On the Origins of Analytical Cartography

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ABSTRACT: This paper examines the development of analytical cartography and the contributions Waldo Tobler has made to it, starting well before his definition of the subject in 1976. Analytical cartography's roots in World War II and the Cold War are examined, and the influences and precedents for the academic course that Tobler described are discussed. The systems of knowledge production developed for analytical cartography in its social context are summarized and are found to show a powerful dependence on a working relationship between academia, industry, government, and the intelligence mapping community. Current research trends in analytical cartography, including the organization of research, its institutions, and its priorities, are discussed, and it is proposed that declassifying the "missing pool" of analytical cartographic research literature could be of great benefit in the future. The four-way academic/industrial/government/intelligence partnership is seen as an opportune direction forward for analytical cartography. The next generational shift in the center of the discipline may occur in networks that even Waldo Tobler did not anticipate.

KEYWORDS: Analytical cartography, Cold War, SAGE, CORONA, military intelligence

Introduction

Twenty-four years ago, the precursor to this journal, *The American Cartographer,* published a seminal paper in the fledgling field of analytical cartography by Waldo R. Tobler (1976), then a professor in the Department of Geography at the University of Michigan. Entitled "Analytical Cartography," this paper reported on the development of the cartography curriculum at Michigan, specifically the Geography 482 class. As a new student at Michigan, starting there after Tobler's departure for the Department of Geography at University of California, Santa Barbara, in 1977, the principal author first took, then taught, Geography 482. In 1990 a textbook for the class was completed, and versions of the class have been taught ever since (Clarke 1987; Clarke 1995). At the University of California, Santa Barbara, the current course is Geography 128 "Analytical and Computer Cartography." A review of nationwide curricula in cartography shows that some form of Tobler's Geography 482 is still taught at most leading educational institutions. Chrisman (1997) recently expanded upon the analytical cartographic approach in his book *Exploring GIS.* A whole generation has now used the intellectual philosophy of analytical cartography and examined the topics covered in the appendix to Tobler's paper, which listed the curriculum then taught at Michigan.

A single academic paper that leads to a whole theme, sub-discipline, or even a paradigm, within cartography is clearly a remarkable thing. Tobler's paper has been cited many times, and sequels to the curriculum presented have been proposed that define analytical cartography by its subject content (Nyerges and Chrisman 1989). Of more concern here are analytical cartography's origins, its institutions and Tobler's unique contributions. Recent intellectual re-scoping of the geographic information systems (GIS) field has given us definitions of geographic information science (Goodchild 1992) and geo-computation (Longley et al. 1999). The pivotal role of the technology of GIS in transforming contemporary mapping science and geography has been discussed at length (Fraser Taylor 1991). Few would doubt the depth of this transformation, and other sub-disciplines of geography, including critical theory and human geography, have now entered into the intellectual dialog defining the discipline (Pickles 1995).

Analytical cartography is a sub-discipline of cartography that lies behind much of the development in geographic information science. Analytical cartography has been described as "the solid bedrock of theory upon which the field of geographic information systems is rapidly building" (Clarke 1995, p.3). More specifically, analytical cartography "deals with the theoretical and mathematical background behind cartography and

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Cartography and Geographic Information Science, Vol. 27, No. 3, 2000, pp.195-204

the rules cartographers employed in the mapping process" (Clarke 1995, p. 4). Some common elements of definition include the use of mathematical principles and techniques, the part of cartography independent of a specific map-making technology, and the use of the transformational view of cartography proposed by Tobler (1979), extended theoretically by Moellering (1980; 1984) and refined by Chrisman (1999).

Analytical cartography is wholly integrated with spatial analysis within geography, and Tobler himself links work in migration, population, interpolation, and map projections under this common approach (Tobler 1999b). Despite Tobler's own varied links to quantitative geography, analytical cartography from the outset dealt with the formalization of the discipline necessary for the digital transition, already well under way in government cartography, but less so elsewhere. In Tobler's paper of 1976, we are told that traditionally, cartographic education in American universities involved making maps by hand. "One knows, *a priori*, that all maps which can be drawn by hand can also be drawn by computer-controlled devices" (Tobler 1976). One knew, of course, because it was already being done that way in the government world of military and intelligence mapping, in what has become to be known as the "codeword mapping community" (Cloud and Clarke 1999). Academic cartography was necessarily playing catch-up at the time with the advances of two decades worth of intensive, but deeply secret, analytical cartography.

