now be offset by any positional difference in the new registration. It is important to recognize that this is a measurement problem, and that exact measurement of location is impossible. Each new registration of the base imagery, in effect, creates a new datum—a new local approximation to WGS84 that may or may not be better than previous approximations. A scientist expects extensive documentation (i.e., metadata) on the registration process, its temporal history, and its implications.

The actual amount of misregistration of base imagery varies over space and over time, depending on the availability of small, recognizable features with known locations that can be used as reference points, on the spatial resolution of the imagery itself, and on many other factors. Potere (7) found that the mean misregistration of Google Earth imagery was ~40 m relative to Landsat GeoCover.

Over Santa Barbara, CA, misregistration has been as much as 40 m at times relative to high-quality global positioning system (GPS) measurements. What is important, of course, is not whether misregistration exists, as it must, but whether it is substantial enough to affect a given application. Moreover, positional uncertainty is only one of the many dimensions of uncertainty that characterize geographic data.

Achievements to Date Against the Gore Vision. Despite the progress they represent, today's generation of virtual globes fall short of Gore's vision of a Digital Earth in several key respects. [Goodchild (8) provides a more complete analysis of the uses of Digital Earth mentioned in the Gore speech, and compares them to those of GISs.] First, whereas Gore imagined a Digital Earth that would allow the user to explore backward in time by using historical data and forward in time by using computational models to simulate future scenarios, virtual globes remain largely centered on portraying the Earth as it looks at the current time. Older imagery is available in Google Earth for many areas, and historical maps have been made accessible as mashups using Keyhole Markup Language. Simulation-model outputs and time-series of imagery have also been linked to virtual globes. However, to date, it is not normally possible for a member of the general public to recover what his or her neighborhood looked like at some arbitrarily defined point in the past, or to use a virtual globe to visualize what his or her world will be like, in terms of urban growth, climate change, or sea-level rise, at some point in the future based on the best scientific modeling.

Second, whereas Gore imagined an environment in which it would be possible to store, retrieve, and share "vast quantities" of Earth-related information, in reality, not all such data are equal in the world of the virtual globes. Although the user can overlay data of various kinds on the base imagery, he or she has no control over the process by which Google acquires and makes available such imagery, and the Terms of Use impose tight restrictions over what can be done with the results. Rather than exploit virtual globes, the strategies developed for sharing of geographic data among scientists tend instead to follow the model of a data library [or geolibrary (9)]: a searchable catalog of holdings, formally structured metadata, and mechanisms for facilitating the downloading of selected data sets (see, e.g., the Geospatial One-Stop, geo.data.gov; or the Global Change Master Directory, gcmd.nasa.gov). Geoportals (10) provide a single point of entry into a distributed set of holdings, but nevertheless impose a significant burden on the user to execute a successful process of search, discovery, extraction, and use that is very different from the user-friendly, visual paradigm of the virtual globes.

Third, Google Earth's emphasis on visualization makes it difficult to communicate information that is not inherently visual. A virtual globe that looks like the Earth itself is intuitively straightforward, easy to navigate, and easy to understand. Topography can be shown in three dimensions, rather than by using the contours and other coded techniques adopted by cartographers; the effects of sea-level rise can be visualized by flooding areas with solid blue. However, other properties important to science, such as temperature fields, the spatial variation of soil types or vegetation properties, biodiversity, or the distributions of social, economic, and demographic variables, are not inherently visual, and not easily conveyed in immediately meaningful ways. Uncertainty is even more problematic, as there are no obviously intuitive ways of conveying its magnitude or implications—we are used to seeing a single, solid world rather than a world of many conflicting possibilities.

Prospects for the Next Generation

Several fundamental changes in society and in the world of digital geographic information have occurred since Gore's speech was formulated in late 1997. Mention has already been made of the advances in bandwidth and 3D graphics that have enabled the standard consumer device to visualize and manipulate a Digital Earth (Fig. 1). The supply of geographic information from satellite-based and ground-based sensors has expanded rapidly, encouraging belief in a new, fourth, or "big data," paradigm of science (11) that emphasizes international collaboration, data-intensive analysis, huge computing resources, and high-end visualization. It also demands improved techniques of search and discovery such as those that can be readily implemented in a virtual globe.

A large part of this new information is the property of governments and corporations, and unavailable to others, or heavily restricted in its reuse. However, the case for open data access is becoming increasingly compelling, given the severity and urgency with which problems must be addressed at a global scale. The thrust toward open data is gaining momentum in several countries that embrace it for reasons of transparency, administrative efficiency, and the economic potential of reuse. They support open government through legislation and practical measures, such as the production of data in machine-readable formats and the creation of data portals.

