FROM VESPUCCI TO GIS

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Abstract

The "spilling-out" represented by Vespucci was not of artistic achievement but of an approach to the investigation of the Earth. It was concerned, as was all exploration at the time, primarily with the Earth's form, of how the world looked: its capes and bays, its human and natural resources. The exploration effort to which Vespucci contributed was a painfully slow process, and it was not until the 19th Century that the process was in any sense complete. Today satellites can complete the same process in hours. Vespucci's contribution lay in his ability to reason from limited observation to a synoptic view: to scale up to the conclusion that the coast he explored formed a new instance of the class "continent", of which three instances were known in the old world. He made other scientific contributions: to the estimation of the Equatorial radius and to the estimation of longitude, both synoptic concepts. The process of mapping never ends, of course, and today we are still concerned with filling gaps in our knowledge of the subsurface, of changes that constantly occur, and of the details missed by earlier efforts. The process of personal (re)discovery, through tourism and communication, also never ends. Much more important than knowledge of form, however, is knowledge of process, of how the world works as a system. Vespucci and his contemporaries knew and learned very little about process, but as mapping has improved so has our collective effort to understand and ultimately to predict change. It is possible to reason from form to process, from the footprints that processes leave, and there are many classic examples in science. But ultimately form cannot confirm process, it can only falsify inappropriate hypotheses. Geographic information systems, a development of the past 40 years, have vastly improved our ability to examine the Earth, integrating knowledge of many kinds into a single computational environment, examining patterns and detecting anomalies, and building and testing models of process. As such they provide an essential link between the observational sciences pioneered by Vespucci, and the knowledge of process that will be essential as humanity struggles to sustain life on this vulnerable planet.

Spilling out

Gathering knowledge of form

One of the persistent themes of this conference is "spilling out", the notion that the concentration of intellectual and artistic achievement that was found in Florence in the 15th and 16th Centuries spread through a process of diffusion to other centers in Europe, influencing individuals and stimulating them to intellectual and artistic activities of their own. Amerigo Vespucci's achievements were part of that spilling out, reaching as they did as far as the New World, and influencing the entire process of European-based geographic discovery. In this paper I examine the nature of that spilling out, and trace the history of humanity's understanding of its home planet, the Earth, from the time of

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Vespucci to the present day.

The Discoveries that the Portuguese initiated in the first half of the 15^{th} Century, and that were continued through the efforts of Columbus, Vespucci, Drake, and many others, were primarily concerned with the acquisition of knowledge about the *form* of the Earth's surface—in other words, of how the world *looks*. Information on the populations, resources, and products of remote lands drove economic interest in trade and a quest for new markets for European products; and information on capes, bays, straits, and islands was essential to successful navigation and thus to secure and profitable trade. Information was jealously guarded, and became one of the most valued commodities in the decades following discovery. Maps were a perfect medium for storing this information—the paper medium was relatively stable, could be taken to sea, and could be readily transferred from one owner to another. Maps could be engraved and thus duplicated in unlimited quantities, and they could be sold by dealers and collected in libraries. Only fire represented a real and constant threat.

Today we are well aware of the limitations of maps (Goodchild, 1988): the major distortions present in early maps because of the difficulty of measuring longitude, especially at sea (Sobel, 1995); the inability of maps to render information about dynamic phenomena, including currents, storms, and seasonal variations in climate; the difficulties inherent in rendering uncertainty of any kind, and the clumsy methods used by early map-makers in this regard; and the distortions that result from projecting the curved surface of the Earth onto a flat sheet (Snyder, 1993). Nevertheless, maps provided an extremely effective method for sharing acquired knowledge about the form of the Earth's surface in newly discovered areas.