This gap between academic and clandestine analytical cartography was, however, one of degree and not of a kind. The mathematician Robert Hamming noted, famously, that "the purpose of computing is insight, not numbers" (Hamming 1962). Tobler made a corollary statement that "the purpose of analytical cartography is the development of geographical theory, not the inventorying of geographical phenomena." Tobler's straightforward definition of analytical cartography is distinctive, but in reality it has been difficult to separate theoretical advances from mundane applications, both in the practical and historical context. Data and theory interplay always, whether the data involved are classified or not.

The purpose of this essay is to examine the social context of the early years of analytical cartography, to expand upon the influences that shaped analytical cartography (and therefore also GIS) and to examine what role analytical cartography should play in the ever changing playing field of computer-based spatial information. We will examine the following questions: (1) what external influences shaped the early growth of computer mapping and analytical cartography, particularly with regard to their role in advancing Tobler's shaping of the discipline; (2) how can analytical cartography's inherently interdisciplinary nature support institutions and infrastructure for the future of the field; and (3) what are some of the theoretical concerns and research issues that will influence the next generations of computer mapping systems?

The Socio-technical Ensemble of Analytical Cartography

Analytical cartography was born into a world much different from today's. When Tobler's 1959 paper "Automation and Cartography" was published, America was gripped by the threats, both real and imagined, of the Cold War (Tobler 1959a). This critical period in recent history is being increasingly seen as the pivot to explaining the modern history of science and technology, especially in information science. Recent studies in the new field of Science and Technology Studies often focus on what they call the "socio-technical ensemble" of a specific technology. The implication is that no particular result of science in the applied sense is "invented" without context but, instead, is the result of seen and unseen influences from society at large via a group of "actors" who make the actual decisions and build the technology—the socio-technical ensemble. This technological systems approach was pioneered by Hughes (1983) and involves consideration of the technological, economic, and political context of scientific and technological change (Bijker 1995). It is important to note that while all of the actors have been involved in the technological and scientific work, they may not have been aware of each other, each other's work, or their own role in the work. This was especially true of the deeply secret programs, where "compartmentalized" or "need-to-know" secrecy isolated the actors and their networks. We will pursue this theme, but focus generally on analytical cartography, and specifically on the contributions of Waldo Tobler.

Stuart Leslie (1993) introduced into the study of the history of science and technology the term military-industrial-academic complex in his work explaining the socio-technological ensembles at the Massachusetts Institute of Technology and Stanford University. This three-way model has been shown to apply extensively to the development of computing technology (Edwards 1996). In many ways, analytical cartography follows the same model, with the added dimension of the nature of the secrecy of the relationship, and the powerful degree of integration between the sciences and technologies involved in mapping. In prior work, we have proposed our own model for the flow of knowledge and expertise between institutions in the mapping science world (Cloud and Clarke 1998; Cloud 1999).

Four major influences converged scientific attention on "automated cartography" during the formative period, which might be defined as the period between the end of World War II and the end of the pioneering CORONA satellite reconnaissance program in 1972 (and, coincidentally, the launch of the first Landsat satellite). The first of these influences was the legacy of the second world war, but the others were solidly founded in the Cold War. The four influences were:

- German advances in analytical mapping methods before World War II;
- The SAGE computer-based control system for Early Warning radar;
- The DISIC camera and its integrated set of hardware and methods that automated the geo-rectification process of imagery under the CORONA program; and
- The CORONA MURAL camera that added the analytical construction of three-dimensional terrain maps to the automated CORONA systems.