The ubiquity of GPS has allowed anyone to measure location on the Earth's surface with an accuracy of a few meters, and to tag other information, such as photographs, with geographic locations. Crowdsourcing is now a major source of geographic information (12), exemplified by the enormously successful, worldwide OpenStreetMap project and Google's MapMaker. New forms of citizen science are encouraging the general public to become involved in the acquisition of data on phenology, weather, disasters, and many other Earth-related phenomena. Many of these trends come together in the term neogeography (13), which implies a breaking down of the traditional distinction between expert and amateur in the world of mapping and geographic information. Thanks to GPS and a range of Web-based services, the average citizen is able to be a consumer and a producer (a "prosumer") of geographic information, and to make maps, such as those generated by in-vehicle navigation systems, that are valid only at an instant in time, centered on the user, representing the world as seen from above or from the ground, and useful only for the purposes of the moment. Many of these services have proven to be effective even through the interface of a simple mobile phone (e.g., Ushahidi, www.ushahidi.com). The citizen as prosumer offers an entirely new vision of the role of the citizen in relation to science: as volunteer observer, as intelligent recipient of the results of science as applied to the citizen's own

Fig. 1. Handheld consumer devices such as this tablet computer can augment a real scene with data obtained from Digital Earth, such as these underground pipes. (Image courtesy of NextSpace.)

surroundings, and as an informed stakeholder in the Earth's future.

Crowd-sourcing produces information of variable quality that lacks the structured sampling and rigorous methods of measurement that scientists emphasize. New methods will be needed to synthesize such crowd-sourced information, and to assure its quality, if it is to be used with confidence by scientists and more broadly in society. In future, techniques of synthesis applied to disparate data of varying quality may be as important as techniques of analysis have been in the past.

These new technologies of neogeography offer an unprecedented opportunity for science to extend its findings from the laboratory not only to the pages of refereed journals, but also to the eyes and minds of the general public. As easy-to-use tools capable of visualizing vast amounts of information at scales from the global to the local, the virtual globes clearly have a major role to play in this new vision of scientific communication. Several aspects of a renewed Digital Earth vision derive from this perspective. The ability to link the global to the local, through rapid zoom, is clearly a key aspect of the virtual globes.

At the same time, it would be wise to recognize that a simple linear model of communication between scientists and the public is naive in several respects. Scientists have much to learn about communication, especially in dealing with the uncertainty inherent in all measurements and predictions, as the recent "Climategate" and its aftermath demonstrated. The general public can often understand concepts of uncertainty and probability if they are explained well, and made an inherent part of systems like Digital Earth. Research over the past two decades has given us a rich understanding of the modeling and visualization of uncertainty in geographic information, and of how to communicate uncertainty to the user. It is vital that the next generation of Digital Earth replace the exaggerated precision of the first generation with techniques that convey uncertainty clearly and unambiguously to the user. More broadly, the social sciences have much to offer on the subject of communication, the cultural differences that characterize the various environments in which Digital Earth is accessed, and the ways in which data are understood and interpreted. Vast differences exist around the world in access to computer hardware, software, and the Internet, as well as in the technical skills and attitudes of users. The next generation of Digital Earth will need a strong commitment to involving the social sciences in its development.

One of the most powerful benefits of georeferencing—in other words, the association of attributes with locations on the Earth's surface—is context. Observations made at a location can readily be linked to other known facts about that location, or about nearby locations, in a rich contextualization. We can distinguish between horizontal context, or the context established by knowledge about nearby locations, and vertical context, or the context established by other things that are known about the same location. Both are captured in the famous principle of Tobler, often termed the First Law of Geography: "All things are related, but nearby things are more related than distant things" (14). A virtual globe provides easy access to context, especially horizontal context, allowing inferences to be made from the conditions surrounding a location. Vertical context is more difficult to visualize, because a virtual globe allows only one layer (or what one might term on a virtual globe a "topping") to be transparently overlaid on the imagery base. Mapping techniques such as cross-hatching might allow for two layers, but, more generally, it would be useful to look for more powerful ways of making the user aware of the vertical context of geographic attributes. Moreover, insights can often be gained not from the horizontal and vertical context of attributes, but by searching for analogous conditions elsewhere on Earth; virtual globes seem especially well suited to this kind of investigation.