The process that the Portuguese largely initiated continued slowly but surely throughout the following five centuries. Mapping is after all an inherently slow process. As humans the reach of our senses is limited by the visual horizon and by the range of sound and smell, and it is unusual for us to be able to see more than 10km at any instant in time. It was unusual, for example, for the topographers of India to be able to map and estimate the elevation of Mt Everest from hundreds of km away on the plains, and for navigators such as Cook and Vancouver to be able to map features such as Pigeon House or Mt Fairweather that lie tens of km inland. An explorer sailing at 100 km/day might map 2000 km^2 of ocean per day, at which rate it would take approximately 1000 explorer-years to visit and map all of the Earth's 350,000,000 km^2 of ocean; moving overland at 10 km/day, a typical rate of progress in the Africa of the 19^{th} Century, and observing a swath similarly 20km wide, an explorer such as Livingstone or Burton would require roughly 2,000 years to map the entirety of the Earth's 150,000,000 km^2 of land. Given these rates, it is not surprising that the process of mapping was so costly and slow.

It was not until the middle of the 20^{th} Century that there could be any degree of general confidence that the form of the Earth's surface was *known*, at least in its comparatively static aspects. The maps of Africa and Antarctica were finally completed at great human cost, and later generations of would-be explorers would have to achieve fame by plumbing the ocean depths; standing in places such as the summit of Everest that were already well known, if not previously visited; exploring subterranean caves; and visiting the Moon and the other planets. Until the 1960s, London's Royal Geographical Society could each year award its gold medals to explorers in the traditional sense of being the first to map and describe places previously unvisited by Europeans; since that time, an increasing proportion of medals have gone to those whose activities are largely sedentary and reflect a much broader interpretation of the role of explorer (see www.rgs.org).

Today, of course, the basic mapping task is completed daily if not hourly by a constellation of Earth-observing satellites (Jensen, 2000). Imagery is now commercially available at a spatial resolution of 62 cm from the Quickbird satellite (Figure 1; at this resolution the Earth's surface comprises approximately 1.5×10^{15} picture elements). Any given point on the surface is re-imaged every few seconds by satellites in geosyncronous orbit, and every few days by satellites in sun-syncronous orbit, allowing rapidly changing phenomena such as hurricanes, urban growth, or the effects of drought to be monitored virtually continuously. Radar sensors allow images to be created through clouds, solving a problem that had plagued previous efforts to image such persistently cloud-covered areas as New Guinea, and hyperspectral sensors partition the spectrum into several hundred bands, allowing very sensitive differentiation of vegetation types, pavement materials, and surface mineralization (Figure 2).

[Figure 1 about here]

[Figure 2 about here]

Paradoxically, however, our knowledge of many geographic phenomena is actually deteriorating at the present time. While satellites can gather and transmit enormous volumes of data, the task of interpretation almost inevitably requires human intervention. Types of mapping that were routine in the 19th and 20th Centuries are now impossibly costly, and governments are less and less willing to fund them (Mapping Science Committee, 1993). Thus topographic maps, which show both phenomena observable from space, such as the locations of roads, and also information such as the names of places that are beyond the vision of satellites, are now in serious decline in many parts of the world (Estes and Mooneyhan, 1994). The most detailed topographic mapping of the U.S., the Geological Survey's 1:24,000 map series of the conterminous states, is now on average over 25 years out of date. National censuses, still the primary source of information on the distribution of people and their demographic, social, and economic characteristics, are under serious threat in many countries because citizens are more and more reluctant to respond to what they perceive as intrusive questions.

The contribution of Vespucci

It would be easy to dismiss Vespucci as just one more name in a long honor roll of explorers—people, almost all of them men, who discovered and mapped the mostly static and physical features of the Earth's surface (Allen, 2002). Vespucci contributed knowledge of approximately 10,000 km of the shoreline of the New World, a major accomplishment but not out of line with the later contributions of Magellan or Cook. Vespucci's contribution is distinguished by his ability to reason from limited observation, to see *the big picture,* and to advance the tools that were available to him. The 10,000 km of shoreline observation led him to the realization that he was mapping the coastline of two new continents, new instances of a class known from three Old World instances—Africa, Asia, and Europe—and an insight that clearly eluded Columbus. He never directly observed continents, of course, and continents were never directly observed until the era of satellites and space travel dawned in the 1950s. Instead, he generalized from

Old-World experience to formulate a model, that the Earth's land masses could be understood as three instances of a new and unobservable concept, and applied the model to the new discoveries. Many centuries later that model was finally embedded in the theory of plate tectonics through a similar leap of inferential logic (Marvin, 1973).