The first major component of the socio-technical ensemble was the recognition of the importance of WW II German advances in geographical science. Prior to the war, German and Swiss optical and precision mapping-related hardware was known to be of the highest quality. In the closing days of WW II, the Allied Powers discovered that the German war effort had made significant advances in geodetic control networks, in analytical photogrammetry, and in cartographic analysis. Map overlays were probably prepared on translucent media and overlaid manually for two different suites of applications. The first was map overlay use to solve problems in military operations, which probably included troop movement, trafficability, and terrain masking. The preparation and use of these overlays were made part of routine procedure, thus forming the origin of the application of systems theory approach to geographic information. The second application was systematic regional-scaled planning for schemes for Aryan colonization in territories overrun by Germany, the secret General Plan for the East. Walter Christaller's Central Place Theory was integral to these planning efforts, and was, in fact, devised for this application (Rossler 1989; 1990). These applications may be the earliest and most significant of the various multiple origins of geographic information systems, or at least of map overlay (Steinitz et al. 1976). The map overlays, and a vast quantity of other material, were discovered by teams of Allied intelligence officers and enlisted operatives (particularly) in the European Theatre toward the end of the war.

Most significant and certainly the most geographically critical were the discoveries of the "Hough Team," a party of several dozen officers and enlisted men and women deployed under the command of Major (later Lt. Colonel) Floyd Hough, later Chief Geodesist, Army Map Service (Cloud and Clarke 1999; Hough 1945). Hough's objective was to secure a broad array of maps, data, and disparate geographic technologies, particularly German analytical photogrammetric equipment, which was known or suspected to be superior to Allied technologies. Near the small village of Saalfeld, however, the Hough Team discovered a cornucopia of geodetic data, either generated by the German army, or captured from other sources, mostly Russian. The materials captured by the Hough Team constituted a revelation to American military geographic institutions. In cartography, geodesy, and photogrammetry, the Germans had been decades ahead of the Allies. Most important of all, these geodetic materials were the missing link between the known datums and mapping of Western Europe and the "denied territory" of the Soviet Union. They later allowed accurate georeferencing, mapping (and targeting) deep inside the Soviet Asian land mass.

The Hough materials remained state secrets for many years, yet they had a major impact on American cartography. While most of the geodetic materials remain classified or restricted even today, the data, equipment, and materials were systematically evaluated by government enterprises, including the Engineering Board of the Department of the Army, and summaries of these investigations, particularly with reference to photogrammetric equipment, were published in the cartographic and photogrammetric literature. During the 1940s and early 1950s, dozens of academic papers discussing the German instruments and methods appeared (e.g., Reagan 1945; Wilson 1946). Knowledge of the methods clearly influenced GIS. For example, while not directly concerned with cartography, Ian McHarg, who later made significant contributions to landscape ecology using overlay analysis, served at the end of WW II as a translator and interrogator of captured German officers, occasionally with technical and scientific occupations (McHarg 1999), although he denies that this experience influenced his later work. Many other prominent cartographers, geodesists, geographers and photogrammetrists made their impact in the practical and theoretical developments during this period, including Arthur Robinson (Chief of the Map Division in the Office of Strategic Services in WW II and later professor at the University of Wisconsin and author of *Elements of Cartography*) and Frederick J. Doyle (Ohio State University professor and photogrammetrist, CIA reconnaissance camera designer, and USGS mapping expert).

The open and explicit nature of scientific progress in analytical cartography, which encompasses the many fields and disciplines often called the mapping sciences, changed significantly in 1958 with the start of the CORONA program. After that date, publications such as *Photogrammetric Engineering* began to feature either very generalized descriptions of technologies, or descriptions of what were called theoretical and future systems that existed in fact but were classified as top secret. As the Soviet space and missile programs developed rapidly, the United States developed several secret technology programs aimed at redressing the balance of the Space Race. The remaining three influential factors in the socio-technical ensemble of analytical cartography arose during the period of technological response to the perceived Soviet threat. The factors can be characterized by three salient clandestine projects from the era: SAGE, DISIC, and MURAL. Their names are capitalized because that was and remains U.S. classified procedure for TOP SECRET programs. Each of these programs accelerated the integration of computers and accurate geo-rectification into analytical cartography, bringing about the digital transition in cartography that Tobler discussed in the 1976 paper. SAGE pioneered global data acquisition and its processing and graphic display by digital computer. The DISIC camera on CORONA allowed automated geo-rectification to great accuracy of imagery taken from space, and the MURAL camera on CORONA introduced systematically geo-rectified stereo imagery and, thus, the third coordinate dimension into scientific, digital cartography on a global scale.

