E

Earth, Size and Shape of the. See Figure of the Earth

Eastern Europe, Boundary Changes in. Eastern Europe is a loosely defined geographical region in the eastern part of the continent. Western domination—political, military, and cultural—was not only reflected on the maps of the region, but cartography was also effective in creating imperial ideologies and distributing the geographical labels for the divided Europe.

At the end of the century, Eastern Europe included different groups of countries: Eastern, Central-Eastern, and Southern European states, geographically covering the region west from the Urals, the mountain range that separates Europe from Asia. The extension of the region into the West was not well defined, and its borders were always drawn according to different historical and cultural factors like religion, language, or the type of alphabet. In modern historiography the transitional zone, *Zwischeneuropa* (Europe in-between), dynamically separated and connected Western and Eastern powers. The nineteenth century had brought much political change in the southern part of the region and—after Serbia—other independent states (Romania, Bulgaria, Albania) were formed in Southeastern Europe.

The situation changed dramatically in the twentieth century and, due to political fragmentation, borders not only proliferated, but remained geographically volatile (fig. 215). Typically, the continuous change was a product of wars and division by power. World War I began symbolically in 1914 with the assassination of the Habsburg heir to the throne in Sarajevo, Bosnia. The military events centered in Europe ended in late 1918, but the war evolved into a global political conflict. The Central Powers (the German Empire, Austro-Hungarian monarchy, and Ottoman Empire) were defeated by the Allies (France, England, Italy, and the United States) and the Paris Peace Conference transformed the map of Europe.

The map of Eastern Europe was always subject to diplomatic alterations from afar, and borders in the region were considered to exist only if accepted by Western powers. The new international borders after World War I marked the culmination of this standard practice. The fundamental imbalance in Paris was best demonstrated by the decisions of the Great Powers and by the exclusion of the Soviet Union, a power in Eastern Europe. Nationality was a key concept for the peacemakers, although it was realized that different nations were based on different grounds. The historical nations were not like the nations based on common language or political interest. In this respect, early maps were extensively used as national propaganda and as evidence for territorial claims.

The activities of earlier historians of cartography (e.g., Joachim Lelewel and Manuel Francisco de Barros e Sousa, Visconde de Santarém) were related to the concept of historical nation and territorial state. In 1916 the *Geograficzno-statystyczny atlas Polski*, by the Polish geographer and cartographer Eugeniusz Romer, was published to make Polish political claims. After 1848 ethnic mapping in the region became an explicitly political instrument and served different nationalist movements in the region. However, this practice was based on the imperial cartography of the Great Powers. Ethnographical mapping in Europe developed out of early modern European state statistics and military and colonial mapping traditions. The role of ethnic maps during the negotiations in Paris was evidence for this imperial policy. The ethnographical maps produced in the region were, in the end, presented to imperial decision makers, who put them into geopolitical context when international borders were demarcated.

In 1919 the goal of the Paris negotiations was to create peace and stability in Europe and prevent future conflicts generally associated with nationalism. But the Eastern European issues were considered unresolved by people living in the region. Instead of applying the Wilsonian doctrine of national self-determination, the

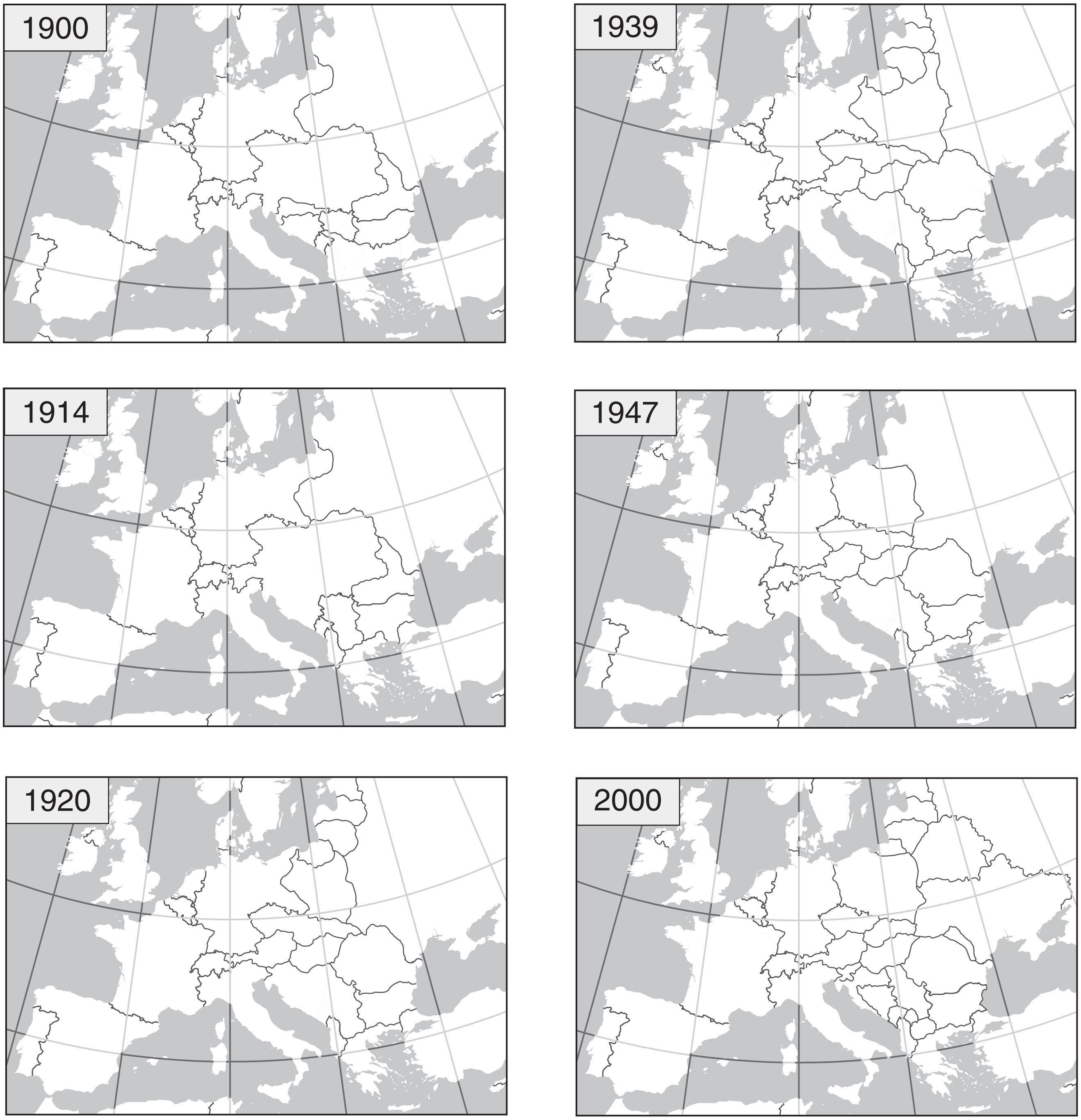

FIG. 215. BOUNDARY CHANGES IN EUROPE, 1900, 1914, 1920, 1939, 1947, AND 2000.

Allied global powers drew new international borders on maps. The claims of the formerly suppressed nationalist groups representing Eastern European regions were not always considered, and arguments from the formerly dominating nations of the defeated countries were ignored. The postwar treaties created as many problems as they solved. The newly created national states actually remained multiethnic, due partly to the inherent problems of the nature of the statistical data and maps that were available. The U.S. expert group of geographers and cartographers, the Inquiry, could draw upon the American Geographical Society's extensive collection of maps and geographical material, while the Royal Geographical Society and military geographical institutions provided geographical intelligence for the British commission. The French academic committee, the Commission de géographie, played the most important role in defining the future European borders. These groups—of secret research advisors and geographic experts, who worked behind the scenes in Paris—drew the new borders on the maps.

Defeated Germany had to accept responsibility for the war in the Versailles Peace Treaty. Its territorial boundaries were redrawn and disputed regions given to countries along the former border. As a result, Germany was cut into two, and East Prussia became isolated. Much of former Prussia and eastern Upper Silesia became parts of the reestablished Poland. The northern part of East Prussia, the Memel territory, was placed under French control (but later seized by Lithuania).

The Austro-Hungarian monarchy collapsed before the representatives of its former member states could separately sign their peace treaty in Paris. The monarchy was a multinational state and the Allied forces divided its territory among smaller national states. Hungary suffered territorial losses: 72 percent of the territory of the Kingdom of Hungary (without the affiliated Croatia and Slavonia) was incorporated into Romania and the new nation-states of Yugoslavia and Czechoslovakia. The borders of the remaining Hungary, a small, landlocked country in East-Central Europe, were demarcated after the treaty was signed. Although the former Austrian Empire also lost about 60 percent of its territory, the Republic of Austria received the westernmost part of Hungary with its German-speaking majority. The only plebiscite regarding Hungarian territories took place in Sopron, where the German majority voted to remain in Hungary. The former Habsburg territories included Bohemia, Galicia and Bukovina, South Tirol, Carniola and the coastal area with Trieste, Dalmatia, and Bosnia and Herzegovina, where the war had started.

Among the new states on the map of Europe was the Triune Kingdom of the Serbs, Croats, and Slovenes, created in 1918. Yugoslavia, as it became known, was a multiethnic state that included groups with different cultural and religious heritages. Czechoslovakia was formed out of the northern territories of the former monarchy including Czech lands (Bohemia and Moravia, which had been under direct Habsburg control since the seventeenth century), Slovakia and Ruthenia (which had been parts of the Kingdom of Hungary), and also areas of Polish population. Romania had belonged to what became the Central Powers, but in 1914 declared neutrality. In 1916, following promises by the Allies of support for the Romanian aim of national unity, it declared war on Austria-Hungary. However, the Romanian army was defeated and much of the country was occupied by German and Austro-Hungarian forces. At the end of the war, with strong support from the French diplomacy, Romania was given large territories (Transylvania, Bukovina, and Bessarabia) formerly belonging to Austria or Hungary. The new borders appeared more objective on paper, but in practice only the roles were reversed as the new nation-states oppressed their minorities. Although both Romania and Yugoslavia had to sign minority treaties and guarantee that their nationalities would be treated equally, their religions would be tolerated, and their national languages would be allowed, this remained a formal act only.

The Russian Empire had also collapsed by the end of World War I, and the Communist revolution in 1917 led to the creation of the Soviet Union in 1922. In 1918 Russia signed the Brest-Litovsk Treaty with Germany and ceded large territories: Finland, Estonia, Poland, Lithuania, and parts of Latvia and Belarus. The Bolshevik government later annulled this treaty, however, and Finland, the Baltic States, Poland, and Moldavia remained independent and did not enter the Soviet Union. The Moldavian Republic joined Romania in 1918 but the Soviet Union did not recognize the union. From 1924 to 1940 the eastern part of former Bessarabia was included in the Soviet Union as the Moldavian Autonomous Soviet Socialist Republic. In 1920, under the Treaty of Sèvres, Greece was promised northern Thrace and Ionia and the surroundings of İzmir. The Italo-Yugoslav border dispute ended with the establishment of the Free State of Fiume, which was formally annexed by Italy in March 1924. The modern Turkish state's borders were settled in 1923 under the Treaty of Lausanne.

The problems of the Paris peace treaty were considered to be among the causes of the social, political, and military events leading to an even more devastating war. In 1938 Nazi Germany annexed Austria (*Anschluß*) and the Sudetenland, an area of Czechoslovakia with a largely German population. The territorial restoration of the former German and Habsburg empires continued in the following year when Bohemia and Moravia became protectorates and Lithuania ceded the Memel territory to Germany. The southern part of Slovakia with its Hungarian majority was returned to Hungary, and Poland occupied Tesin (Teschen) in northern Moravia. In 1939 the Molotov-Ribbentrop Pact was signed between Nazi Germany and the Soviet Union, resulting in the division of Poland between the Soviet Union and Germany and the Soviet occupation of the Baltic States. During World War II many boundary changes occurred. The territory controlled by Nazi Germany expanded, although only parts were incorporated into the Reich. In the Vienna Awards (1938, 1940) the borders were revised and southern Slovakia and northern Transylvania with its Hungarian majority were returned to Hungary. In 1940 Bulgaria regained southern Dobruja from Romania, and the treaty was followed by a population exchange.

After World War II the map of Eastern Europe was redrawn again according to the new balance of power. The major change was the expansion of the influence of the Soviet Union. The new superpower annexed the Baltic States, Ruthenia, Bessarabia, and Bukovina, the northeastern part of former East Prussia. Finland under pressure ceded Karelia and the islands in the Gulf of Finland. In 1946 Winston Churchill's famous speech in Fulton already mentioned the Iron Curtain from the Baltic to the Adriatic Sea. In the following decades the countries behind that wall were locked in Eastern Europe (alternatively called the Eastern or Soviet Bloc). The group of satellite states under Soviet influence after 1945 was often considered synonymous with Eastern Europe.

In 1947, the Paris Peace treaties were signed. In principle, the 1938 borders (delimited after World War I) were restored with minor modifications (e.g., for strategic reasons two settlements formerly in Hungary were annexed to Slovakia). Italy lost its territories in the Balkans (Istria, Fiume, Zadar, and Carniola). The new Socialist Federal Republic of Yugoslavia took over the Dalmatian Islands; the Dodecanese were given to Greece. In 1949, the Federal Republic of Germany and the German Democratic Republic were established in the former military occupation zones and Germany was divided. In 1954 the former Free State of Trieste (created in 1947) was divided between Italy and Yugoslavia (the provisional border was fixed as late as 1975).

The last wave of border changes in the last decade of the century was related to the crisis and the collapse of the Soviet Union. East and West Germany reunited in 1990 and in 1991 new independent states, formerly parts of the Soviet Union, were created in Eastern Europe: Belarus, Estonia, Latvia, Lithuania, Moldova, and Ukraine. In the same year, Yugoslavia dissolved at a cost of yet another war, and Slovenia, Croatia, and Macedonia declared independence, with Bosnia and Herzegovina following in 1992. The remaining territory became the Federal Republic of Yugoslavia. In the same year Czechoslovakia split into the Czech and Slovak republics.

The Eastern European member states of the European Union (since 2004) demonstrated the reversal of the historical process and the decline of the importance of traditional territorial borders. However, while borders became less important and even symbolic in the European Union, the border of this political-economic unity still divides the continent in Eastern Europe.