Again unlike the vast majority of his fellow explorers, Vespucci's work was also distinguished by the advances he was able to make in the tools that supported the process of exploration. In most other cases, advances in the technology of exploration were borrowed from others, or made by people who never themselves explored. The compass was imported from China, for example, and the final solution to the problem of measuring longitude was achieved by the clockmaker Harrison (Sobel, 1995). Vespucci, on the other hand, made significant contributions, though less than final, to the longitude problem, and also to the estimation of the Earth's radius. As with the continental inference, both cases reveal an ability to reason from limited observations to a larger, synoptic view.

In summary, Vespucci illustrates something of the unique character of the *spilling out*: that it included much more than the energy and entrepreneurship displayed by explorers everywhere—the search for fame, glory, and fortune beyond the known horizon. In Vespucci's case, the unique crucible that was Florence instilled a sense of what today we would identify as among the most important characteristics of the scientific method: an ability to reason from limited observations to the formulation of new theories, models, and generalizations about the natural world.

From form to process

Mapping as an endless process

The process of mapping initiated in the 15th Century never ends. Humans continue to discover new phenomena by drilling under the ocean floor, and the recent discoveries of massive anhydrite deposits on the floor of the Mediterranean have led to dramatic rethinking of that basin's geologic history. New caves are continually being discovered, as well as new geologic structures and mineral deposits.

When phenomena are dynamic the process of mapping is never finished. Tectonics, erosion, the melting of icecaps, urban growth, and other human modifications of the landscape, such as the construction of the Three Gorges Dam, all cause differences to develop between maps and the phenomena they purport to represent. In essence, the temporal resolution of mapping should match the nature of the processes that modify the landscape. If tectonic processes are modifying the landscape of California at rates comparable to the growth of fingernails, then a map that is a decade old will have errors of tens of cm, and a map that is a century old will have errors in the meter range.

Mapping is also an endless process from the perspective of spatial resolution or detail. Vespucci was content to observe and describe at a relatively coarse level, with little interest in features smaller than 1 km. Today, surveyors demand positional accuracies at the mm level for major construction projects such as the Channel Tunnel, and intelligence applications demand satellite imagery that is often far better than 1 m in resolution. Much recent research effort has gone into the process of *scaling down*—of inferring high-resolution information from comparatively coarse information. For example, the global climate models that forecast future conditions under various scenarios of increasing atmospheric CO_2 typically compute at resolutions in the hundreds of km, but their forecasts are often down-scaled by combining them with more-detailed information on surface characteristics such as slope, soil, and land cover.

While the classic age of discovery entered a process of decline in the early 20th Century, each of these arguments above supports the notion that discovery remains as important as ever, though it is now largely confined to the spaces of other planets, to the sub-surface, to the discovery of dynamic phenomena, and to the discovery of details that were overlooked in the earlier period. But in one additional respect discovery and mapping remain as important as ever. The fact that Edmund Hillary and Tensing Norgay set foot on the top of Mt Everest in 1953 has not deterred hundreds of others from also seeking to add experience of that location to their personal geography—instead, it seems to have encouraged them (Krakauer, 1997). Discovery in the 21st Century has become much more individualistic than in the past; discoveries are made not so much to advance the economic wealth of sponsors, as they were in the days of Vespucci and Columbus, but for personal enlightenment and achievement. In effect the Earth's surface is being rediscovered over and over again; and the fact that people have been there before seems less and less of a deterrent.

The importance of process

While the age of exploration is clearly in decline, of not finished, the previous section outlined four reasons why discovery and mapping are still active priorities, and helps to explain why total expenditures on the acquisition of geographic information continue to grow (Longley *et al.*, 2001), despite the previous observation that in many ways the current state of mapping is actually in decline.