Among the responses to the Cold War air threat was an unprecedented early warning system including the Pinetree, DEW and Mid-Canada "lines" of linked radar stations (Buderi 1996). These systems required constant real-time operation in remote areas, and severely strained existing command, communications, and control systems. The Air Force's response was a massive command and control project called SAGE, based on the Office of Naval Research's Whirlwind computer (Redmond and Smith 1980). SAGE (Semi-Automatic Ground Environment) was a command-and-control system designed to warn of attacks by Soviet bombers. University and other research on SAGE pioneered developments in real-time computing and core memory use that eventually spread throughout the computer industry, in particular time-sharing operating systems (National Research Council 1999). Technical and scientific development of part of the SAGE system took place at the Rand Corporation in Santa Monica, California. SAGE required the ability to map incoming aircraft and missiles on a global scale on radar oscilloscopes similar to the system shown in Figure 1.

SAGE may have influenced analytical cartography directly. Waldo Tobler worked on SAGE at the Systems Development Corporation (SDC), an offshoot of RAND, from 1957 to 1958, after completing his MA in Geography at the University of Washington. While there, following an interest aroused by reading a paper on the Azimuthal Equidistant projection, he took a class in map projections from Richard Kao, a mathematician and expert on the topic from the University of Michigan. While in Santa Monica, Tobler built upon computer experience learned in William Garrison's classes at Washington, and at SDC he was exposed to computer-driven plotters at a local electronics company. The paper "Automation and Cartography" was written at this time; this was his second paper on the topic, an earlier version having been published in the German cartographic literature.

Tobler's role on SAGE was to generate graphics and plastic overlay templates for radar screens that were used in simulations for training radar operators to respond to emergency situations. Often the maps were manually generated, but the use of the Duplexed IBM 704 led to experiments with computer mapping and plotting directly. Tobler's later academic work toward a Ph.D. reflects this influence yet is outside of the early warning radar systems context. For example, consider the first sentence of the appendix to the paper "Some Notes on Azimuthal Projections" (Tobler 1959b, Appendix B, p. 14): "A photograph of the earth taken by a camera mounted in a satellite may be considered to be a map, and in particular a map whose geometry is identical to an azimuthal projection." Tobler later linked the map projection research directly to analytical photogrammetry, via the work of Tissot. According to Tobler, "Tissot's results are completely general and can be applied to aerial photographs, to radar images, or to camera lenses" (Tobler 1962). The importance of projections at the time was unmistakable. Arthur Robinson's first edition of the cartographic classic *Elements of Cartography* contains a 54-page chapter on "The Employment of Map Projections," including a more thorough coverage of Tissot's theorem than is currently common (Robinson 1953).

While SAGE drew upon a large number of cartographers (analytical and otherwise), it was another top-secret program that led to the first degree of systems integration necessary for true geographic information science. In 1958, the officially secret but publicly acknowledged Air Force experimental space reconnaissance project WS-117L was officially cancelled, but, in fact, it was reconstituted at unprecedented levels of government secrecy and renamed the CORONA project. CORONA's role in pioneering successful space flight, satellite reconnaissance, space technology, systems integration, and recovery of film from space has been well documented elsewhere (Day et al. 1998; McDonald 1997a; Peebles 1997; Ruffner 1995). Absolutely critical to CORONA was an alliance between the CIA, industry and academia. Contractors (e.g., General Dynamics, Lockheed, ITEK, Kodak, and Autometrics) worked extremely closely with the CIA and Air Force on CORONA.