More important, perhaps, would be the development of ways of capturing the linkages that exist between locations and across scales. Maps are powerful ways of visualizing the properties of locations, such as elevation or soil type, or what one might term "unary" geographic information. However, they are much less powerful at portraying the linkages that exist between places, such as flows of migrants or the configurations of social networks—information that one might term binary because it involves the properties of locations taken two at a time. A map of migration flows between each pair of the more than 3,100 US counties, for example, would show a mass of lines that would be impossible to comprehend without sophisticated techniques of abstraction and generalization (e.g., ref. 15), whereas a map of county life expectancy or ethnicity is easily understood. Linkages are clearly important to our understanding of environmental and social processes, and access to information about them should be an important part of a renewed vision. This is especially true when linkages represent the impacts of changing conditions in one location on conditions in another location, such as downstream or downwind.

The Gore speech describes a Digital Earth that would be capable of presenting predictions about the Earth's future—of climate change and sea-level rise, for example, or food supplies. Such predictions are commonly the outputs of simulation models, and represented in the extreme by projects that aim to develop a Digital Earth capable of predicting a vast array of properties at fine resolution in space and time, such as Europe's FuturICT (www.futurict.eu) or Japan's Earth Simulator (www.jamstec.go.jp/esc/index.en.html). They might be generated in one of two distinct ways: by running a model in its own software environment and then visualizing the results by overlaying them as a topping on a Digital Earth, or by running a model within the Digital Earth software environment itself, perhaps by using the virtual globe's discrete global grid as a set of finite elements. The latter might allow the virtual-globe user to modify parameters or boundary conditions, to evaluate alternative scenarios. In essence, such approaches would allow the user to investigate how the Earth works and how it might evolve in the future, rather than to observe how it currently looks. In the spirit of neogeography, these approaches might allow the user to augment reality with visualizations from the user's own perspective. They would require substantial investment in model management, given the vast number of models that are already available, their lack of interoperability, and the difficulty of choosing between them.

It would be important to incorporate a few simple analytic functions in the interests of supporting the evaluation of scenarios. A subset of the functions generally available in GIS would allow the user to obtain summary statistics for areas, for example, or to compute correlations. However, wholesale adoption of the functionality of a GIS is likely to lead to the same kinds of inaccessibilities the average citizen already encounters with GIS software. Careful consideration of cognitive issues will be needed to find an appropriate compromise between the scientist's need for advanced functionality and the general public's need for simplicity and ease of use.

Although it is always risky to offer any kind of prediction of technological futures, several trends are already apparent that should be incorporated in a renewed vision of Digital Earth. We already have the means to keep track of many kinds of objects: many vehicles, and the mobile phones of their occupants, are constantly tracked by using GPS and managed as "probes" to collect data on traffic speeds and congestion; commercial shipments are often tracked, as are pets, parolees, and many types of animals, in the interests of research. In the future, we should envision a world in which it will be possible to know the locations of everything at all times, through a georeferenced "Internet of

Things." We are also seeing a massive expansion in the functionality of mobile devices, and can envision a world in which computing will be ubiquitous, and in which Digital Earth will be accessible anywhere, at any time.

Although GPS positioning generally works more effectively outdoors, and geographic information is mostly 2D despite the increasing prevalence of 3D building representations in virtual globes, we should anticipate a day when it will be possible to support georeferencing and navigation within detailed 3D structures anywhere on the planet to centimeter accuracies (see, e.g., the work of the D_City Network, dcitynetwork.net and Fig. 2).

Despite these advances, the problem of archiving remains: we have, as yet, no satisfactory solution to the long-term preservation of the vast amounts of digital data already created, along with the exponential growth in data that seems likely to continue for some time to come. Much of what we know of the history of the planet is recorded on paper, and some of it has already survived for centuries. However, it is very hard at this point to see how century-long preservation of digital media can be achieved, together with the means to search and retrieve useful information. Extensive research and development will be needed if the records now being assembled for Digital Earth are to survive for more than a few years.

Finally, today's world of Digital Earth is predominantly silent, using only the visual channel to communicate with the user. Sound is at least as rich a medium for communication as vision, yet it plays almost no part in the communication of geographic information. The next generation of Digital Earth might make use of audio in several ways: by allowing the user to make requests through speech, by storing the sounds and stories associated with locations, and by responding to spoken place names. Audio is already strongly associated with small portable or wearable devices, which may in the future become the primary modality for access to Digital Earth.