But a more profound trend has emerged in the past century or so that has done more to change the face of mapping than any of the arguments presented thus far. As humans, we more and more need to understand not how the world *looks* but how it *works*. As custodians of the planet, it is incumbent on us to ensure that the Earth's surface is passed on in habitable, usable form to future generations. It would be unwise of us, for example, to make massive changes in any aspect of the Earth's surface without understanding in advance the impacts that those changes might have. We know that the Earth's atmosphere, oceans, and biological systems are tightly inter-related, such that changes in any one impact the others. So it would be irresponsible to remove the trees from a large proportion of the land surface, for example, without first determining the impact that would have on climate, or to remove the ozone layer through the manufacture and release of chlorinated flourocarbons. Yet this kind of experiment is precisely what we are doing, through changes as massive as the injection of vast amounts of greenhouse gases, including CO_2, into the atmosphere as a result of the burning of fossil fuels.

Vespucci learned very little in his travels about how the world works, and the process of unraveling the dynamics of the Earth system had to wait several centuries for significant progress, beginning with the work of the early geologists such as Hutton and Smith and the biologists Wallace and Darwin. But as mapping has improved, so too has our ability to reason about process, and ultimately to predict the effects of change. Mapping, and its modern equivalents in the geographic information technologies—

remote sensing, geographic information systems, and the Global Positioning System—provide the enabling tools for much of this progress.

Inferring process from form

With very few exceptions the processes that shaped the Earth's surface and continue to regulate its behavior are beyond our powers of direct observation. We observe occasional earthquakes and hurricanes, and make decisions about migration and shopping behavior, but the details of how the Grand Canyon developed, or why the towns of Iowa are located where they are, are far beyond the reach of our senses. Instead, much of what we know about the processes that shape the Earth is inferred by reasoning from observations of form.

The goodness of fit between the Atlantic coastlines of Africa and South America must have struck observers almost as soon as the first sufficiently accurate maps became available in the 16th Century. Improved mapping simply improved the goodness of fit. But it took many developments in geology, and several more centuries, before the theories of continental drift and plate tectonics were elaborated (Marvin, 1973); and even then, it took decades and further observations before they were widely accepted. Today we have detailed maps of alternating magnetic patterns on the Atlantic floor, and detailed maps of the matching geologic structures of the two continents, both of which add additional evidence from form to support ideas of process. And of course we now have the means to make direct observations of the processes of spreading and the formation of new crust along the Mid-Atlantic Ridge. In effect, a theory of process that was deduced from observations of form has now been confirmed by direct observation.

Reasoning from form to process is never easy and straightforward, however. In a famous example from epidemiology, Dr John Snow mapped the cases of cholera in an outbreak in London in 1854 (Gilbert, 1958; Figure 3). The cases showed a clear concentric pattern centered on a public water pump in Broad Street, consistent with the hypothesis that the disease resulted from drinking water from the pump. To Snow the map was clear evidence of cause, because it showed the pattern expected under the hypothesis. But at least two other processes would have left similar footprints: a process of contagion, in which an initial carrier located near the pump spread the disease through the neighborhood; and a process of varying vulnerability, in which residents of the neighborhood were for some reason predisposed. Both of these alternative hypotheses require a coincidence—the location of the initial carrier near the pump, and a concentric pattern of predisposition respectively—and so one might cite the principle of Occam's razor to favor Snow's hypothesis, but this is a comparatively weak argument on which to base public-health policy. In short, the example illustrates the almost inevitable ambiguity in reasoning from form to process. A simple way to resolve part of the ambiguity would be to introduce dynamics, since a temporal sequence of cases would clearly resolve between Snow's hypothesis and the contagion hypothesis.

[Figure 3 about here]

One of the best-known theories of human geography concerns the locations of settlements, and the patterns made by towns and villages. The work of Christaller (1966) and Lösch (1967) showed how simple assumptions about the behavior of farmers, urban residents, and shopkeepers led to characteristic patterns of settlements on the Earth's surface: in areas of uniform agricultural potential settlements would form a simple nested hierarchy, each level in the hierarchy forming a regular hexagonal pattern. Numerous studies have attempted to find such patterns in the form of the settlement landscape, with mixed success. For example, one might expect the boundaries of counties to be hexagonal, centered on the settlements that form each county's administrative seat. A simple analysis of county boundaries will show that the average number of neighbors of each county is remarkably close to 6. Apparently, settlements exhibit the characteristic footprint pattern anticipated by the theory.