Academia often also played a pivotal role, particularly Harvard and Boston Universities and the Ohio State University (Cloud and Clarke 1999). Considerable linkages between the actors within the network of participants show up in academic circles. For example, the Harvard University Optics laboratory, which had worked on bomb sights during World War II, moved to Boston University when Harvard demilitarized its campus after the war. From the Boston University laboratory, Richard Leghorn and Walter Levison helped design and develop the series of cameras that led to the KH or Keyhole series for CORONA. In 1957 Leghorn and Levison co-founded the Itek corporation from the Boston University Optics Laboratory, and went on to build cameras for CORONA and other programs. Leghorn was later Chief of Intelligence and Reconnaissance Systems Development at the Pentagon, and he is the originator of the "Open Skies" concept. Thus the same individual working on the same technology area went from the military, to the academia, to industry, and to the intelligence world within the CORONA project.

From an analytical cartographic standpoint, CORONA led to three major technological and scientific breakthroughs in mapping. First, when the initial satellite images successfully revealed Soviet military bases, space launch pads, and air defense systems, it was quickly realized that existing American maps and geodetic controls were too inaccurate to wage or prevent war by ICBM. This perception accelerated ongoing research by the geodetic and mapping agencies of the Department of Defence (DOD) to produce a Figure of the Earth suitable for the nuclear age. A major component of the effort built on the unique resources in photogrammetry, cartography, and geodesy assembled at the Ohio State University. Faculty and staff there had been mobilized for military research and training for the Second World War, and, in the post-war period, the university became a major center for research on Cold War geographic challenges (Moellering 1991). A crash program to minimize the problems of geodetic control involved sending hundreds of CORONA technicians and scientists to Ohio State, where a Ph.D. program in geodetic science had been constructed to build the science base in geodesy and photogrammetry for mapping Asia and doing image interpretation from CORONA and other imagery (Cloud 1999).

Another breakthrough was the design of two remarkable mapping cameras, the ARGON and DISIC, which were pivotal to CORONA. Incredibly enough, the Hough team's captured German and Russian geodetic materials provided a critical link between the European and Asiatic datums, which involved a re-discovery of ruined survey towers on the Trans-Siberian railroad using CORONA imagery. The identification of these towers allowed first-order geodetic control to be extended across the great bulk of Eurasia—without setting foot on the "denied territory" there—an unprecedented achievement in the history of geodesy. This and a variety of other important breakthroughs in electronic distance measuring devices, densification of global gravity data networks, and major advances in computational power, led to the important series of Earth-centered global datums (WGS 60, WGS 66, WGS 72) that was a first stepping stone on the way to WGS 84 and the global positioning system (GPS) of today.

CORONA's remarkable success placed a demand on the image rectification, co-registration, and geographic data management process. Mechanical, photo-electric, and, later, electronic technologies were developed for information management. Starting about 1966, the Dual Integrated Stellar Index Camera (DISIC) on CORONA (still classified even today) coupled a lower-resolution calibrated index camera with two stellar cameras, providing much tighter geo-rectification for CORONA. DISIC was paired with improvements in automatic position correcting and spacecraft attitude adjustment systems, particularly the Universal Photogrammetric Data Reduction and Mapping System (UPDRAMS). UPDRAMS was designed to accept a wide range of mapping and reconnaissance photographic inputs, with emphasis on the reduction of covert satellite photography. The corrected data were run through automatic or semi-automatic map compilation programs, such as the Universal Automatic Map Compilation Equipment (UNAMACE) which produced rectified orthophotos, and the Automatic Stereo-mapper model 11 (AS-11) which produced rectified contours. The couplings between the CORONA film, the DISIC system, UPDRAMS, and the UNAMACE and AS-11 created a mapping and geo-data system beyond the capabilities and purposes of the original CORONA reconnaissance mission. As the CIA noted, "Enhanced by improvements in system attitude control and ephemeris data plus the addition of a stellar-index camera, CORONA eventually became almost the sole source of DMAs military mapping program." These methods and technologies pioneered "automated cartography." Thus, previous projections of future developments in automated cartography published in the open cartographic literature (e.g., Doyle 1953; Rosenberg 1955) were first realized, in fact, in the deeply classified world, rather than in the academic world.