The Way Forward

It is one thing to describe a vision for the next generation of Digital Earth, but it may be quite another to imagine how it might be achieved. The top-down option for implementing Gore's Digital Earth through large-scale public investment stuttered to a halt shortly after the 2000 US Presidential election, and in the current funding climate, a top-down initiative for a next generation seems equally unlikely.

In reality, the first generation resulted from advances in Earth observation; from a timely evolution of bandwidth and 3D visualization, the latter driven in part by the video game industry; from the modest stimulus provided by government funding; from the impetus provided by a US Vice President; by the commercial possibilities sensed by large corporations such as Google and Microsoft; and by the interests and enthusiasm of the open-source community. Underlying this was a sense among a loose-knit community that Digital Earth was both possible and desirable. We believe similar factors can drive a next generation.

The next generation of Digital Earth will not be a single system but, rather, multiple connected infrastructures based on open access and participation across multiple technological platforms that will address the needs of different audiences (16). A more dynamic view has also been proposed of Digital Earth as a digital nervous system of the globe, actively informing about events happening on (or close to) the Earth's surface by connecting to sensor networks and situation-aware systems (17).

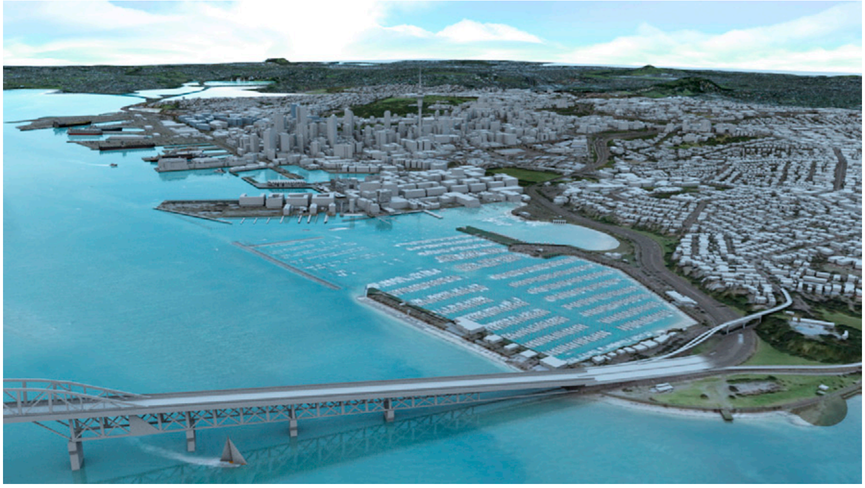

Fig. 2. A rendering of Auckland, New Zealand, using 3D models of all of its buildings and other built structures. (Image courtesy of NextSpace.)

Although great progress has been made in overcoming differences of software and data formats in sharing and communicating geographic information, issues of semantics continue to present major challenges. Differences of mapping practice, the ways in which land is classified, and the meanings attached to data are being addressed by projects such as the European Community's Infrastructure for Spatial Information in the European Community (inspire.jrc.ec.europa.eu). However, the Earth's surface is clearly heterogeneous, and any community will inevitably devise its own ways of describing its own surroundings. Although remote sensing achieves a degree of uniformity, other sources of geographic information tend to reflect the standards and practices of their source. One has only to compare, for example, the maps of the political boundaries of the Himalayan region provided by Google Maps in the US with those provided by Google Maps in China and India (Fig. 3) to realize the impossibility of achieving uniformity when mapping the human condition.

Any effort to develop a next-generation Digital Earth will require new governance models. In addition to the ISDE (www.digitalearth-isde.org), many other organizations, including the Global Spatial Data Infrastructure Association (www.gsdi.org), the International Council for Science and its Committee on Data for Science and Technology (www.codata.org), the Group on Earth Observations (and its geoportal, the GEO System of Systems, www.earthobservations.org), the UN Committee of Experts on Global Geospatial Information Management (ggim.un.org), and many national agencies will address various aspects of the future Digital Earth. These organizations can play a helpful role in endorsing the concept of a next-generation Digital Earth, and helping to elaborate its vision. Along with the scientific community, they can also play a useful role in ensuring that the next generation meets the highest standards of scientific rigor, especially careful and detailed documentation of uncertainty. Perhaps there is also room for a Digital Earth code of ethics that could set standards for behavior in a complex, collaborative enterprise.