Unfortunately it turns out that virtually any irregular tesselation exhibits the same property, whether or not the processes responsible for the tesselation have any relationship to the theories of Christaller and Lösch, provided that almost all nodes are formed by three edges (that the nodes of the boundary network are 3-valent; the US state boundary network famously has only one 4-valent node). This is a simple consequence of a theorem originally discovered by Euler, that in a tesselation the number of faces less the number of edges plus the number of nodes will be 1, and 2 if the rest of the world is counted as a face (Okabe, Boots, and Sugihara, 1992). In short, the same form is produced in this case by any process.

In essence, and as these examples show, spatial or *cross-sectional* form can never confirm hypotheses about process, though it can sometimes aid in rejecting false hypotheses. But form is all that is available in many instances, given the limited ability of human observation to track dynamic change. Satellite images are inherently cross-sectional, as are decennial censuses and topographic maps. Thus cross-sectional data is often all we have, especially in relation to processes that operate over time-scales that are long with respect to human experience.

Geographic information systems

In the past few decades the mapping sciences, and the study of phenomena portrayed on maps, have undergone radical transformation as a result of increasing use of digital technologies. It is not at all obvious that the contents of a map, or the reality of the Earth's surface, can be usefully expressed in the language of the digital computer, which has only two characters, but today many coding schemes are available, and a vast amount of digital geographic information is now readily accessible on the Web—indeed, the volume of such data accessible through NASA's EOSDIS site alone is now in excess of 1 PB (1 petabyte equals 10^{15} bytes).

Digital representation of geographic information conveys enormous advantages over its paper-map predecessor (Longley *et al.*, 2001). Unlimited copying and transmission is possible, at close to the speed of light. Analysis, tranformation, and manipulation can be performed through the medium of geographic information systems (GIS), which are software systems that perform virtually any imaginable operation on geographic data (Figure 4). Data can be displayed without any of the limitations of the paper-map medium, and today advanced forms of rendering and visualization of moving, three-dimensional phenomena are routine. GIS can be used to develop and evaluate planning scenarios, modeling and visualizing the impacts of alternative decisions and thus vastly improving the quality of public debate.

[Figure 4 about here]

The first GIS was constructed by the Government of Canada in the mid 1960s for a simple purpose, the calculation of the areas of irregularly shaped parcels of land (Foresman, 1998). Traditionally two manual methods have been available for measuring areas from maps, both costly, tedious, and inaccurate: a mechanical measuring device known as a planimeter, and a process of overlaying and counting dots of known density. The genius of the Canada Geographic Information System was the recognition that if the obvious technical difficulties of representing maps in a computer could be addressed, the necessary calculations could be made extremely rapidly and accurately, and at almost no cost. Many of the key innovations that are recognized today as fundamental advances in the development of GIS were made during the development of CGIS.

Today, GIS is a mature application domain of computing. A commercial software development sector has emerged, and there are now hundreds of thousands of system installations worldwide. Millions of people make daily use of the simple GIS functions provided by such Web services as MapQuest, and the functions provided by in-vehicle navigation systems, which are also in essence primitive GISs. Virtually all published maps are now created and edited in such systems, even though the final product may be on paper, and remote sensing provides a vast and powerful resource of raw data. Simple GIS functions are now provided through cellphones, in applications termed *location-based services*, based on the cellphone's ability to know where it is, and to modify the information that it provides accordingly.

There are several reasons why a GIS provides a much more powerful platform than the paper map for reasoning about process. First, while much of GIS architecture still reflects its origins in the storage of static data derived from maps, there have been major and rapid advances in recent years in the ability to handle time, not least through the adoption of object-oriented principles of database design, in place of earlier models that were more strongly linked to the map (Worboys and Duckham, 2004). Techniques for working with dynamic data—methods of analysis, modeling, and visualization—still lag behind, but are advancing rapidly (Peuquet, 2002). Second, GIS is increasingly being adapted to support for simulation. For example, there have been impressive recent demonstrations of the use of GIS as a platform for *cellular automata* (Goodchild and Janelle, 2004). These models represent reality as a raster of regular cells, and represent processes through rules of cell transition. They have been applied with impressive results to the modeling of urban growth, allowing users to investigate the impacts of various growth controls and regulatory alternatives. Interesting results are emerging also in the area of *agent-based* modeling, in which software is used to emulate the behavior of individual agents as they move about and modify the geographic landscape. Simulation models allow researchers to investigate process directly, by comparing results obtained through computation to the reality captured through observation. Third, computing technology itself continues to advance in power and versatility, and operations such as the measurement of area that were major achievements in the 1960s are now almost unmentionably crude and simple. Computing power and storage capacity are now sufficient to contemplate simulations of large, complex systems. Finally, software development has made great strides, and high-level programming languages allow new tools to be constructed quickly and cheaply. Gone are the days when it required millions of lines of new code to build a GIS; the task can now be achieved through the combination of a few readily available, re-usable software components.