With the success of the KH-4 "Mural" camera in 1962, CORONA returned stereo imagery. To the georectification task already mastered was added the need to process overlapping imagery via a stereo model and to extract three-dimensional information about the terrain, buildings, etc. While the principles of stereo imaging had been understood for over a century, CORONA demanded systems that could provide both accuracy and rapid throughput. Once the analog equipment of the early CORONA program gave way to computer-assisted and eventually digital processing, new possibilities for using terrain elevation data became evident. The need for an understanding of digital topography led to research outside of CORONA, much of it funded by the U.S. Army Research Office. Waldo Tobler later worked on terrain analysis methods, using principles from image processing that he had learned from Azriel Rosenfeld (Tobler 1968; 1999).

Figure 1. SAGE-era Radar Tracking Console. [Source: SLC-10 Vandenberg Air Force Base, National Historic Landmark. Photograph by the author. Note the built-in ashtray and coffee cup holders].

As Tobler stated in *Analytical Cartography*, he "wished to emphasize that mathematical methods are involved, but also that an objective is the solution of concrete problems" (Tobler 1976). One great concrete problem was in accurate topographic map production, and CORONA itself played a major role in topographic mapping at the United States Geological Survey and elsewhere (Baclawski 1997). Out of this work came the first space-based analytical photogrammetry (and cartography) of the stereo model and its derivation (Selander 1997), and also the methods, equipment, experience and infrastructure for "industrial-scale" use of the data (Light 1971). Light stated "that the 'pixel concept' shows great promise for reduction of topographic imagery and information to usable, storable, retrievable, displayable form." The familiar Digital Elevation Models and Triangulated Irregular Networks evolved for these and earlier data types and became the basis for enormous digital "libraries." The legacy of these pioneering programs includes contemporary national and global digital elevation coverages (Gittings 1999). Light's metaphor of the "image of the world in a barrel," based on the nickname devised by the staff of the U.S. Army Topographic Command for a cylindrically shaped mass storage device, lives on a third of a century later in the latest concept definitions of the Digital Earth project.

This brief consideration of the influences that shaped the origins of analytical cartography has focussed on the government as the motivator for change within cartography. Generally speaking, academic departments were slow to adapt to the new cartography, and the emerging field of GIS was even slower. This may have been partly due to the fact that the first generation of graduates of analytical cartography found careers in government agencies, especially such mapping agencies as the Defense Mapping Agency and its separate predecessor service-level constituences, the United States Geological Survey, the CIA and the National Reconnaissance Office, rather than going into teaching and academic research. Tobler noted the "gap between official government cartography and academic geographical cartography" (Tobler 1976).

Nowhere was this gap more evident than in the 1967 National Academy of Science's Summer Study on the potential uses of space satellites (NAS 1969). This study, convened and funded by the National Aeronautics and Space Administration (NASA), was directed toward brainstorming "useful applications of Earth-oriented satellites." The list of the 112 participants is a veritable who's-who of the military/industrial/academic personnel of the era. Waldo Tobler participated, along with Frederick Doyle and Amron Katz (a pioneer CORONA camera designer), on Panel 13 of this meeting, writing a report on "Geodesy and Cartography." As CORONA was in full swing at the time (and actually being used for the purposes proposed in the report, unknown to some of the participants), this section of the civilian NAS report was intercepted and classified as Top Secret, and so did not see the light of day until the 1980s. While in some cases the academic community was able to work creatively with the military and intelligence mapping community, through a complex system of knowledge sharing we have called elsewhere the "shuttered box" (Cloud and Clarke 1998), Tobler's observation on the separation was based on reality.

The driving force of digital transition in cartography (the computer) was at first poorly represented on academic campuses, and even then only in programs primarily in computer graphics and image processing. Geographic information systems were invented (or reinvented) in many different disciplines as computer software became more functional (Foresman 1998). Traditional academic departmental organization, along with parallel organization of research funding sources, worked to impede cross-disciplinary contacts to best exploit GIS. While some of these barriers remain, today the interdisciplinary nature of integrative research is far better recognized. Similarly, each successive generation of software made the tools and methods more accessible and easier to use and teach with. By the mid-1980s, GIS had started its rise to primacy in geography departments and elsewhere, and analytical cartography was carried along as part of the theory so necessary to understand the tools and applications.