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SEE ALSO: Boundary Disputes; Boundary Surveying: Europe; Cvijić, Jovan; Geopolitics and Cartography; Military Mapping by Major Powers; Military Mapping of Geographic Areas: Europe; Paris Peace Conference (1919); Russia and the Soviet Union, Fragmentation of; World War I; World War II

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Eckert, Max. Max Eckert (Eckert-Greifendorff), the German geographer who wrote the first comprehensive German textbook on mapping science, is credited, together with Karl Peucker, with establishing cartography as an academic discipline in Central Europe. Eckert was born on 10 April 1868 in Chemnitz, Saxony, where he taught in primary school for a short time before entering the University of Leipzig. He studied German language and literature, history, political economics, and geography under Friedrich Ratzel and received his doctorate in 1895. From 1895 to 1899 he served as Ratzel's assistant, and between 1900 and 1907 he worked again as a teacher. In 1903 he was approved for lecturing at the University of Kiel by Otto Krümmel. In his thesis for habilitation (postdoctoral certification for lecturing), titled "Das Gottesackerplateau: Ein Karrenfeld im Allgäu," he introduced a dot-style method of representing relief that used graduated points and proved a total failure. In 1907 Eckert was called to the new chair of economic geography and cartography at the Technical University in Aachen (North Rhine-Westphalia), where he was appointed full professor in 1923 and taught until 1935, when he retired. During his tenure at the Technical University he carried out research trips through Europe, Canada, and the United States.

In addition to his comprehensive work in physical geography, Eckert carried out studies in economic geography and cartography. He contributed to theoretical and applied cartography and from 1907 onward worked tirelessly to develop cartography as an academic disci-

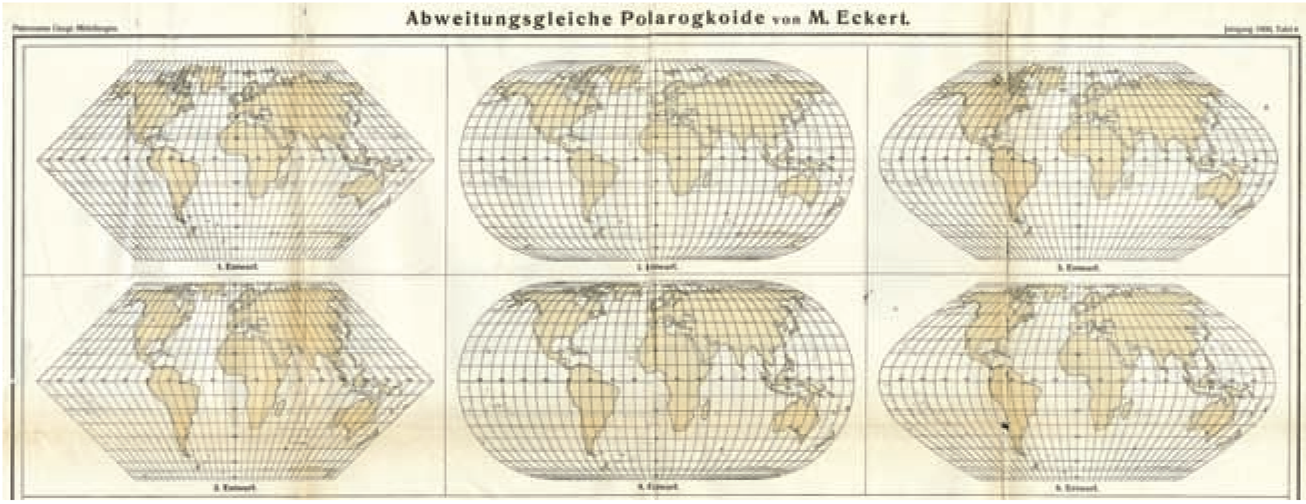

FIG. 216. PROJECTIONS PUBLISHED AS ECKERT I, II, III, IV, V, AND VI, 1906. Size of the entire plate: 41.4 × 72.9 cm; size of detail: 27.3 × 72.9 cm. From Max Eckert, "Neue Entwürfe für Erdkarten," *Petermanns Mitteilungen* 52 (1906): 97–109, pl. 8.

pline. While still an assistant he started to edit *Neuer methodischer Schulatlas* (first edition 1902; seventy-five editions up to 1922), and in 1898 he published the first of several studies on the methodology of cartographic education. As a teacher of economic geography, Eckert recognized the need for a modern, functional world map, and in 1906 he published six pseudocylindrical projections, Eckert I to Eckert VI, all with poles and central meridians half the length of the equator (fig. 216). Some of these projections are well known and have been used not only in Europe but also in a few American atlases, in the *National Atlas of Japan*, and for thematic maps by the National Geographic Society. In 1908 Eckert, in collaboration with Krümmel, published the booklet *Geographisches Praktikum*, a cartographic workbook for universities. In 1912 he edited *Wirtschaftsatlas der deutschen Kolonien*, a pioneering set of fifty-two sheets published in Berlin by Dietrich Reimer. During World War I, Eckert served in the German army's military surveying and military cartography divisions and created new types of military maps.

After the war Eckert concentrated on cartography. In the 1920s he edited his fundamental work *Die Kartenwissenschaft*, which was based on more than thirty years of teaching at various levels as well as on systematic studies of the maps and cartographic publications of various countries. Published as two volumes (1921 and 1925), this comprehensive book of 1,520 pages—including an index, more than 1,000 references, and mention of 2,000 individual maps—linked cartography's past with the contemporary cartography of the time. A planned third volume, a facsimile atlas, was never published. *Die Kartenwissenschaft* served as a basis for theoretical cartography and cartographic methodology (thematic cartography) for the next generation of German-speaking authors, including Erik Arnberger, Werner Witt, and Eduard Imhof. Because of this influential textbook, in which the history of cartography plays a major role, Eckert is recognized as the founder of German academic cartography.

In 1936 he edited one of the first student-oriented textbooks, *Kartenkunde*—part of the Göschen series published in Berlin and Leipzig by the de Gruyter firm. Eckert died on 26 December 1938, after a car accident in Aachen. His last publication, *Kartographie: Ihre Aufgaben und Bedeutung für die Kultur der Gegenwart*, was published posthumously in 1939. In the 1930s Eckert failed in his attempt to establish a German cartographic institute. His last studies on theoretical cartography were influenced by his support for the National Socialist movement.

Eckert was active in several areas of theoretical cartography and methodology, most notably map projections, relief representation, and cartographic education. He was also prominent in applied cartography as the author or coauthor of fifty-one maps and atlases, including various school atlases, geographical and historical wall maps of Germany, and numerous regional maps of Saxony and the Rhineland. At the close of the twentieth century *Die Kartenwissenschaft* remained an important work on the history of cartography and cartographic terminology.

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SEE ALSO: Academic Paradigms in Cartography: Europe; Education and Cartography: Cartographic Textbooks

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Education and Cartography.

EDUCATING MAPMAKERS
CARTOGRAPHIC TEXTBOOKS
TEACHING WITH MAPS

Educating Mapmakers. Education in mapmaking can be grouped into three general periods. The first was before the end of World War II, when cartography was considered a necessary skill for geographers but a field lacking a theoretical foundation (Buttenfield 1998). The second period lasted from about 1950 to about 1980, when structure was given to academic curricula and programs in cartography. This was largely due to the influence of three founding “fathers of academic cartography” in the United States: Arthur H. Robinson at the University of Wisconsin in Madison, George F. Jenks at the University of Kansas, and John Clinton Sherman at the University of Washington (Buttenfield 1998, 188). The third period began in the late 1970s to early 1980s, after the initial programs had been established and their academic offspring began to broaden the scope of the discipline by developing programs at additional institutions and adding breadth to the research themes with additional areas of inquiry. This last period coincided with the quantitative revolution in geography, rapid advancements in computer technology, and the growth of geographic information systems (GIS), factors that reshaped the discipline and led to the assimilation of cartography into broader computer-based geographic information science programs.

Prior to the 1940s, cartographic programs were small, less structured, and available in very few institutions. They were most often located within geography programs, and formal instruction in topographic mapping was rare, although civil engineering programs also played an important role in educating mapmakers in the earlier part of the century; Ohio State University established its program in geodetic science (McMaster and McMaster 2002). In the United States, four notable educators during this time period were J. Paul Goode, Erwin Raisz, Richard Edes Harrison, and Guy-Harold Smith (McMaster and Thrower 1991). Goode and Raisz were recognized primarily for their contributions to the practice of cartography. Goode was noted for his world map projections, which included the uninterrupted Goode homolosine projection from which he constructed the Goode interrupted homolosine equal area projection, as well as *Goode's School Atlas*, first published in 1923 and still used in classrooms today. Raisz's *General Cartography* (1938; rev. ed. 1948) was the first general textbook on cartography in the U.S. and the only one widely used until Robinson's *Elements of Cartography* was published in 1953 (its sixth and last edition in 1995). Raisz is best known for his beautifully hand-drawn and calligraphically styled landform maps. Harrison and Smith, although also recognized for the maps they produced, were noted primarily for their influence on one of the founding fathers—Harrison having taught Jenks at Syracuse and Smith having taught Robinson at Ohio State University (McMaster and Thrower 1991, 154–55). Sherman's foray into cartography was more circumstantial—while instructing at the University of Washington and working on his doctoral degree, he adopted the introductory cartography class when William Pierson left the department.

In Europe, academic thematic cartography evolved as a result of the increased need for maps, typically published in regional and national atlases, of sociodemographic and economic information, as well as to identify the location of natural resources (Fabrikant 2003, 82). In Germany at the turn of the twentieth century key individuals teaching at academic institutions included Alfred Hettner in Heidelberg; Albrecht Penck, a professor at the University of Vienna and later at the University of Berlin; Walter Behrmann, who taught at Frankfurt University and then at the University of Berlin and is known for designing the Behrmann projection in 1910; Max Eckert, author of *Die Kartenwissenschaft* (1921–25) in Aachen; Friedrich Ratzel, first in Munich then in Leipzig; Hermann Wagner in Göttingen; and Max Groll, who received a lecturer position in cartography at the University of Berlin in 1902. In Austria, Karl Peucker (educated in Berlin and Breslau) started his academic career in cartography at the Exportakademie in 1910 and became known as a writer of influential works on theoretical cartography and an editor of atlases. The Russian geographer Nikolay N. Baranskiy started lecturing on economic cartography in the geography department of the Moskovskiy gosudarstvennyy universitet in 1932. In 1925, Eduard Imhof founded what is considered by some to be the world's first academic cartography department at the Eidgenössische Technische Hochschule in Zurich (ETH), and as early as 1923 Imhof was lecturing on cartographic design. His research focused on the development of Swiss high school and secondary school atlases and the Swiss national atlas (Fabrikant 2003).

Cartography became established at the universities in Berlin (with Penck, at this point joined by Norbert Krebs and Ernst Tiessen), Vienna (with Peucker), and Zurich (with Imhof), and new programs were developed after World War I in Frankfurt am Main (with Behrmann), Breslau (with Walter Geisler), Greifswald (with Werner Witt), Halle (with Otto Schlüter), and Hannover (with Nikolaus Creutzburg) (Fabrikant 2003, 82). Although academic cartography in Germany and Austria was confined to war-related activities under Nazi control during World War II, publications on various aspects of theoretical cartography, such as classification, color, and map types, continued to appear in academic journals such as the *International Yearbook of Cartography*.

In Europe, a series of thematic cartography textbooks were written. In the 1960s and 1970s, three were being used (Arnberger 1966; Witt 1967; and Imhof 1972), none of which was translated into English. A. I. Preobrazhenskiy's economic cartography textbook, *Ekonomicheskaya kartografiya*, based on many of Baranskiy's cartography principles, appeared in Russian in 1953 and was translated into German in 1956. *Maps and Diagrams*, by geographers Francis John Monkhouse and Henry Robert Wilkinson (1952), was another main textbook for cartography instruction before the 1960s. Groll is well known for a two-volume cartography textbook (*Kartenkunde*, 1912) that was revised a number of times. In 1970, under the title *Kartographie*, Günter Hake extended Groll's textbook into its eighth edition (Hake, Grünreich, and Meng 2002), and it became a standard text for educating mapmakers. Despite the activities and contributions of these teachers and researchers, there was no collective effort or cohesive set of circumstances in Europe that set down the roots for cartography as an academic discipline worldwide. For this, we must turn back to the United States to see how the three founding fathers were able to lay the groundwork for what can be recognized as academic cartography, including curricula, textbooks, and graduate programs.

From the 1950s to the 1980s, three factors played an important role in the ability of Robinson, Jenks, and Sherman to institutionalize cartography within universities. The first was an influx of students after World War II, many able to attend college in the United States under the GI Bill. This led to an increase in faculty within departments and, therefore, the opportunity for greater specialization (Chrisman 1998). Nonetheless, geography programs with faculty specializing in cartography were still limited. In the United States, until the 1960s only one faculty member at most was devoted to teaching and research in cartography, with the exception of the University of Wisconsin–Madison, which had two, Robinson and Randall D. Sale (McMaster and McMaster 2002, 311). Enrollments continued to rise until they ultimately peaked in the 1970s. During this period, there was an increased demand for cartographic education, both by students responding to potential job opportunities and by the employers in government, private industry, and academia who were seeking cartographers. Since the 1970s, enrollments in cartography declined, and there was a growing tendency to couple cartography with GIS, which became the new attractor for students seeking concentrations that would lead more reliably to postgraduate employment.

A second important factor that influenced the development of academic cartography from the 1950s onward was federal government support to bolster cartographic education and program development. After World War II, universities were flooded with an unprecedented amount of funding that allowed universities to conduct research, hold workshops, improve facilities, hire faculty, and support students. For example, in the summers of 1951 and 1952, Jenks was awarded a grant by the Fund for the Advancement of Education to survey the major mapmaking establishments in the federal government and a number of quasi-public laboratories to determine how to devise a curriculum to provide the best training for mapmaking. The National Science Foundation sponsored two summer workshops, in the summers of 1963 and 1966, led by Jenks and Sherman, to prepare new geography professors to teach cartography (Jenks 1991, 162–63). In the 1960s, the Geography Department at the University of Wisconsin was awarded National Defense Education Act fellowships for graduate work in cartography that allowed the department to purchase both classroom and laboratory equipment (McMaster and McMaster 2002, 312).