Conclusion

Vespucci's exploits may represent the furthest geographic reach of the spilling out from Florence that occurred in the 15th and 16th Centuries. They were somewhat different in character from other contributions, being directed to our understanding of the form of the Earth's surface rather than to artistic achievement or economic activity. As contributions to the history of exploration they were distinguished by their emphasis on reasoning from limited observation and experience to broader conceptualizations of the nature of the Earth's surface, and hence to the science of geography. Like all of his contemporaries, he was concerned with form rather than process, and knew little about the dynamic processes that continue to shape the Earth's surface.

Today, observation of form continues at an ever-increasing rate, as consellations of satellites and legions of GPS users collect raw geographic data. But the process of compilation and interpretation is unfortunately in comparative decline, because governments are less and less willing to pay the high cost of map-making. Instead, raw data are fed into automated systems that perform routine transformations, and into computational models that emulate the action of real-world processes.

Today, anyone navigating along the coast of S. America will likely be equipped with GPS (Kennedy, 2002), and will know position to better than 30m at all times. Many will have systems that integrate GPS with digital charts, providing continuous monitoring of depth and of surrounding features. Dynamic information on weather systems may be available through satellite communication, and radar may provide continuous monitoring of the movement of other nearby vessels. The captain of a large bulk carrier will have access to GIS-based analysis that continuously finds the optimum track for the vessel, based on knowledge of currents and winds, and is linked to the vessel's autopilot.

By contrast, navigators in Vespucci's time had only uncertain knowledge of the Earth's form, only primitive instruments for determining latitude, and even-more-primitive methods for determining longitude. They had only paper on which to record observations, without any of the databases, drawing packages, and sophisticated software of today's cartographers. Their observations had to be painstakingly compiled into map form, and either copied by hand or tediously engraved for printing. The information captured on maps could be disseminated, but only at the speed of human travel, measured in tens of km per day. From this perspective the notion of spilling out becomes even more remarkable: that knowledge and expertise could pass uncorrupted through such a slow and unreliable communication system that had none of the format standards, parity checks, and other quality assurances of electronic communication.

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Figure captions

1. An image created by the Quickbird satellite of an area of downtown Los Angeles. The 62cm resolution of the image is sufficient to see individual vehicles. (Source: DigitalGlobe) *Needs permission from Digital Globe, crop the red area on right

2. The AVIRIS hyperspectral sensor allows surface types to be discriminated based on their spectral signatures. In this image of part of Goleta, California, wood shingle roofs (which are easily ignited in a fire) have been colored red. (Courtesy: Prof Dar Roberts)

3. Recreation of the map made by Dr John Snow of cases resulting from a cholera outbreak in London in 1854, a well-known example of reasoning from cross-sectional data. (Source: Gilbert, 1958) *Needs permission from Geographical Journal.

4. The analytic power of contemporary GIS is illustrated here with GeoDa, a package for exploratory spatial data analysis developed by Luc Anselin at the University of Illinois, Urbana-Champaign (www.csiss.org/clearinghouse/GeoDa/). Each window presents a different perspective on the same data set. Top left: a map; top right, a scatterplot; bottom right, a map characterizing each area's value in comparison with those of its neighbors; and bottom left, a histogram. The areas highlighted with the cursor in the top left window are automatically and dynamically highlighted in all other windows. (Courtesy: Prof Luc Anselin)