Tobler's definition of analytical cartography provided the critical interdisciplinary linkages that were often missing in other technical fields of geography, and that were absolutely central to the classified systems. The curriculum for Geography 482 at Michigan included coverage of remote sensing, image processing, computer cartography and graphics, spatial analysis, map projections, computer programming, GIS, and geodesy. While the history of analytical cartography remains to be written, many of the research challenges are as rich today as they were in the late 1970s. For example, automated extraction of cartographic features from imagery for direct placement onto maps—the automated feature extraction problem—remains to be solved, at least in the open literature. Despite recent advances in automatic feature extraction, the inclusion of the human interpreter in the processing of spatial information remains essential. Training machines to duplicate human vision tasks has been the topic of vast amounts of work in computer vision, artificial intelligence and in some areas of graphics, such as text recognition and map labeling. Completely automated extraction of cartographic features in their geographic coordinate space remains as a holy grail for futuramic analytical cartography.

Institutions of Analytical Cartography

Analytical cartography grew few formal institutions outside of the classified world. Besides a few books, and many academic papers, journals in the field tended to either disappear (e.g. *Geoprocessing*), or fully integrate with GIS (*The American Cartographer*). Some important conferences and meetings were short lived, and never had continuity. Exceptions were the two conference series—AUTO-CARTO, the International Symposium on Computer-Assisted Cartography, and the Spatial Data Handling Symposium—of which only the latter survives. As issues related to algorithms and data structures moved from theory to application, the software development end of analytical cartography moved over to various professional conferences and publications series (Clarke 1999a).

The professional societies built around an interest in analytical cartography that was central to the classified programs, especially CORONA (Ondrejka 1997). The American Congress on Surveying and Mapping and its member group, the American Cartographic Association, embraced during the 1980s and 1990s the broader context (and wider audience) of geographic information systems. Analytical cartography is very often alive and well in the University system but has changed name, discipline, or content to suit the applications orientation of GIS—what Tobler called the "popular title" of computer cartography. One could argue that this has led to a dearth of new research from academia on analytical cartography. For sure, most recent innovations have come from the software industry behind GIS (automated text labelling, object orientation, etc.), or from the government's role as the seeder of new technologies.

One could ask, without there ever being any formal institutions behind analytical cartography, does the field need any now? This can be answered in several ways. One model of knowledge production, the historically influential Vannevar Bush view of research (Blanpied 1998), holds that pure research contributes to a "pool of knowledge" that can be tapped for applications at some future time. The CORONA experience, and the methods for managing research pioneered by the Defence Advanced Projects Agency (DARPA) have clearly demonstrated that scientific progress can be forced forward rapidly when resources are concentrated on specific problems, and when initial failure is tolerated. We now find ourselves in an era characterized by a pool of government (military and intelligence) knowledge that is being opened up only by intervention through government programs and exchanges, in particular the Dual Use program and activities under the Cooperative Research and Development Act, both of which primarily benefit industry and commerce.

The concept of pure science as a "pool of knowledge" that applications can subsequently exploit, has recently been questioned, yet it remains a versatile model. Analytical cartography, perhaps like some other scientific endeavors, suffers from the fact that much of the pool is "off limits." The declassification of the historical remote sensing programs like CORONA, and the release of material under the Freedom of Information Act and other programs, have led to a reappraisal of the origins, motives and influences of post-war American science and technology (National Research Council 1999).

While the release of the CORONA imagery has proved to be a valuable resource for earth and environmental science (McDonald 1997b), experience has shown that the technical documentation and research reports that accompanied the imagery were also invaluable to making the data useful to science, especially in directing a reappraisal of unclassified work that was contemporaneous with the black science, the so-called "black" or missing literature that forms the pool of untapped cartographic knowledge. The CORONA declassification in 1995, for example, released over 38,000 pages of documents into the publicly accessible National Reconnaissance Office (NRO) archives and the National Archives. The prospect of the release of additional material, more up-to-date and therefore closer to the scientific agenda of today is excellent and, hopefully, has a great deal to offer the next decade of cartographic research.