Government support continued to be a factor in the latter part of the century. In the mid-1980s, a solicitation by the National Science Foundation to establish a National Center for Geographic Information and Analysis provided the impetus for many departments to strengthen and reinvigorate their cartography and mapping science programs. Although awarded in 1988 to a consortium of the State University of New York (SUNY)–Buffalo, the University of California at Santa Barbara, and the University of Maine in Orono, other universities, such as Syracuse and Ohio State, benefited from this competition by increasing or improving their cartography faculty.

The third factor affecting the training of mapmakers was technology. When Jenks conducted his study in the early 1950s, few geographers were involved in mapmaking. During his interviews, he witnessed mapmaking done by scribing and drafting on base materials with painted surfaces. In the 1960s, computers were beginning to be found on college campuses, but they were being used for mapping only in military establishments and oil companies. In the late 1960s, geography departments such as those at the University of Wisconsin and the University of Washington were doing their best to keep up with the rapidly changing technology of plastics, scribing, peel coats, and color proofing systems. By the 1970s, computers were being used to make maps in the laboratories of federal agencies as well as those of many companies and universities.

The influence of computers on cartography was evidenced at multiple institutions. Sherman and his students took classes in FORTRAN programming and database development from civil engineering professor Edgar M. Horwood at the University of Washington. One of Horwood's classes on geocoding and computer mapping techniques is thought to have been the first academic offering on computer processing of geographic information (Chrisman 1998, 36). By the 1980s, computer-assisted cartography was a course found in many academic cartography programs. The initial gap between remote sensing and the more closely coupled fields of GIS and computer cartography slowly narrowed but remained distinct. By the end of the century, there was closer integration with GIS; a transition from manual pen and ink to digital computer production methods; less emphasis on procedural programming, such as FORTRAN, and greater emphasis on commercial over-the-counter software; and more emphasis on dynamic cartography, including animation, multimedia, and web mapping.

Under the advantageous conditions of the second period in academic cartography, Jenks, Robinson, Sherman, and their academic offspring were able to build their academic programs, develop curricula, write textbooks, and graduate the next generation of cartographers. At the same time, increased enrollments, greater specialization, government funding, and increased faculty pools led to closer ties with public policy and a need to justify funding, which in part led to the development of quantitative methods (Chrisman 1998, 34–35).

Curricula in cartography in the 1980s focused on coordinate systems, symbolization and design, map production, and computer-assisted cartography. While symbolization and design remained a mainstay of the discipline, the production cartography classes common in the 1980s were later replaced with courses in topical areas such as analytical cartography, animation, and multimedia. By the end of the century, cartography classes balanced production methods with the conceptual principles of cartography, as well as the core principles of GIS. A 1999 report identified six research foci of academic cartography: visualization, cognition, symbolization and design, digital spatial data, analytical cartography, and social cartography (Brewer and McMaster 1999). Historical cartography classes were found in only a handful of universities (McMaster 1997, 1429).

Students were also offered opportunities or sometimes required to participate in internships and apprenticeships. In the United States, internships with local firms or agencies are more common, and are often organized from within geography departments. One exception is the National Geographic Society Internship in Geography, offered since 1981 and designed for geography and cartography majors at U.S. colleges and universities currently in their junior or senior year of academic work, as well as master's degree students.

In other places, particularly Europe, apprenticeships were more common because cartography departments are typically associated with engineering schools and thus have a more applied focus. These schools formed independent academic units, as opposed to the cartography programs within geography departments at universities. Examples of European cartography centers include the ETH, founded by Imhof in 1925; ITC Enschede (International Institute for Geo-Information Science and Earth Observation), founded in 1950 by the former prime minister of the Netherlands, Willem Schermerhorn, to provide training in mapmaking as an aid to developing countries; Freie Universität Berlin (Abteilung Kartographie within the Institut für Geographische Wissenschaften, founded in 1963); and Technische Universität Dresden, founded by Wolfgang Pillewizer in 1959 (Fabrikant 2003, 83). For example, the ETH, the only institution that offers official training for a professional diploma in cartography in Switzerland, requires a four-year apprenticeship during which apprentices also attend weekly theoretical courses at the School for Graphic Design in Bern (according to the Swiss national report for the International Cartographic Association conference in 2007).

In Great Britain the Experimental Cartography Unit (ECU) at the Royal College of Art, under the leadership of David P. Bickmore, was a center of cartographic innovation (Chrisman 1998; McMaster and McMaster 2003). Other academic centers for cartography included the University of Glasgow with J. S. Keates, the University of Paris with Jacques Bertin, Moskovskiy gosudarstvennyy universitet with Konstantin Alekseyevich Salishchev, and Wuhan cehui keji daxue 武汉测绘科技大学 (Wuhan Technical University of Surveying and Mapping) in China.

In Canada, a similar program could be found in the College of Geographic Sciences (COGS), formerly the Nova Scotia Land Survey Institute (NSLSI), which was established as a training institution for survey and map production. It became noted for geomatics education in the 1970s and later incorporated remote sensing and GIS. In the United States, Salem State College (now University), was well known in the 1970s and 1980s for its master's program in applied cartography.

Another opportunity for students to gain practical experience was in cartography production labs that in the United States have long been associated with geography programs and in the latter part of the century were found only in departments with cartography programs. Cartography labs have always been essential for teaching, but some were also created specifically for production work through professional service contracts with the goal of being economically self-sustaining, if not profitable. Many academic cartographers have been involved with running cartography labs, which was, for some, their entry into academic cartography (McMaster and McMaster 2002, 311–13). In the 1950s, an academic cartography lab typically had a darkroom, a process camera, a local printer, a few light tables, a programmable calculator, and an abandoned plane table. By the end of the century, cartography labs required major investments in software and computers to facilitate cartographic teaching.

AILEEN BUCKLEY

SEE ALSO: Academic Paradigms in Cartography; Electronic Cartography: (1) Conferences on Computer-Aided Mapping in North America, (2) Conferences on Computer-Aided Mapping in Latin America; Journalistic Cartography

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Cartographic Textbooks. A look at some key cartographic textbooks published in Europe and North America during the twentieth century reveals a flow of terms, definitions, concepts, and methods meandering between cartography as a craft and as an academic subject. Considering that a textbook is a standard work used in schools or colleges for the formal study of a subject, those trends naturally reflected cartography's emergence as an academic discipline during the same period. For centuries cartography had been a subsidiary part of the study of geography, a discipline whose textbooks often included sections about constructing and drawing maps. The growing number of separate publications about cartography during the nineteenth century consisted mainly of technical manuals giving instructions for constructing map projections, military sketching, pen-and-ink drawing, hand coloring, and the like. During the twentieth century many cartographers and teachers of cartography, including the authors of the key cartographic textbooks discussed here, continued to have their academic roots in geography despite the growth of cartography as a discipline.

Comparison of European and North American textbooks published before the mid-twentieth century reveals a focus on design issues and on the craft of mapmaking. However, cartography in the United States lagged behind Europe in both discipline development and textbook publication. When the Association of American Geographers was founded in 1904, cartography was not yet considered a profession in the United States (Robinson 1979, 97).

In 1908 Max Eckert, a pioneer of German academic cartography, opened the new century with a call to emulate several authors who had recently begun "to raise cartography to the standard of a science" by critically examining "the nature of maps" through "detailed investigation of their properties, as revealed by a study of their contents, their methods of representation, their scope and their various purposes" (1908, 344–45). It was a call that he later repeated in his book *Die Kartenwissenschaft* (1921–25). Nevertheless, until the mid-twentieth century, textbooks published on both sides of the Atlantic continued to focus on the craft of mapmaking.

Max Groll's *Kartenkunde*, a long-lived German textbook first published in 1912, exemplified the craft approach. Groll had cartographic experience teaching at the University of Berlin and working in the government hydrographic institute. The first volume, *Die Projektionen*, covered the construction, characteristics, and uses of map projections. The second volume, *Der Karteninhalt*, discussed surveying, map compilation and reproduction, cartometry, and the history of cartography. After Groll's death in 1916, Otto Graf edited the second edition (1922–23). In 1936 Eckert, whose *Die Kartenwissenschaft* had been advertised in the Graf edition, produced a new edition of *Kartenkunde* that, after his death in 1938, underwent several revisions by Wilhelm Kleffner (1943, 1950). The title changed to *Kartographie* in 1970 with the first edition by Günter Hake, who, assisted by others, continued his involvement until his death in 2000. The successive editions reflected changing authorship and cartographic technology, but the introduction to the 2002 edition by Hake, Dietmar Grünreich, and Liqiu Meng, the first to include maps on a CD-ROM, reaffirmed its intended role as an introductory text for technical colleges.

Although Eckert also provided guidelines for map production, field measurement, and projection selection and construction in *Die Kartenwissenschaft*, he interwove scientific cartography with production-oriented discussions in the text (Scharfe 1986). Praised at the time as a "monumental product of industry" (Wright 1926, 517), the work, which exceeds 1,500 pages, was seminal in advocating cartography as a science (Montello 2002, 287). Eckert's long experience teaching geography led him to view maps, especially thematic maps, as key in conveying the link between physical and human geography to students (Scharfe 1986, 65–66). He also stressed the history of cartography as essential for deep understanding of current practices (Eckert 1921–25, 1:24–25). Unfortunately, World War II kept his contributions from receiving the attention they deserved (Scharfe 1986, 66).

Another trailblazing textbook predating World War II was *General Cartography* by Erwin Raisz (1938). Raisz, son of a Hungarian civil engineer, had trained in engineering before emigrating in 1923 to the United States, completing a PhD in geology before becoming lecturer in cartography at Harvard University in 1930. Well received on both sides of the Atlantic, Raisz's textbook was described by Arthur R. Hinks of the Royal Geographical Society as "the most ambitious and comprehensive book on cartography in the English language. . . . not only a treatise on the history, science, and art of cartography, but a manual of the craft" (1940, 351). Raisz clearly shared Eckert's concern with the history of cartography, devoting the opening chapter of *General Cartography* to its evolution from indigenous and ancient cartography to American cartographic surveys, publishers, and products. While Raisz differed from Eckert in treating cartography more as a craft than as a science, he also differed from Groll in devoting more attention to different types of maps, including thematic maps, and less to map measurement, scale, and production. Despite reigning in America as "the *only* cartography textbook" for some fifteen years (Robinson 1970, 189), *General Cartography* was revised only once (1948), perhaps because it was too personalized (McMaster and Thrower 1991, 154).

The cartographic requirements of World War II changed mapmaking in the United States into a profession and academic discipline. The number of cartography courses offered at educational institutions increased, as did the number of institutions offering them. Cartographic textbook publication and adoption for academic use escalated in the United States postwar.

Maps and Diagrams (1952), a textbook by British geographers Francis John Monkhouse and Henry Robert Wilkinson, stemmed from the innovative cartography course they taught at the University of Liverpool (Anonymous 1975, 336). They took the emphasis on different types of maps even farther than Raisz. Only the first chapter, "Materials and Techniques," discussed general map production and design, while map projections were not mentioned at all. The bulk of the book was devoted to the production of specific types of maps and diagrams, including chapters on relief maps and diagrams, climatic maps and diagrams, economic maps and diagrams, population maps and diagrams, and maps and diagrams of settlements. Its popularity as a compendium of cartographic techniques for students was attested by its three editions (1952, 1963, and 1971) and numerous reprintings. That role, as well as the strong tradition of hand lettering in Britain, may account for the inclusion of both manual and mechanical lettering techniques, ranging from hand lettering with quill and metal pens, stencils, and templates to dry-transfer and stick-up typographic lettering. The 1950s and 1960s were a period when photomechanical techniques dominated but coexisted with manual and mechanical techniques, each having its niche in cartographic situations ranging from classrooms to large commercial and government operations.

Published just one year later, Arthur H. Robinson's

Elements of Cartography (1953) took a very different approach to cartography from that of *Maps and Diagrams*. The first chapter of the first edition of *Elements of Cartography* was titled "The Art and Science of Cartography." There Robinson defined his view of what cartography is and should be. He argued, as had Eckert in *Die Kartenwissenschaft* thirty years earlier, that cartography as a discipline should engage both craft (art) and science. His concept of cartography was shaped by his academic background and teaching of the subject, by drawing ideas from the fields of art and psychology into his research, and by his experiences as a cartographer, especially during World War II. The continuation of the idea of cartography as art and science into the late twentieth century was largely due to the publication of *Elements of Cartography* through its sixth edition (1995). In addition to being one of the most influential twentieth-century cartography textbooks, its successive revisions form a historical record of changing cartographic concepts and technologies. For example, having laid the intellectual foundations of cognitive cartographic research in his earlier book, *The Look of Maps* (1952), Robinson updated successive editions of *Elements of Cartography* with the results of new research in that and other aspects of cartography.

Erik Arnberger, who taught cartography at the University of Vienna, focused more narrowly on thematic cartography in his *Handbuch der thematischen Kartographie* (1966). Although maps depicting special subjects had become common during the nineteenth century, the term "thematic cartography" was first employed by Nikolaus Creutzburg at a German cartographic conference in Stuttgart in 1952 (Arnberger 1966, 5). Arnberger was the first to pull disparate veins of thought and discussion together in a cohesive textbook on thematic cartography. Like Eckert before him, Arnberger dwelt on historical linkages and advocated the establishment of cartography as a science. His first six chapters focused on methods of thematic mapping, with the seventh and longest chapter devoted to history and past literature.

Thematic cartography also became the subject of an American textbook, *Principles of Thematic Map Design*, by Borden D. Dent almost two decades later (1985). Whereas Arnberger had looked holistically at thematic mapping as a discipline or science, the approach of Dent, who taught cartography at Georgia State University, was to consider the role of design in thematic cartography and the application of its principles. Consequently, he devoted entire chapters to topics such as figure-ground color, and typography, as well as to specific thematic mapping methods.