However, in the realities of today's economies, it seems most likely that innovation will come from the private sector, together with volunteer initiatives centered around open-source tools. The private sector is fundamentally competitive, but organizations such as the Open Geospatial Consortium (www.opengeospatial.org) have been able to achieve remarkable degrees of cooperation and interoperability. A similar collaboration

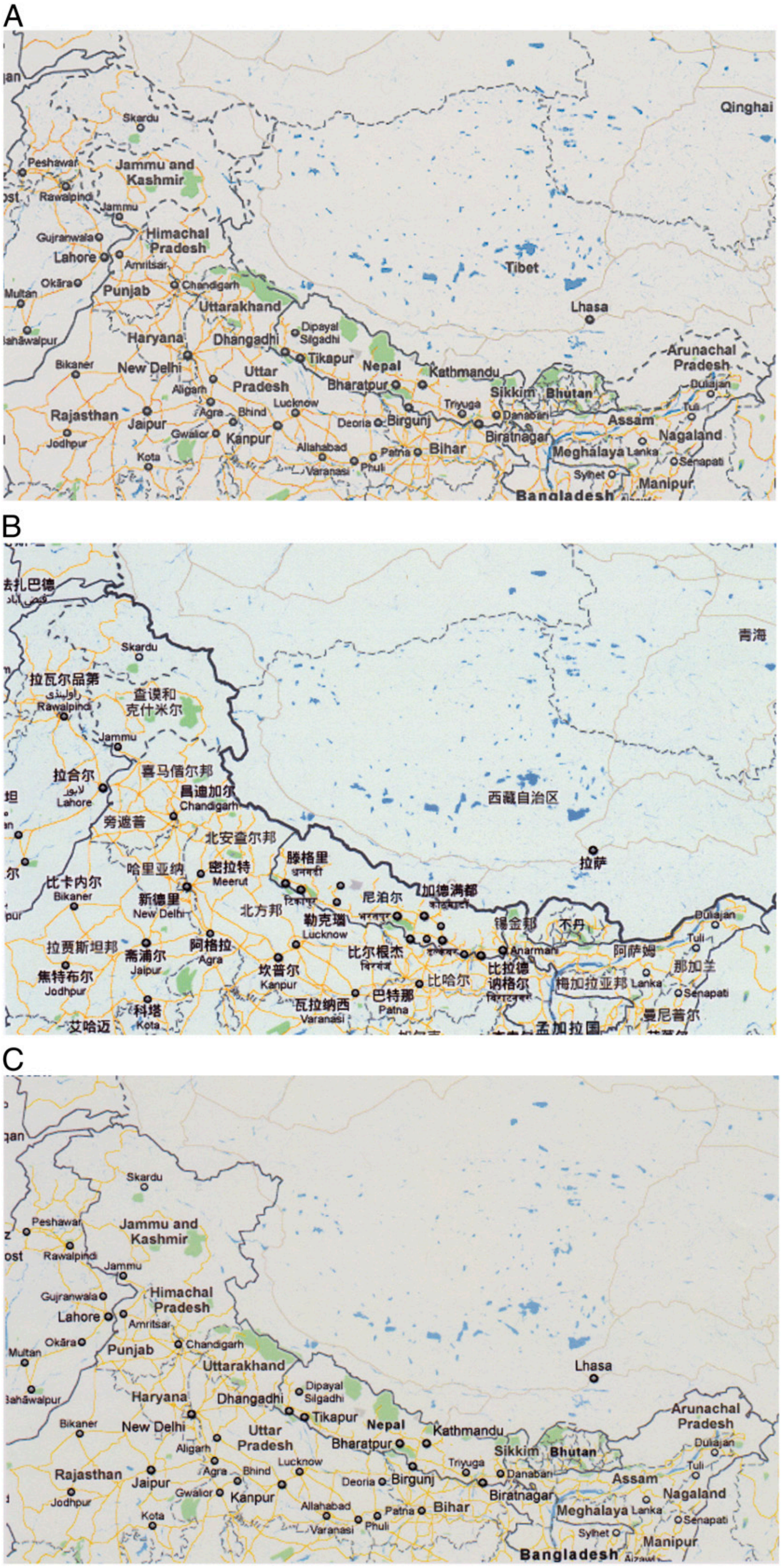

Fig. 3. Three versions of the boundaries of the Himalayas, as provided by Google Maps in response to queries from (*A*) the US (Copyright Google, Kingway, MapKing, Mapabc, SK M&C, TeleAtlas, ZENRIN), (*B*) China [Copyright GS(2011)6020 Google, Kingway, MapKing, Mapabc, TeleAtlas], and (*C*) India (Copyright Google, LeadDog Consulting, Mapabc, TeleAtlas).

among the private sector, academia, nongovernmental organizations, and government, focused on Digital Earth, might be similarly successful.