Another component of the intelligence/science community relations is the MEDEA Project. MEDEA is a scientific committee tasked to obtain vital environmental data from classified information collected by spy satellites and other sensors that could be instrumental in accurately assessing deforestation and other significant environmental problems, and identifying indicators of global warming (Beardsley 1994). The MEDEA committee has been influential in planning data acquisition for science, implying that future declassifications will provide an increased boon to academic research (Richelson 1998). These declassification efforts, therefore, have great value to analytical cartography and should be welcomed and encouraged by cartographic scientists. As commercial one-meter imagery becomes commonplace with the launch of ICONOS II in 1999, resolution restrictions that date back to the Cold War on the current intelligence systems will diminish by an order of magnitude.

Despite the earlier Cold War emphasis on progress in classified cartography programs, with the end of the Cold War, academic research and applications have assumed more central roles in the development of contemporary analytical cartography. A more appropriate model for the next decade might be a three-way collaboration—between government, industry *and* the academia—or the Leslie (1993) model. This is obviously more important than ever without the overriding dominance of national security so central to the Cold War. Some institutions are responding to this need. For example, the recent request for proposals from the National Imagery and Mapping Agency's NURI (NIMA-University Research Initiative) has involved collaborative identification of research foci of maximum mutual benefit, especially between the Department of Defense (DOD) and the National Science Foundation (NSF).

While such collaboration between nominally civilian and military and intelligence agencies is far from the approach to government support of research envisioned by Vannevar Bush that led to the founding of NSF, it very much reflects the systems of knowledge production that emerged from successful experience during the Cold War. Neither should it remain unstated that such an approach necessarily involves both positive and negative dimensions for each of the involved parties. While clandestine collaboration had many successes within programs like CORONA, the path of progress was fraught with cost overruns, inefficiency and unproductive rivalries, not to mention the opportunity costs involved. Foremost among these costs may be the gap in the literature of analytical cartography.

Conclusion

The history of analytical cartography has been immersed in the government, industrial, and academic triad. We can now publicly acknowledge the central roles played by military and intelligence mapping communities in this ensemble. The newest major institution in the evolution of analytical cartography, which is the World Wide Web, is itself the product of previous collaboration by researchers spanning all these communities. The Internet is a 'network of networks', and the original network, the ARPA-Net, was designed specifically to ensure robust and secure communications and data transfer during or despite nuclear war. The inherent utility of that network has now been demonstrated for other applications that span the planet. The World Wide Web for cartography has taken on the role of map librarian, map distributor, map publisher, and software provider. Having already led the way as a knowledge provider, the Internet map server technologies have made web-mapping a daily activity for many computer-literate Americans.

Beyond the present capabilities of the wired networks, the developments in mathematical theory and encryption algorithms that underlie progress in wireless communications and high mobility computing are likely to lead to another revolution in analytical cartography, the second of our lifetimes. The driving force this time will be commerce, and, hopefully, human welfare and economic and environmental sustainability. Driven by dual use—the military/civilian application of classified assets—and fed by the newly recovered "missing pool" of previously classified knowledge, the new analytical cartography will challenge human visual perception, involving complex spatial dimensions, web-telepresence, multiple simultaneous views, computer simulation, virtual and augmented reality, error-free navigation, and real-time field geography (Clarke 1999b). Just as CORONA's new view of the world spawned both a whole new science and an industry to rectify, integrate, register, cross-correlate, and convert images into information, the so-called ubiquitous computing will demand that cartography redesign the map from the bottom up into its own new geometries and reveal uses and applications undreamed of in our cartographic philosophies. As Tobler suggested, the technologies and representations will change with the new cartographic technology. Fortunately, as Tobler also noted, the principles and mathematics of mapping will remain virtually the same.

ACKNOWLEDGMENTS

Partial support for this project from the National Science Foundation (SBR-9810440) is gratefully acknowledged. Thanks to Waldo Tobler, who read and commented on an early version of this paper, and to the two anonymous reviewers for their productive suggestions.

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