In North America the best known German-language cartographic textbook was *Kartographische Geländedarstellung* by Eduard Imhof (1965), cartographer and teacher at the Eidgenössische Technische Hochschule in Zurich. His book's recognition in North America was partly due to its translation into English as *Cartographic Relief Presentation* (1982). It was intended to fill the need for a textbook covering the design and production of representations of topographic relief surfaces. "Representation of relief is the foundation for all the remaining contents of the map. The proper rendering of terrain is one of the primary tasks of cartography" (Imhof 1982, v). In his textbook he systematically examined nearly every aspect of topographic representation, ranging from very generalized scales to techniques of drawing rock outcrops in detail. The book began with a concise chapter on historical developments in the field followed by chapters on topographic measurement and accuracy and further chapters on representation principles and techniques, ending with a chapter on future directions. Forming a counterpoint to the detailed illustrations and technical instructions, Imhof's profound and often prophetic thoughts about cartography-related issues of science, technology, economics, art, aesthetics, graphical thinking, and map design recur throughout the book. For example, in the chapter on shading and shadows Imhof praised Leonardo da Vinci's mastery of the depiction of light and shade (chiaroscuro) as one of the highest achievements in art and suggested that mastering the light-dark effect in three-dimensional shading of terrain holds similar significance in cartography (Imhof 1982, 185). An authoritative source for understanding basic and advanced principles of relief representation, *Cartographic Relief Presentation* was republished by ESRI Press in 2007.

Jacques Bertin's *Sémiologie graphique* (1967, in English 1983), was not a cartography textbook in the strict sense, although its author taught and practiced cartography at several academic institutions in France. Broader in scope, the book was relevant to cartography, and many of the topics and ideas (visual variables, for example) were directly applicable to map design. Under Bertin's influence, academic cartography shifted focus from the mapmaker and the mapmaking process to the map reader. In addressing symbolization from the standpoint of visual and cognitive processing, he pioneered the design of representation from the viewer's perspective. On the other hand, the book's prescriptive advice about representing information was generally unsupported by empirical evidence. Cartographers outside France were slow to evaluate and implement the ideas presented in *Sémiologie graphique* until after it appeared in English. For example, it was not cited in Dent's *Principles of Thematic Map Design*, published in 1985. As increasing attention was given to visual processing and cognition in cartographic research, Bertin's ideas provided a continuing source of inspiration for cartographers, although some of his ideas remained untested (MacEachren 1995).

How Maps Work (1995), by Alan MacEachren of Pennsylvania State University, followed the trajectory set by Bertin's *Sémiologie graphique*, Robinson's *The Look of Maps*, and perhaps also Edward R. Tufte's *The Visual Display of Quantitative Information* (1983), but with a stronger grounding in theoretical and empirical science and more of a cartographic focus. The three earlier books were, for all their discussion of the map and graphic user's understanding, still design-focused. *How Maps Work* was not a book about how to make maps; rather, it was about how the map user understands data visualization and processing. Therefore, while it is arguable that *How Maps Work* is not a cartography textbook in the same sense as most of the others discussed here, its importance to the new direction of cartography makes it a necessary part of this discussion. *How Maps Work* did not redefine cartography on its own, though. A growing amount of research focusing on cognitive issues in cartography had already been emerging under the influence of Robinson's *The Look of Maps* (Montello 2002). However, most of that research was presented at meetings, published in journals, or discussed briefly in textbooks that were otherwise focused on map production. Significantly, *How Maps Work* provided cartographers, for the first time, with a thorough discussion of map understanding, spatial data visualization, and scientific theories from many disciplines.

Thus, both the beginning and the end of the century were marked by cartography textbooks making calls for new directions in academic cartography, and, in so doing, changing the discipline of cartography. While other textbooks published during the intervening decades were important, they were more reactive, responding to changes in the discipline. For example, *Elements of Cartography* perfectly reflected cartography's conversion into a profession, discipline, and academic area of study. *How Maps Work* may also have been "the right book at just the right time" (Patton 1998, 164) because of its ability to capture, synthesize, define, and project the emergent area of cognition, representation, and visualization in cartography. Progress might have been faster if World War II had not separated Eckert's *Die Kartenwissenschaft* and the next "art and science of cartography" textbook, *Elements of Cartography*. The international spread of new ideas was also slowed by the lag between publication of textbooks in the original language and in foreign translations. It is likely that, had the works of Groll, Eckert, and Arnberger been translated into English, those textbooks would have been more influential in the English-speaking countries. Setting such hindsights aside, it is clear that, under the influence of Bertin and MacEachren and their textbooks, cognitive cartography and visualization (drawing upon a growing body of scientific investigations into how mapping activities transform data and how map users process, perceive, understand, and use data) grew to represent the dominant new trends in the discipline toward the end of the century.

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SEE ALSO: Academic Paradigms in Cartography; Bertin, Jacques; Eckert, Max; Hinks, Arthur R(obert); Map: Map Typologies; Raisz, Erwin (Josephus); Robinson, Arthur H(oward)

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Teaching with Maps. Maps have been used to teach geography at both elementary and secondary levels throughout the twentieth century. If nothing else, maps have decorated the walls of classrooms at all grade levels in much of Europe and North America. Beyond decoration, it is unclear how, or even whether, those maps were used for instruction. Research on the nature of strategies for teaching with maps suggests that maps have, in fact, played a pedagogic role in the United States. Anecdotal reports by classroom teachers provide additional evidence of teaching with maps. But because research on the actual use of maps in teaching is limited (Stoltman 1991), it is unclear how maps have contributed to learning in geography classrooms.

Three themes have dominated research addressing teaching with maps and published between 1902 and 2000 in the *Journal of Geography*, the premier United States geography education journal. For convenience, these themes are labeled primacy, continuity, and pedagogy. *Primacy* refers to teaching with maps as the core of geographic education whereby teaching with, about, and through maps is equated with "doing geography." *Continuity* refers to the minimal change in teaching with maps over the last century, and reflects the persistent, repetitive character of discussions among geographers and educators about the roles and purposes of maps in teaching geography. The third theme, *pedagogy*, emerges from an overwhelming concern with how to teach with maps. Despite a few notable exceptions, research and writing about teaching with maps have focused on "best practices" with scant attention to empirical studies that evaluate learning. This entry addresses each theme in turn but also highlights significant connections.

The theme of teaching with maps as the core of geography education is as old as geography's standing as a "modern" school subject. In their seminal work, *The Teaching of Geography in Elementary Schools* (1913), Richard Elwood Dodge, professor of geography at Columbia University's Teachers College, and his colleague Clara Barbara Kirchwey asserted that "maps are of fundamental importance in geographic study, and the ability to use a map is one of the most important acquisitions to be secured from school geography work" (128). Three decades later the influential "Report of Committee on Standards of Certification" identified the map as "a device which is fundamental to geographic method" (Meyer 1943, 52). The 102 articles on the subject published in the *Journal of Geography* between 1922 and 1949 underscored the disciplinary emphasis on teaching with maps (Chew, Corfield, and Whittemore 1950). A midcentury study of geography teachers in California found map exercises ranked as the most useful practice in geography teaching and were used more frequently than any other teaching technique (Gandy 1965). The importance of maps to geography education was restated in the *National Geography Standards* (Geography Education Standards Project 1994), the first standard of which states that the geographically informed person knows and understands "how to use maps and other geographic representations, tools, and technologies to acquire, process, and report information from a spatial perspective" (61). Developed with strong support from the National Geographic Society and the National Council for Geographic Education, the standards repeated eminent geographic educator Peter Haggett's proclamation that "geography is the art of the mappable" (1990, 6) and outlined concrete expectations for the use of maps by students.

While teaching with maps has been a core theme of geography education in the United States throughout the twentieth and early twenty-first centuries, because of geography's placement in the social studies curriculum, the subject has had varying degrees of prominence depending on where and when it was taught. In particular, state departments of education have varied widely in their recognition of geography as a distinct subject as well as in the number and type of college geography courses required for education majors planning to teach social studies. Moreover, interest in geography often reflected the country's involvement in overseas conflict. In any event, the effectiveness and success of teaching with maps was most certainly linked to the success of geography in establishing itself as a fundamental topic of instruction. Although maps can be used in a wide variety of courses—and ideally would be used across the curriculum—they were most likely to be used in geography.

Not only has teaching with maps been a consistent theme and focus of geography education, but there has been astounding consistency in the terminology used to justify teaching with maps, in the topics and methods deemed suitable for teaching with maps, and in the arguments surrounding the role and purposes of teaching with maps. There has even been a distinct circularity in calls to address perceived weaknesses in geography education because of the lack of teaching with maps. Since the early 1900s, the *Journal of Geography* has urged teachers to help students develop the "habit of mind" to use maps, atlases, and globes. In the early twentieth century, it was recommended that constant drill was the best way to achieve this result; in the early twenty-first century more progressive methods are advocated.

A second persistent metaphor was the notion of maps as tools.

Topics related to teaching with maps have changed little over the past 100 years, focusing on five primary topics: (1) using maps to learn place locations, (2) learning about the fundamentals of maps, (3) teaching with and about "special" maps, (4) developing students' mental maps, and, in more recent years, (5) maps and technology. Introducing students to the basic parts of a map—scale, latitude and longitude, and, to a lesser extent, projection and symbol selection—have been an important component of teaching about maps at all grade levels throughout the century. Guidelines on how to teach with maps issued in the 1930s prescribed step-by-step strategies for improving students' map reading skills that were echoed by publications in the 1980s (Shannon 1934; Anderson 1986). In both instances, students were instructed to look for a map's title, key or legend, compass rose, author, and date. The acronym TODALSIGS (title, orientation, date, author, legend, scale, index, grid, source) (fig. 217), introduced in a series of imaginative and well-received articles about teaching with maps, was widely used to help students remember what to look for in a map (Anderson 1986).

Studies over the past century have repeatedly found that students have limited abilities with maps (Gregory 1912; Williams 1952; Miller 1965; Gregg 1997), which suggests that teaching with maps has been either unsuccessful or nonexistent. In a search for explanations, some geographers have argued that map skills have been overlooked because "teachers often take map skills for granted. Basic map skills are deceptively simple in appearance" (Conroy 1966, 111). Consequently, educators might believe that students can intuitively read and use a map—an idea disputed by a number of studies (e.g., Liben and Downs 1997). Other research has suggested that teachers lack the requisite map knowledge and skills (Tower 1908; Giannangelo and Frazee 1977; Gregg 2001); without such knowledge and skills, effective and comprehensive teaching of maps will be limited. Still another possibility is indifference: educators have contended that maps are important, but students' use and knowledge of maps contradicted the primacy of the map as the core of geography education (Bartz 1970).

T	=	Title	:	What, where, and when
O	=	Orientation	:	Directions
D	=	Date	:	When map was made
A	=	Author	:	Who made the map
L	=	Legend	:	What the symbols mean
S	=	Scale	:	What map distance is
I	=	Index	:	Map address of places
G	=	Grid	:	Locates places on a map
s	=	source	:	Of map information

FIG. 217. MAP ELEMENTS SUGGESTED BY JEREMY ANDERSON.
From Anderson 1986, 9. Permission courtesy of the National Council for Geographic Education, Washington, D.C.

Interest in teaching about specialized maps (e.g., cartograms, topographic maps, and thematic maps) illustrates the circularity of discussions about teaching with maps. In the typical cycle, geography educators have issued warnings that maps were being neglected and called for a renewed interest in teaching map skills or for teachers to make fuller use of specialized thematic maps, suggesting that they were not commonly used in primary and secondary teaching. This warning typically triggered a spate of articles outlining specific strategies (e.g., McAulay 1964; Gilmartin 1982), followed by a period of quiet, and then a renewed warning that students were not mastering map skills or were unable to use them to address complex questions.

The topic of maps and technology is another reflection of this circularity. Connections between technology and teaching with maps are apparent in the use of airplanes to teach "aerial geography" in the 1920s and 1930s, the use of overhead projectors and map transparencies in the 1970s, and the use of mapmaking software with personal computers in the 1980s. Early advances in computer-based mapping initiated a growing interest in integrating remote sensing and geographic information systems (GIS) into map instruction.

Arguments surrounding the role and purposes of teaching with maps provides the last example of circularity. Repeatedly, geography educators have debated the reasons why students should develop the "habit of mind" to use maps. Although maps are obviously useful for finding locations, geography educators have warned that too frequently this was the only use of maps, especially by poorly trained geography/social studies teachers. As normal school professor William Charles Moore (1906, 323) noted, "The study of maps means something more than location. Most maps, however, with which pupils become familiar in their school course are not of much use for any other purpose." In the 100 years since Moore made this statement, many other geographers and educators have voiced similar sentiments. This presents a dilemma for geography educators: although maps are useful, among other things, for helping students learn about place location, the drill and practice methods of learning locations amount to rote memorization, which leads many students to think of geography as boring and dull. Unfortunately, state and national assessment in the United States as well as research on teaching practices and anecdotal evidence suggest that maps have been used to show locations and little else (Bednarz, Acheson, and Bednarz 2006).

Research has focused far more on "best practices" for teaching with maps rather than a systematic analysis of their effect on learning. Most recommendations about teaching with maps reflect either the authors' expertise or intuitive, classroom-based wisdom rather than empirical research. Most of these studies focus on the mechanics of map learning, but a few recommend methods for helping students develop more advanced map-interpretation skills (Espenshade 1966). This emphasis on "how-to" rather than "why" or "to what end" has made map instruction and learning a dull, rote endeavor rather than a dynamic intellectual process.

Far less attention has been paid to other aspects of teaching with maps. Three key topics accorded little formal attention by North American educators are: (1) constructing maps using sound cartographic principles (e.g., drawing a map to scale), (2) critically evaluating the quality of maps, and (3) interpreting and analyzing map information. It has been argued that students truly understand maps only when given the task of constructing a map with cartographic principles in mind. Although the authors of the 1994 *National Geography Standards* strongly encouraged this approach, there is little indication that this strategy was more widely used in the early twenty-first century. And while professional cartographers have long recognized the importance of critical evaluation in their own work, there has been little indication that it was occurring in schools. Nor were students using a variety of maps to interpret and analyze spatial patterns despite repeated calls for such instruction (Gregg 1997).

In sum, the North American map instruction literature of the twentieth century exudes an eerie sameness in which educators asserted that maps are central to geography education and made repeated calls for more explicit instruction to teach students to read and use maps. The 1994 standards reiterated wisdom accumulated through 100 years of geographic teaching and reflected a comparatively modest amount of empirical research.