Collaboration at this scale will also be necessary to tackle the growing issues of privacy and ethics that are associated with access to fine-resolution geographic information (18). Technologies such as GPS and radio-frequency identification (RFID) raise the possibility of a future in which it will be possible to know and record where anything is, at all times. Fine-resolution imaging from space can identify objects on the surface less than 1 m across, and imaging from the ground can be used to recognize faces and license plates, creating a world that Dobson and Fisher characterize as "geoslavery" (19). To date, efforts to protect privacy have been patchwork in nature: for example, some countries now require Google Street View imagery to blur faces and license plates, and mobile-phone service providers in the US are restricted in their use of locational information. Against this one must place the evident willingness of people to publicize their location through services such as FourSquare or Google Latitude. To date, no principle of privacy protection has emerged that finds an acceptable, consistent position between the extremes of universal access and universal protection. At minimum, perhaps any individual should have a guarantee of control over his or her own locational privacy, able to turn it on or off at will.

It is clear to us that the first generation is powerful but limited, that technology is advancing rapidly and making possible what might have been inconceivable a few years ago, and that humanity needs better ways of linking the scientific community and its discoveries about the ways the Earth works and is structured with the general public and their growing concern about the planet's future. We would even go so far as to argue that access to scientifically grounded information about the planet's future is a basic human right; that it should be available to all, independent of national policies and strategies, and in a form that is readily understood and absorbed. This is, after all, the only planet we have, and we all have a vested interest in its future. Digital Earth seems to us the most accessible and compelling way to organize, visualize, and use that investment.

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1. Gore A (1992) *Earth in the Balance: Ecology and the Human Spirit* (Houghton Mifflin, Boston).
2. Butler D (2006) Virtual globes: The Web-wide world. *Nature* 439:776–778.
3. Yu L, Gong P (2012) Google Earth as a virtual globe tool for Earth science applications at the global scale: Progress and perspectives. *Int J Remote Sens* 33: 3966–3986.
4. Craglia M, et al. (2008) Next-Generation Digital Earth. A position paper from the Vespucci Initiative for the Advancement of Geographic Information Science. *Int J Spatial Data Infrastructures Res* 3:146–167.
5. Sahr K, White D, Kimerling AJ (2003) Geodesic discrete global grid systems. *Cartography and Geographic Information Science* 30:121–134.
6. Bar-Zeev A (2007) How Google Earth [really] works, RealityPrime Advanced Technology Research, July 3, 2007. Available at www.realityprime.com/articles/how-google-earth-really-works. Accessed July 16, 2011.
7. Potere D (2008) Horizontal positional accuracy of Google Earth's high-resolution imagery archive. *Sensors* 8: 7973–7981.
8. Goodchild MF (2008) The use cases of digital earth. *Int J Digital Earth* 1:17–30.
9. National Research Council (1999) *Distributed Geolibraries: Spatial Information Resources: Summary of a Workshop* (National Academy Press, Washington, DC).
10. Maguire DJ, Longley PA (2005) The emergence of geoportals and their role in spatial data infrastructures. *Comput Environ Urban Syst* 29:3–14.
11. Hey AJG, Tansley S, Tolle KM (2009) *The Fourth Paradigm: Data-Intensive Scientific Discovery* (Microsoft Research, Redmond, WA).
12. Goodchild MF (2007) Citizens as sensors: The world of volunteered geography. *GeoJournal* 69:211–221.
13. Turner A (2006) *Introduction to Neogeography* (O'Reilly, Sebastopol, CA).
14. Sui DZ (2004) Tobler's First Law of Geography: A big idea for a small planet? *Ann Assoc Am Geogr* 94: 269–277.
15. Tobler WR (1975) *WINDS: A Computer Program for the Analysis of Geographical Interactions. Cartographic Laboratory Report No. 13* (Univ Michigan, Ann Arbor).
16. Craglia M, et al. (2012) Digital Earth 2020: towards a vision for the next decade. *Int J Digital Earth* 5:4–21.
17. De Longueville B, Annoni A, Schade S, Ostlander N, Whitmore C (2010) Digital Earth's nervous system for crisis events: real-time sensor Web enablement of volunteered geographic information. *International Journal of Digital Earth* 3:242–259.
18. Curry MR (1998) *Digital Places: Living with Geographic Information Technologies* (Routledge, New York).
19. Dobson JE, Fisher PF (2003) Geoslavery. *IEEE Technol Soc Mag* 47:47–52.