GILLIAN ACHESON AND SARAH WITHAM BEDNARZ

SEE ALSO: Atlas: School Atlas; Historians and Cartography; Visualization and Maps

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Electoral Map. An electoral map is any type of cartographic illustration of the organization, conduct, and results of a formal administrative vote. Most electoral maps depict actual votes cast by the general public in a democratic ballot. These votes can be cast for candidates for any level of elected office—local, provincial, or national—but also for referenda, ballot initiatives, and plebiscites. In addition, election maps can depict roll-call votes cast by these elected officials in legislative bodies ranging in scale from city councils, provincial, department, or state legislatures all the way to national parliaments. Votes mapped in these legislative forums are usually differentiated and plotted by the election district or the riding of the representative or member of Parliament casting the vote. Closely associated with electoral maps, therefore, are precinct, ward, county, riding, and district boundary maps, which not only define where votes take place but also make possible the plotting of legislative votes.

The history of electoral cartography has its roots firmly in the late nineteenth century. With the development of statistical and thematic cartography in the middle and late nineteenth century, votes tied to election districts, or at least collected in a specific geographical area such as a ward or county, were logical phenomena to map. This is especially so insofar as district boundaries and vote totals are public information. Even earlier, in the late eighteenth century and early nineteenth century, laws were beginning to be written establishing geographical districts in which representatives were to be elected (Martis 1982). The study of the theory of drawing and possible manipulation of election districts has been and still is an important area of research for those interested in electoral geography (Sauer 1918; Morrill 1981; Monmonier 2001).

Based on strong precedent, the election map is an integral part of both academic and public cartography in the twentieth century. Because statistical cartography had Prussian and Austrian roots, it is not surprising that some of the first major works of twentieth-century electoral cartography were of the German Reichstag elections. In *Kartogramm zur Reichstagswahl* by Hermann Haack and H. Wiechel (1903), a value-by-area cartogram is used to portray German 1903 parliamentary election results (Eckert 1921–25, 2:150). This map is a breakthrough in both cartographic technique and electoral geography. The maps of Reichstag elections in 1887, 1890, 1893, 1898, 1903, and 1907 (*Karte der Deutschen Reichstagswahlen*) and the sheet map of the 1907 elections by colonial illustrator and cartographer Gustav Freytag (fig. 218) are particularly stunning.

Clearly, electoral cartography predated the formal field of electoral geography by several decades. The recognized father of electoral geography is André Siegfried. Siegfried's seminal work, *Tableau politique de la France* (1913), although deterministic in nature, is the first extensive detailed electoral geography study and part of the intellectual origins of the field. It has 102 maps, all black-and-white, and statistical figures plus a large folio insert reference map. Siegfried's cartography argues his case effectively with choroplethic correlations between political party voting patterns and topography, soil, religion, and various economic factors (fig. 219).

Three years later the academic journal *Geographical Review* included a large map significant to both cartography and electoral studies (fig. 220). This map has two significant features. First, it was printed using four inks when nearly a century later many journals still eschewed color cartography in favor of less costly black-and-white election graphics. Second, the map depicts eight parliamentary elections from the period 1885 through 1910. The mapping of several elections allows depiction over time of the political strength of the Liberal, Conservative, and (Irish) Nationalist parties. Previously, single-election maps were the norm. Rendering these election results in color reveals a strong, vivid geographical pattern of political party support.

In the late nineteenth and early twentieth centuries American historian Frederick Jackson Turner emerged as a leader of statistical history and the portrayal of various phenomena on maps (Billington 1973; Block 1980). Turner developed intellectually in the 1870s and 1880s, when the U.S. census atlases and private atlases began to appear, and he was greatly affected by them. Also, part of his graduate training was at Johns Hopkins University, where he was influenced by geographer Daniel Coit Gilman, president of the university and founder of its geographical and statistical bureau. In 1893, only three years after receiving his PhD, Turner published his famous frontier thesis (*The Significance of the Frontier in American History*) and set in motion his involvement with geography, history, and mapping. One of his first graduate students, Orin Grant Libby, produced a dissertation and map on "The Geographical Distribution of the Vote of the Thirteen States on the Federal Constitution, 1787–88." In his second most famous work, *The Significance of Sections in American History* (1932), and in his posthumously published *The United States, 1830–1850* (1935), Turner used numerous presidential election maps with county-level data as critical pieces of evidence for his theory that American history is best explained by the emergence of three great sections: North, South, and West.

In 1912, historian Charles Oscar Paullin, with the sponsorship of the Carnegie Institution and the support of academics interested in maps (Albert Bushnell Hart, J. Franklin Jameson, and others in the Turnerian school of statistical history), began work on a monumental cartographic project, the *Atlas of the Historical Geography of the United States* (Cappon 1979). Later, geographer John Kirtland Wright and the American Geographical Society became involved. Wright's participation in the project brought substantial cartographic expertise, and he later became a significant figure in cartography and geography with his discussions of the terms "choropleth," "dasymetric," and "geosophy." When the atlas was finally published in 1932, it became an epic work of historical research and cartography covering almost every conceivable field of study (Paullin 1932). One of the centerpieces of the book is seventy-two electoral maps evenly divided between presidential election maps by

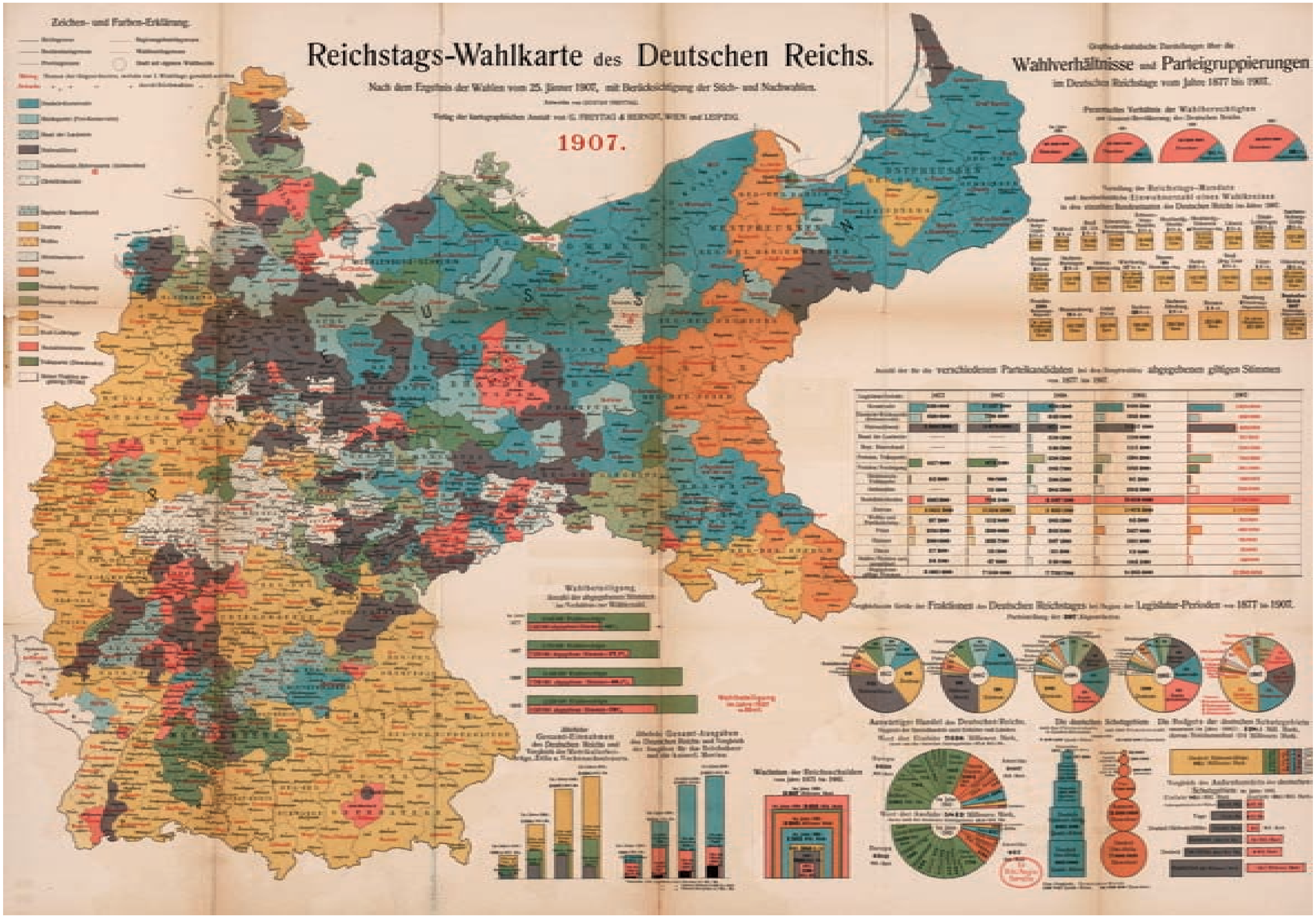

FIG. 218. GUSTAV FREYTAG, *REICHSTAGS-WAHLKARTE DES DEUTSCHEN REICHS* (VIENNA: FREYTAG & BERNDT, 1907). Color lithograph with vivid colors to differentiate the geography of political party support and plentiful statistical data and charts to compare results from a number of previous elections. The Freytag map is an eye-catching example of the art of statistical cartography at the beginning of the twentieth century.

Size of the original: ca. 75.2 × 51 cm. Image courtesy of the Staatsbibliothek zu Berlin–Preußischer Kulturbesitz; Kartenabteilung.

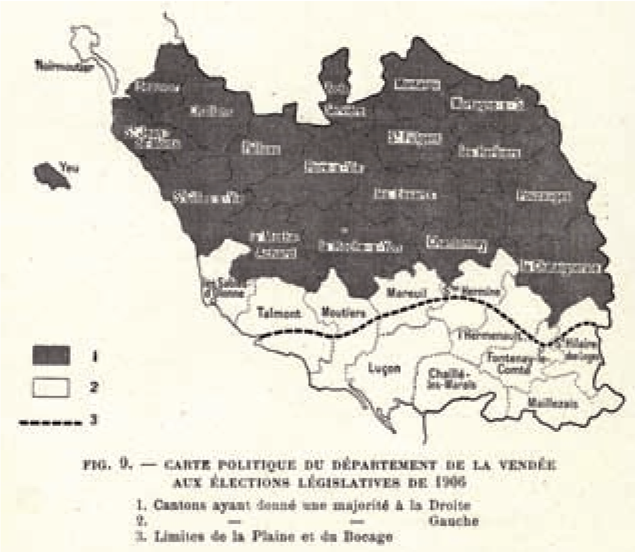

FIG. 219. ANDRÉ SIEGFRIED, *CARTE POLITIQUE DU DÉPARTMENT DE LA VENDÉE AUX ÉLECTIONS LÉGISLATIVES DE 1906*. The map shows correlation between topographic region and the vote for right- and left-wing candidates in the 1906 legislative elections.
Size of the original: 8.9 × 10.1 cm. From Siegfried 1913, 34 (fig. 9).

county and critical congressional roll-call votes by district, all printed in four inks (fig. 221). The presidential election maps in the atlas are thought to provide the first complete longitudinal coverage of national elections in color using small geographical units. Additional political maps cover such topics as property qualifications for suffrage, women's voting rights, and prohibition.

Within the history profession the influence of those interested in data and statistics waned, and in the years after World War II general interest in mapping and cartography lessened. By contrast, geography and other social sciences became more interested in election studies, with François Goguel leading the way with his classic *Géographie des élections françaises* (1951). In addition, during the middle and late twentieth century, government agencies and private publishers issued numerous sheet maps and atlases of national elections for virtually every advanced democratic nation.

In social science generally, quantitative analysis grew steadily throughout the twentieth century as an important methodological tool. Within geography, spatial statistical analysis and spatial modeling emerged during the 1950s and 1960s. In the ensuing decades many electoral geographers adopted various quantitative methodologies to conduct more scientific and theoretically sound election studies. Election maps began to illustrate not just actual votes but also various statistical analyses. One of the first electoral geography studies using quantitative analysis employed regression models to examine voting in England and Wales (Roberts and Rumage 1965). In the map of the percentage of party vote the authors used standard deviations, rather than traditional a priori categories, to determine breakpoints in their seven intensity categories. Furthermore, two voting maps portrayed residuals from regression to detect ideological support patterns. Several years later a groundbreaking work, *Section and Party*, used factor analysis to analyze the state electoral vote in U.S. presidential elections (Archer and Taylor 1981). The authors not only identified critical elections and political party eras, but also produced cartograms in which factor scores assigned states to the North, South, or West. Toward the end of the twentieth century an exemplary article mapped the Nazi Party vote in the 1930 Reichstag election using statistical values produced using Moran's *I* test for spatial autocorrelation, regression coefficients, and weighted least-squares estimation (O'Loughlin, Flint, and Anselin 1994). Like others from the era, this article is also significant because geographical information science (GISci) software helped the authors integrate voting data with geographical boundaries.

As in all of cartography and geography, GISci had a profound impact on the analysis and illustration of elections. In addition to facilitating the use of ever larger electoral data sets and the integration of spatial models, GISci software helps nongeographers and noncartographers produce their own election maps. The Internet and the World Wide Web have also promoted the publication and distribution of election maps. Websites of varying quality, both commercial and free, emerged in the late twentieth and early twentieth-first centuries to bring election maps and election mapping to the masses. The combination of GISci and the web encouraged creative as well as rapid mapping of elections. The innovative cartograms of the 2004 U.S. presidential election have placed the geography of elections in a new light for a general public not familiar with this technique (figs. 222 and 223).

Various media outlets have introduced vote mapping or expanded their coverage. In covering quadrennial presidential elections in the United States, television reports have long emphasized the electoral college. Throughout the twentieth century newspapers and news magazines have produced electoral college maps, supplemented by maps of governors and senators by state, and more recently members of the House of Representatives by congressional district. As color became more common in the print media, local newspapers have covered local and state elections with large, sophisticated four-color maps. No longer limited to the printed newspaper, local election maps are often posted on the news publisher's website.

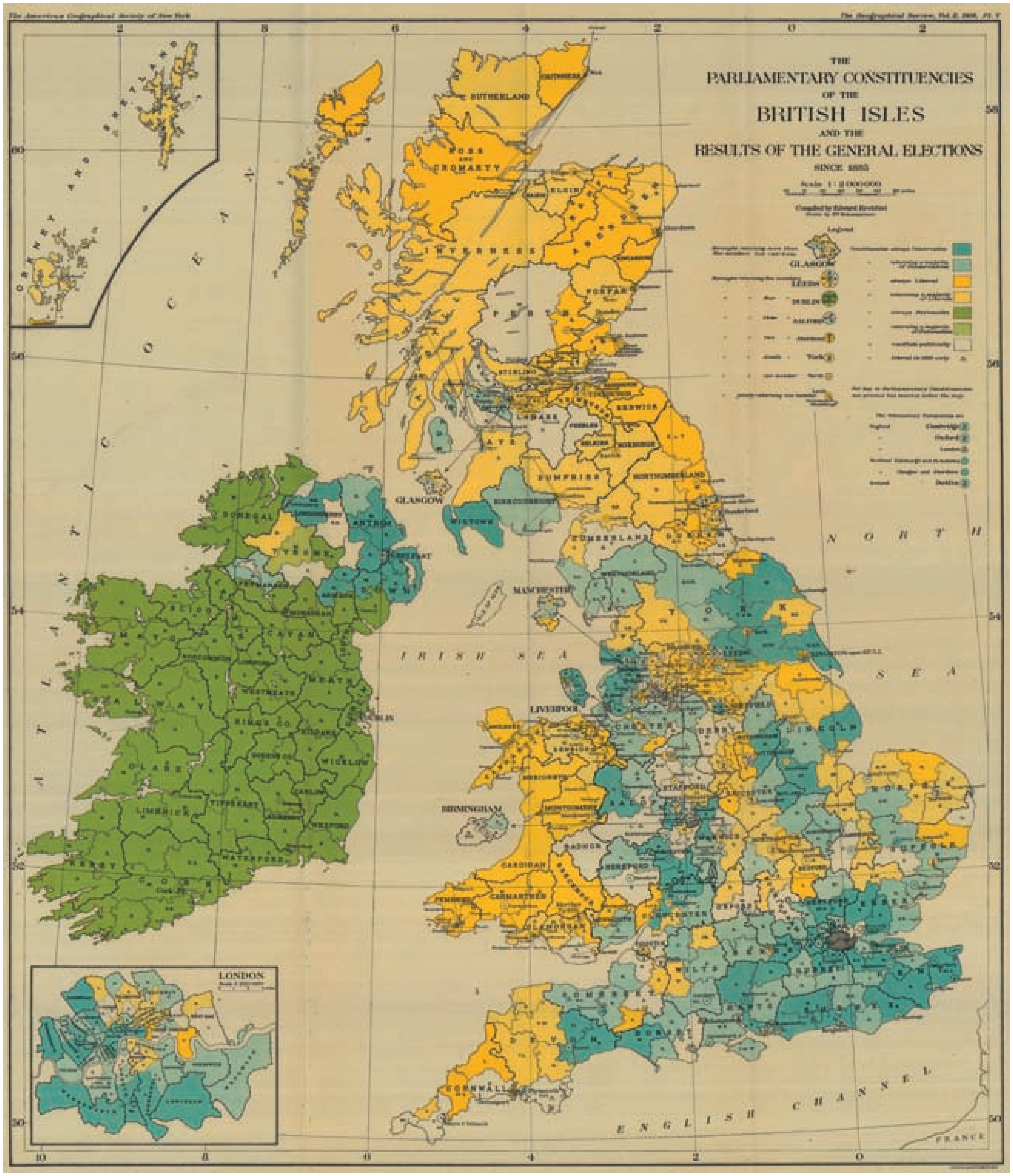

FIG. 220. EDWARD B. KREHBIEL, COMP., *THE PARLIAMENTARY CONSTITUENCIES OF THE BRITISH ISLES AND THE RESULTS OF THE GENERAL ELECTIONS SINCE 1885*. The mapping of several elections allows the longitudinal depiction of the strength of the Liberal, Conservative, and (Irish) Nationalist parties revealing a strong regional pattern of political support.
Size of the original: 50.7 × 43.4 cm. From Krehbiel's "Geographic Influences in British Elections," *Geographical Review* 2 (1916): 419–32, pl. V.

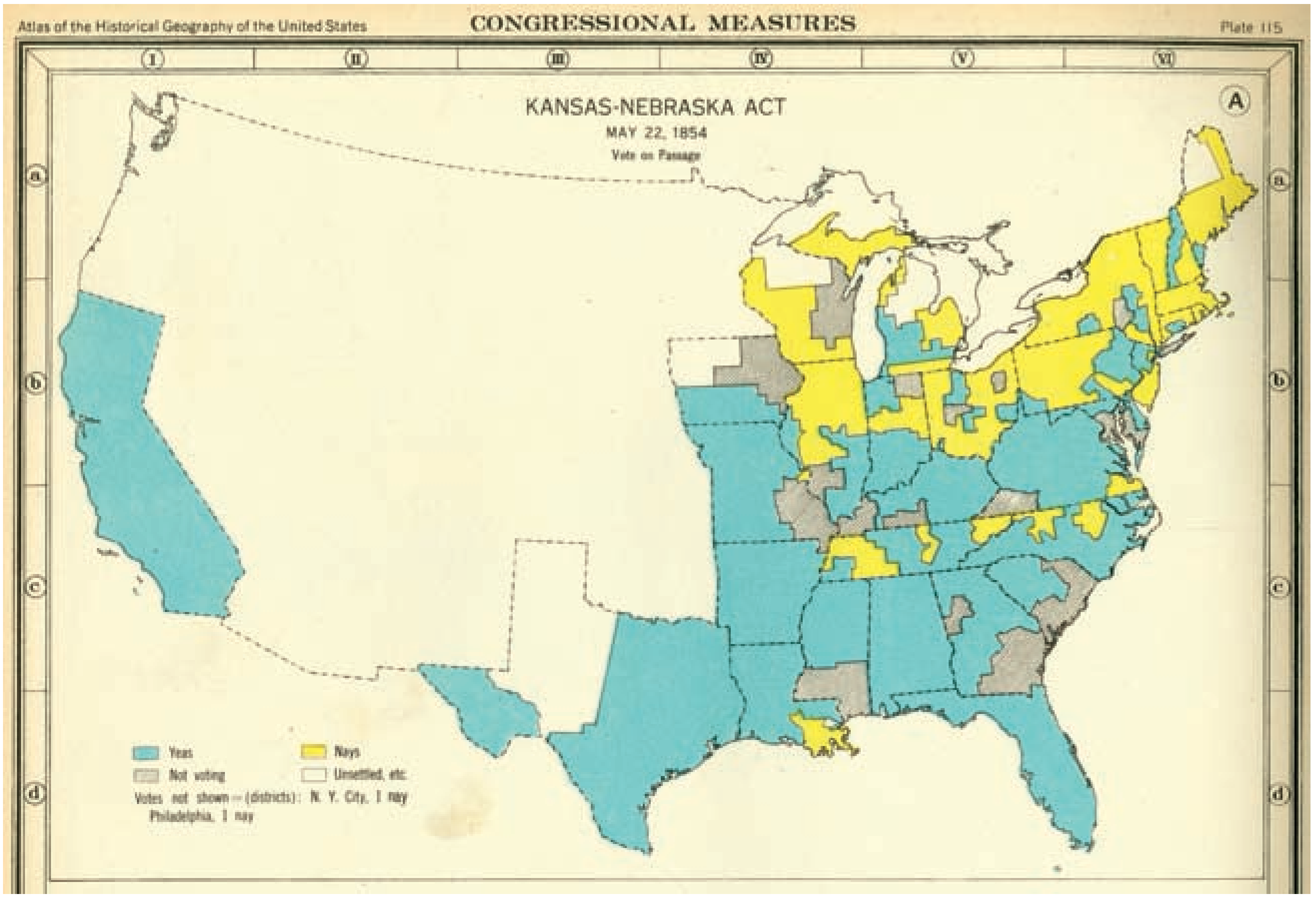

FIG. 221. *KANSAS-NEBRASKA ACT*, ROLL-CALL VOTES, 1854. This is one of thirty-one critical United States Congress roll-call votes mapped by congressional district contained in what many consider one of the finest early twentieth-century scholarly historical atlases.

Size of the original: 16.3 × 24.3 cm. From Paullin 1932, pl. 115 (top). Permission courtesy of the Carnegie Institution of Washington, Washington, D.C.

National television networks in the United States have altered, perhaps permanently, the political lexicon and preferred colors for electoral cartography. During the presidential elections in the 1980s and 1990s it became more and more common to portray states won by the Republicans in red and those won by the Democrats in blue. In European cartography, by contrast, the tradition is to show the left-leaning parties in red, the traditional color of the left. Although no set color scheme had evolved for American political parties, many academic and professional cartographers in the middle portion of the twentieth century thought it more logical and appropriate to use the European tradition, for example, to color Democrat areas red. But by the end of the 2000 presidential election and the early part of the twenty-first century the terms "red states" (meaning Republican) and "blue states" (meaning Democratic) were so common that academic election cartographers were helpless to resist the trend.

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SEE ALSO: Administrative Cartography; Census Mapping; Electronic Cartography: Computer-Aided Boundary Drawing; Journalistic Cartography

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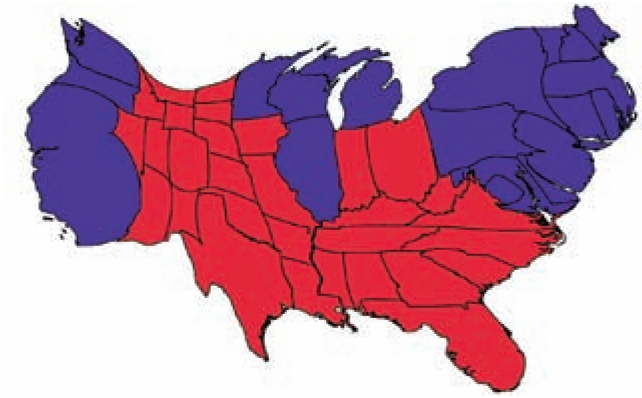

FIG. 222. CARTOGRAM WITH THE SIZES OF STATES PROPORTIONAL TO THE NUMBER OF ELECTORAL COLLEGE VOTES. Cartograms have been used throughout the twentieth century to illustrate a wide variety of data. Here computer-drawn cartograms of the 2004 U.S. presidential elections were posted on the World Wide Web a few days after the November vote and published in a journal a few months later. Figures 222 and 223 follow the now commonly accepted blue state = Democratic, red state = Republican color convention. From Michael Gastner, C. R. Shalizi, and M. E. J. Newman, "Maps and Cartograms of the 2004 US Presidential Election Results," *Advances in Complex Systems* 8 (2005):117–23, esp. 119 (fig. 3).

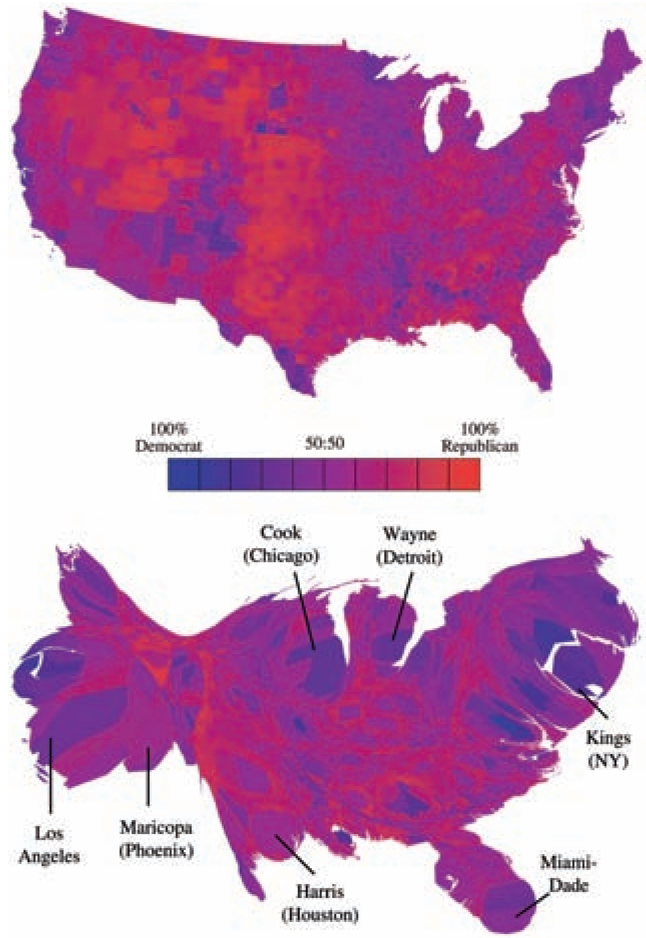

FIG. 223. ELECTION RESULTS ON THE BLUE–PURPLE–RED SCALE, 2004. Map (top) and cartogram (bottom) showing 2004 U.S. presidential election results. The amount of blue or red in the color of each county is proportional to the fraction of votes for that candidate (third party candidates are excluded). Cartograms depicting the actual size of the vote in the over 3,000 U.S. counties are possible only with computer-assisted cartography. In the cartogram the size of small-population rural counties (mostly Republican) is diminished and the size of the large-population urban counties (mostly Democratic) is increased in proportion to the actual vote size.
From Gastner, Shalizi, and Newman 2005, 122 (fig. 8).

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Electromagnetic Distance Measurement. Ole Rømer, who showed in the 1660s that light moves with a finite speed, understood the principle of using light to measure distances from one point to another. In the 1920s, after having achieved the first fairly reliable determination of the speed of light, Albert A. Michelson attempted an optical measurement of distances. It was, however, the rapid development of electronics during and after World War II that made the practical implementation of this idea possible. Although most electronic distance measuring instruments (EDMs) were developed as geodetic instruments, models suitable for surveyors were soon to follow. Although EDMs were substantially more expensive than chains and tapes, they were also more efficient, and they quickly displaced traditional distance measuring instruments.

Further exploitation of the time-distance principle led to Shoran (short-range navigation), a radio-based technique developed for blind bombing during World War II. Working with the Army Air Forces in 1946, Carl I. Aslakson of the U.S. Coast and Geodetic Survey used Shoran to measure the distance between several first-order triangulation points in the western part of the

United States. Shoran surveys in the Caribbean and then of the entire Atlantic Missile Range were followed by Shoran and Hiran (high-precision Shoran) ties between Scotland and Norway, between Crete and Egypt, and across the North Atlantic.

The Geodimeter, designed and produced in Sweden, was unveiled in 1953. It was heavy (over 200 pounds) and expensive; it required a generator for power; and since it used visible light, it operated best at night. It was also extremely precise and yielded results in areas where conventional taping was inconvenient. Of the ten instruments produced, all were purchased by geodetic agencies of national governments. In the spring of 1960, when the U.S. Air Force was planning a test of its new Azusa Mod II tracking system in the Atlantic Missile Range and needed to know the positions of nine tracking cameras located forty to fifty miles from the launch site at Cape Canaveral, the Coast and Geodetic Survey used a Model 2 Geodimeter and produced measurements accurate to about 1 part in 1,200,000. This was said to be the greatest accuracy ever attained in any extensive geodetic survey and ten times greater than the rigid standards prescribed for first-order triangulation. The Cape Canaveral survey eventually morphed into the transcontinental traverse. The later-model Geodimeters used on this high-precision quasi-military project were smaller and more convenient. The Model 6, introduced in 1964, had transistorized circuitry. The Model 8, introduced in 1967, had a helium-neon light source.

The Tellurometer, designed and produced in South Africa and unveiled in 1957, was the first microwave EDM. A second model, introduced in 1959, was designed to meet the demanding specifications of the military establishments of the North Atlantic Treaty Organization countries. The U.S. Department of Defense eventually bought numerous Tellurometers for its surveys in Africa, Southeast Asia, the Middle East, and South and Central America. It also provided funds so that the Cubic Corporation of San Diego could develop a domestic equivalent, which was marketed as the Electrotape.

Spectra-Physics, a firm located in Mountain View, California, developed the Geodolite, the first laser-based EDM. The feasibility model was unveiled in 1964 and used as an airborne profile recorder. Of the thirty Geodolites that were eventually built, most were purchased by federal agencies or by private firms working on federal contracts.

The Wild DI-10, introduced in 1968, was a small and convenient short-range infrared EDM with a gallium arsenide light-emitting diode and a digital readout. An EDM of this sort, when combined with a theodolite, became a total station, the versatile survey instrument in wide use at the end of the twentieth century for property and engineering surveys and accident reconstruction.

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SEE ALSO: Property Mapping Practices

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Electronic Atlas. See Atlas: Electronic Atlas

Electronic Cartography.

ELECTRONIC CARTOGRAPHY AND THE CONCEPT OF DIGITAL MAP
DATA STRUCTURES AND THE STORAGE AND RETRIEVAL OF SPATIAL DATA
DATA CAPTURE AND DATA CONVERSION
DISPLAY HARDWARE
ELECTRONIC MAP GENERALIZATION
ELECTRONIC MAP LABELING
COMPUTER-AIDED BOUNDARY DRAWING
INTELLECTUAL MOVEMENTS IN ELECTRONIC CARTOGRAPHY
CONFERENCES ON COMPUTER-AIDED MAPPING IN NORTH AMERICA AND EUROPE
CONFERENCES ON COMPUTER-AIDED MAPPING IN LATIN AMERICA

Electronic Cartography and the Concept of Digital Map. The use and evolution of computers (and associated devices) has had a transformative effect on cartography. Beginning in the 1950s, computers and electromechanical plotting devices were used to attempt to automate the drafting process. Engineers wanted to create a cartographic robot. The available digital data sets were simple, consisting of a series of x, y coordinates that were used to maneuver a drawing or scribing tool around a map sheet. The result was a black-and-white line drawing or color separate plate used to print a map. By the twenty-first century, printed maps have been largely replaced by full-color displays on computer screens, rendered by computer programs, and based on digital data that attempt to model geographic phenomena as they exist. In addition to graphics, these data sets are used by geographic information systems (GIS) in a wide variety of commercial, military, and scientific applications. This transformation was enabled by two major symbiotic components: the vision and creation of a digital database useful for analysis and display of geographic information and the rapid advances in computers, remote sensing devices, Global Positioning Systems (GPS), and telecommunications.

Waldo R. Tobler (1959), among the first to address the topic of electronic cartography, went beyond the ideas of using automated systems to improve map production. "Data concerning spatially distributed phenomena need not be stored on a map but can be coded into other symbologies," Tobler stated (1959, 526). This is one of the initial conceptualizations of a digital map—spatial data encoded in a computer database, independent of an analog product. The creation of comprehensive digital databases and maps, however, would be decades in the making.

The first efforts were concerned with two factors: a reduction in time to produce a map and a reduction in the overall cost. These ambitions were constrained by three factors: the computing environment, the visualization tools, and the digital databases. The available computers were large, expensive, and used in batch mode (users could not directly interact with the computer; commands were submitted on punched cards or magnetic tape). The visualizations consisted of plotters drawing (or scribing) lines and line printers using ASCII symbols to create crude, patterned, choropleth maps or shaded images. Not until 1967 was the first direct view storage tube vector graphics display, the Tektronix 611 CRT, generally available (at a cost of $2,500). It enabled cartographers to view and edit graphic displays interactively. Digital databases were nonexistent. The data used in electronic cartography had to be collected by digitization from existing graphics (fig. 224). Initially this was done manually by tracing the necessary linework using cumbersome two-axis drafting tables fitted with encoding devices that recorded the position of the stylus. General, multipurpose databases were rare, the notable exception being the World Data Bank produced by the U.S. Central Intelligence Agency and offered in successively greater geographic detail from the 1960s through the late 1970s.

Two early pioneers, David P. Bickmore and A. Raymond Boyle, dealt with these limitations by constructing a computerized system, the Oxford System of Automated Cartography, to meet the needs of cartographers. This activity employed the first free-floating cursor digitizer and possibly the first map made using a photohead on a precision plotting device. Boyle later designed an entire interactive digitizing and editing system, called CART-8, based on a PDP-8 minicomputer, digitizing table, and Tectronix 611 displays. In the early 1970s this system cost about $100,000, very expensive for a system that could be used by only one person. Such experimental equipment was so expensive that the field had to await technical advances in computer graphics used for the computer-aided design of automobiles, integrated circuits, or textiles (fig. 225). Even with other industry sectors absorbing the development costs, cartographic equipment remained costly, making cost savings over traditional methods difficult to achieve.

Based on his initial success of the Oxford system, Bickmore obtained funding from the British government to establish the Experimental Cartography Unit (ECU). In 1967, ECU pioneered the computer-assisted construction of high-quality printed maps (Rhind 1988). The ECU and other agencies, such as the U.S. military mapping services, the U.S. Central Intelligence Agency, and the U.K.'s Ordnance Survey, collected and utilized initial simple cartographic data sets (tracings of coastlines, major rivers, and political boundaries) to create simple outline maps. Efforts were made to create patterns for choropleth maps and to place text, but these

FIG. 224. M&S DIGITIZING AND EDITING EQUIPMENT, CA. 1978. M&S Computing Inc. (now Intergraph Corporation) DDES (digital data editing system) was used for manual digitizing of printed maps and for interactive correction of digitizing errors. Image courtesy of the U.S. Geological Survey.

FIG. 225. MAP BEING LOADED ON A SCITEX DRUM SCANNER, CA. 1984. This scanner was used to digitize feature separates from USGS 1:100,000 scale topographic maps as part of the production program that led to the creation of TIGER. Image courtesy of the U.S. Geological Survey.

efforts were only partially successful. It did become possible to use computers to quickly create maps of varying scales, coverage, and projection. Indeed, researchers moved quickly from using computers to calculate map projection coordinates to the concept of mathematically analyzing and manipulating geographic data in general—that is, analytical cartography (Tobler 1976).

By the 1970s, government mapping agencies wished to do more than automate the cartographic finishing operation (although that task had yet to be achieved to any great degree). In 1973, the International Cartographic Association (ICA) defined automated cartographic systems as "automated methods of producing charts and chart products, in graphic and digital form, with the view of radically reducing total production time" (ICA 1973, 2). In order to reduce the time required to produce a topographic map, the U.S. Geological Survey (USGS) introduced computers and automation into field surveying, photogrammetry, and the collection of elevation data from stereo models. By the late 1970s, the USGS was using the Gestalt Photo Mapper (a $1 million device that scanned a stereo pair of aerial photographs, producing an orthorectified image and an array of elevation points called a digital elevation model [DEM]) to create thousands of DEMs for the United States. These elevation data did not meet USGS topographic mapping accuracy standards, but they were one of the first and most popular digital data products of the USGS. One reason for this popularity lies in another transformative event that was occurring. Computer software packages called geographic information systems (GIS) were coming into existence. Their raison d'être was the mathematical analysis of geographic data, not the production of maps (although most had elemental map plotting capability). The GIS needed the same digital spatial data required by the electronic mapmakers. From the 1980s these two enterprises were inexorably linked (Guptill and Starr 1988).

The 1980s saw an increasing demand for digital data to meet the needs of scientists and managers utilizing GIS. Other systems required digital data as well. U.S. military cruise missiles needed DEM data of their target sites, which allowed the missile to fly at a set height above the ground, hugging the terrain. Traditional mapping agencies were the source for these data, but the agencies were under constant budgetary pressure. They faced a three-faceted dilemma: they had to maintain the traditional map production line to meet their prior commitments for products; they had additional requirements to produce data for GIS users (often with budget increases but lacking the accuracy and content to support traditional cartographic production); and finally, they had to control costs by automating map production to the standards of traditional maps, which was turning out to be more difficult than initially believed. Maps with simple symbology and limited labeling could be produced without much difficulty. However, traditional name and label placement turned out to be a very difficult challenge. Such tasks became severe bottlenecks, both in throughput and cost. For the automation task to succeed, digital databases had to become more complete models of geographic reality; computer display software had to produce more sophisticated symbology; and the problems of conflict detection and feature displacement, intelligent labeling, and geographic names had to become cheaper and more powerful. During the 1990s these challenges were met.

Complex printed maps, such as topographic maps or road maps, had been created by digital means during the 1980s. But it was not until the early 1990s that the hardware and software systems proved to be cost-effective for large-volume production. In 1991, the American Automobile Association utilized a comprehensive road database to produce, entirely by computer, sets of full-size city street maps. Rand McNally switched from using manual methods to computer production of their annual road atlas in 1993.

Mapping agencies in other countries adopted electronic cartography in the last decades of the twentieth century as well. The Japanese Geographical Survey Institute began collecting digital information from the 1:200,000 map series in 1974, and in 1984 initiated the creation of its "Large Scale Map Database," which includes all the content of the 1:10,000 and 1:25,000 maps (Warita and Nonomura 1997, 34–35). Similarly the French Institut géographique national, in the early 1980s, moved from traditional production of paper maps to the collection of digital data and the electronic production of products (Grelot 1997, 228). The transition to electronic cartography did not occur until the late 1980s or 1990s in Mexico (Jarque 1997, 64), Russia (Zhdanov 1997, 75–76), and China (Chen 1987, 219–20).

Early digital data models were based on simple geometric constructs (points, lines, areas, and regular grids), and an appropriate geometric type was used for a given type of map object (e.g., lines for the road network). Each geometric type was kept in a separate database or file (called a layer), and the layers were manipulated separately. This artificial constraint was necessary given the then-current hardware and software limitations. With the development of more comprehensive database technology (extended relational and object-oriented databases), researchers began to create more comprehensive models of geographic reality. Hydrological networks were viewed as a connected system of water features, and not by assuming that springs are points, streams are lines, and lakes are polygons. This database design philosophy changed the way in which national mapping agencies created spatial databases (Guptill 1986) and eventually changed how users interact with electronic maps. These concepts were instantiated in 1988 in the TIGER (Topologically Integrated Geographic Encoding and Referencing) database, a seamless database of the United States' transportation networks, hydrography, and administrative boundaries created by the U.S. Geological Survey and the U. S. Census Bureau (Marx 1990).

In the last decade of the century advances in four areas dramatically changed the collection and use of map data. First, computers and communications technology dropped in cost and doubled in performance every eighteen months while becoming available to over half the world's population. Second, individuals could accurately locate themselves by using GPS chip sets embedded in mobile phones and low-cost personal navigation devices (PND). Third, high-resolution digital imagery (1 m or better) from aerial photography and satellites became freely available to the general public. Finally, all these devices and data sets were connected via the Internet and World Wide Web and were accessible from almost anywhere on the planet.

In 2005, Google dramatically changed people's interaction with maps by introducing two web-based products, Google Maps and Google Earth. Google's offerings quickly became widely popular. Ironically, less than a decade after electronic map production became operational, maps printed on paper appealed to a diminishing set of users. But maps on a computer screen (or PND or mobile phone) became commonplace, and services, such as trip routing, yellow page listings, real estate sales, and other location-based services, dramatically increased the number of map users. Users' ability to edit and update the information shown on these devices removed traditional mapping agencies from a central role in map production.

Fifty years of effort in using computer technology to make maps have resulted in a far different scenario from that envisioned by the pioneers. Instead of up-to-date printed maps rolling off fully automated assembly lines, individuals interact with their personal electronic maps, locating themselves and their friends and adding geographic content to global databases. Electronic maps have allowed billions to become more aware of their geographic surroundings and to make maps a component of their daily lives. Maps have moved from the purview of specialists to the domain of the common person—and the world has been inexorably transformed.

STEPHEN C. GUPTILL

SEE ALSO: Digital Library; Experimental Cartography Unit, Royal College of Art (U.K.); Geographic Information System (GIS): Computational Geography as a New Modality; Map: Electronic Map

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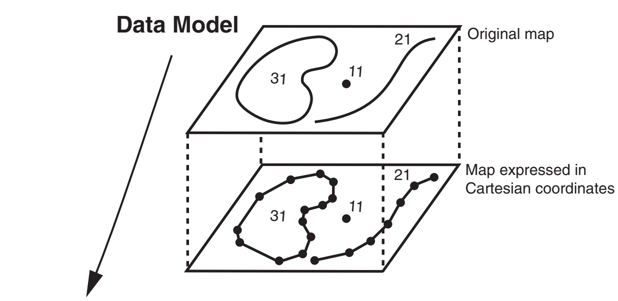
Data Structures and the Storage and Retrieval of Spatial Data. The first representation of geographic space for use with a computer is generally attributed to Waldo R. Tobler, who created the first computer-generated maps in the late 1950s (Tobler 1959). These early computer maps were usually gridded, in what became known as the raster format. This type of data model was used for the earliest developments in electronic cartography simply because the only computer output device commonly available was the line printer. Thus the map was quantized into a matrix of cells, which could be printed a row at a time in order to build up variations in shading that formed an entire image. The grid was also a familiar representational technique used for quantitative geographic data, as well as other forms of spatial data, in use since the ancient Greeks. The level of general familiarity and seemingly overall comfort with this representational form undoubtedly was a major factor in the popularity and longevity of one of the first generally available computer mapping programs, SYMAP (synagraphic mapping), developed by Howard T. Fisher in 1964. Although maps produced with SYMAP were visually crude and did not approach the sophistication and accuracy of manually produced professional products, the program provided a quick and relatively easy way to generate maps. Grid-based mapping dominated for a long time, largely because of cost. Every computing installation of the 1960s and 1970s had a line printer, and anyone with access to a computing facility and appropriate software could print a map. SYMAP provided many university students with their first exposure to computer mapping until well into the 1980s.

The earliest geographic information systems (GISs) utilized either this same grid representational format or what became known as the vector format. With vector data, the points, lines, and polygons on the map become the basic logical units stored in the data file. The development of the vector model was a natural extension of traditional, manual drafting techniques that cartography shared with engineering and the graphic arts. The very first developments in computer representation of geographic and other forms of spatial data in vector form was motivated by the desire to maintain the (real or perceived) accuracy of these cartographic elements. What is generally acknowledged to be the first GIS, the Canada Geographic Information System (CGIS), became fully functional in 1971 and was based upon a vector data model.

For approximately two decades data models specifically used for geographic data were classified into these two distinct types: vector and raster.

The Progression of Vector Models

The first and simplest vector data model, used in the earliest vector-mode GIS and drawing software, became known as the spaghetti data model. This is a direct line-for-line translation of the paper map. The basic logical entities are points, lines, and polygons. As shown in figure 226, each entity on the map becomes one logical record in the digital file and is defined by a string of *x, y* coordinates. Although all entities are spatially defined, no spatial relationships are retained. Digital cartographic data files in which coordinate strings were heaped together with no explicit structure became known as "spaghetti files."



Data Structure

Feature	Number	Location
Point	11	X, Y
Line	21	X_1Y_1, X_2Y_2, ..., X_nY_n
Polygon	31	X_1Y_1, X_2Y_2, ..., X_1Y_1

FIG. 226. THE SPAGHETTI DATA MODEL.
After Peuquet 1984, 77 (fig. 5), adapted from Dangermond 1982.

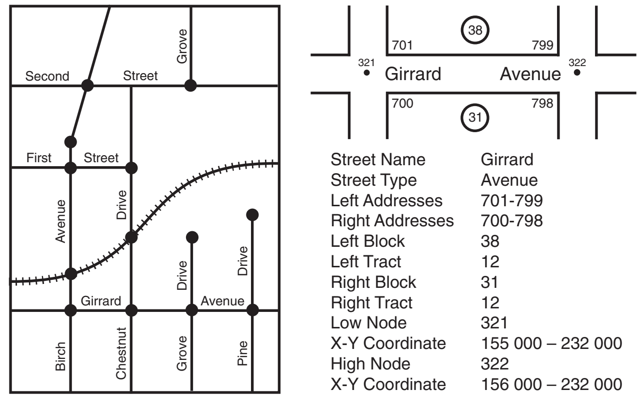


FIG. 227. GRAPHIC ELEMENTS OF THE GBF/DIME FORMAT AND ITS CORRESPONDING FILE ORGANIZATION. A street map showing intersections as nodes dividing streets into segments (left), a closeup of one street segment (top right), and the street segment as a single record stored in the GBF/DIME file (bottom right).
After Peuquet 1984, 79 (fig. 8).

The U.S. Census Bureau (1970) developed the GBF/DIME (Geographic Base File/Dual Independent Map Encoding) format in 1968 for digitally storing addresses and urban maps to aid in the gathering and tabulation of census data. This data model was a major advance in that, for the first time, topology was explicitly incorporated as an integral component of a vector representation (fig. 227). While relative spatial relationships stored within a DIME file offered opportunities for various types of analyses, the primary purpose of the original design was automated error checking by software that looked for omissions or inconsistencies.

While the GBF/DIME data model incorporated explicit topological information, polygon boundaries must be reconstructed from numerous individual straight-line segments. The problem here is that line-segment records are stored as a simple list. Thus, retrieval of each line segment, in sequence around the polygon, can be accomplished only by an exhaustive search through the entire file. Similarly, information about an individual node (e.g., a street intersection or another location at which linear features meet) can be retrieved only by searching for all line segments that meet or cross.

Hierarchical vector models overcame this problem by more closely following the conceptual structure of the basic map line elements and providing an explicit retrieval mechanism based on polygons composed of the linear features that comprise their boundaries and linear

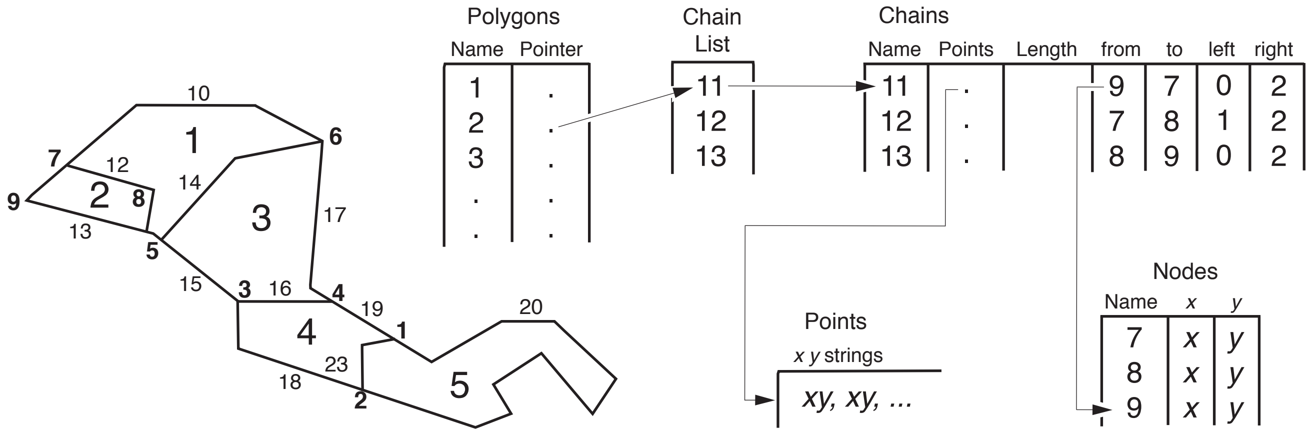


FIG. 228. THE POLYVRT DATA MODEL. Polygons, chains (of straight line segments denoting polygon boundaries), points, and nodes (where chains meet) are stored in separate files linked by pointers.

After Peuquet 1984, 80 (fig. 9).

features composed of strings of point locations. When these feature types are stored separately, links can relate one type of feature to another, as shown in figure 228.

One of the earliest hierarchical vector models, called POLYVRT (polygon converter), was developed by Thomas K. Peucker (later Poiker) and Nicholas R. Chrisman (1975) and implemented at the Harvard Laboratory for Computer Graphics and Spatial Analysis. This type of model offers considerable versatility, particularly if it includes topological information. It can also be augmented to represent highly complex data, such as enclaves or exclaves on a political map; adding further levels to the hierarchy, such as an additional level of polygons (e.g., counties within states), does not violate the basic concept of the model.

The hierarchical vector model provided a significant computational advantage over nonhierarchical vector models for retrieval and manipulation. But this increased efficiency depends on the explicit storage of multiple entity types in physically separate files. Moreover, their physical separation in the database required stored links, or pointers, to other entity types. These structural elements add significantly to the total volume of information that must be stored as well as to the complexity of adding and maintaining the information. Nevertheless, this overhead does not outweigh the advantages of the flexibility and overall functional effectiveness of this type of spatial data model. Because of its computational efficiency, the hierarchical vector type of spatial data model was used as the primary representational scheme in a number of commercial GIS software packages, most notably ARC/INFO (later ArcInfo) and ArcGIS products by Environmental Systems Research Institute (ESRI).

Tessellation Models

Although commonly known as "raster" models, this class of models is best termed the tessellation-type model. The raster designation—the term was used in the television electronics industry to describe line-by-line imaging—became widely used in cartography the 1970s, when civilian remote sensing satellites began to capture data directly in digital form and computer-controlled cathode ray tubes (CRTs) were introduced as graphic-display devices. Satellite imaging systems and video displays operated, and still operate, in scan-line fashion.

Although the raster data model was the major practical alternative to vector spatial data models for storing geographic data, particularly for applications requiring image interpretation, it quickly became recognized that other systematic subdivisions of space, or tessellations, have practical uses as spatial data models. In essence, a tessellation in two dimensions is analogous to a mosaic. Donna J. Peuquet (1984) reviewed the potential types of tessellation models and their advantages and disadvantages as spatial data models. Of the potential tessellation models, the regular-square or rectangular mesh has remained the most widely used data structure, primarily because it is familiar to users as well as directly compatible with Cartesian (x, y) coordinates. Two other tessellation models have also been used for storing and using spatial data in GIS: the hexagonal mesh and the triangulated irregular network (TIN).

Hierarchical tessellation models attracted much attention among GIS researchers in the 1980s, specifically with the application of the quadtree structure, based on the recursive spatial decomposition of a square

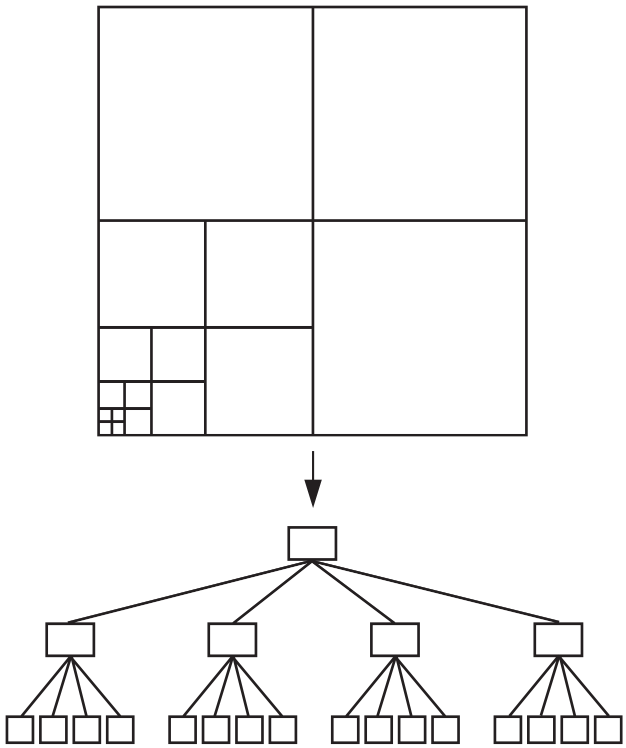


FIG. 229. THE QUADTREE DATA MODEL. The conceptual scheme of a recursive spatial subdivision of a large square progressively into four smaller squares translates at the implementation level into a regular tree structure where each node in the tree has four descendants, down to the smallest subdivision. After Peuquet 1984, 88 (fig. 16).

(fig. 229). The quadtree was first described within the context of a spatial data model by Allen Klinger (1971). Given the development of many variations (Samet 2006), the quadtree scheme based on the regular subdivision of continuous space into four subunits became known more specifically as the Area Quadtree. The Area Quadtree representation was the basis for at least one commercial GIS, SPANS (Ebdon 1992).

Excitement over quadtree representation reflected recognition of several important advantages. It is a multiscale structure that still retains compatibility with Cartesian x, y systems. And as an adaptation of the binary search tree for two dimensions, tree structures are a highly efficient database retrieval mechanism for the display and analysis of very large databases across a range of scales. Of the many hierarchical tessellation variants developed, the R-tree became perhaps the most widely used for digital geographic data storage and handling. This representation is based on nested, and potentially overlapping, minimum bounding rectangles (MBRs), as shown in figure 230.

This class of spatial data model was also recognized as a promising approach for dealing with global databases. Perhaps the most adaptable was Geoffrey Dutton's (1996) octahedral quaternary triangular mesh (O-QTM), a global hierarchical data model based on an octahedron inscribed within a sphere.

Representing Temporal Dynamics

The integral role that time plays in geographic phenomena and thus in geographic data was described conceptually by Brian J. L. Berry (1964) as a three-dimensional matrix with space, time, and attribute dimensions. During the 1970s a number of authors used this concept of a three-dimensional matrix to further emphasize the importance of temporal data, as an adjunct to spatial data, and the problems and prospects of spatial-temporal geographic analysis. Berry's framework added to the broader interest among academic geographers in time and space-time analysis, inspired during the late 1960s and the 1970s by Torsten Hägerstrand's Time Geography (1967). Nevertheless, the inclusion of the temporal dimension in geographic databases was the rare exception. Umit Basoglu and Joel L. Morrison (1978) provided a very early space-time database design and implementation that was a hierarchical vector structure.

The first articles calling for the incorporation of time in geographic databases based on the development of a comprehensive design framework didn't appear until the late 1980s (e.g., Langran and Chrisman 1988). Before that time, the construction and use of geographic databases incorporating spatial dynamics were hampered by a lack of temporal data as well as by the limited memory and slow processing speed of available computing hardware relative to the significantly increased amount of data needed to include the temporal dimension. The representation of information past and present became technologically feasible through rapidly declining storage costs and increasing processing capacity.

The conceptual approach most often used is known as "sequent snapshots" or "sequential images" because the data consist of multiple snapshots of values for a given variable over a defined area for specific point in time. This is a pragmatic solution that is compatible with the standard thematic "layer" approach utilized in GIS software for both raster- and vector-based models. To represent temporal dynamics in a geographic database, each layer represents a complete snapshot of a given thematic domain at a known point in time. Gail Langran (1992), who described variants of the snapshot approach that provide more compact representations by recording only the changes, also discussed implementation issues for these variants in both raster and vector form. The representation of space-time dynamics attracted much attention among geographic information researchers throughout the 1990s, when it became apparent that the

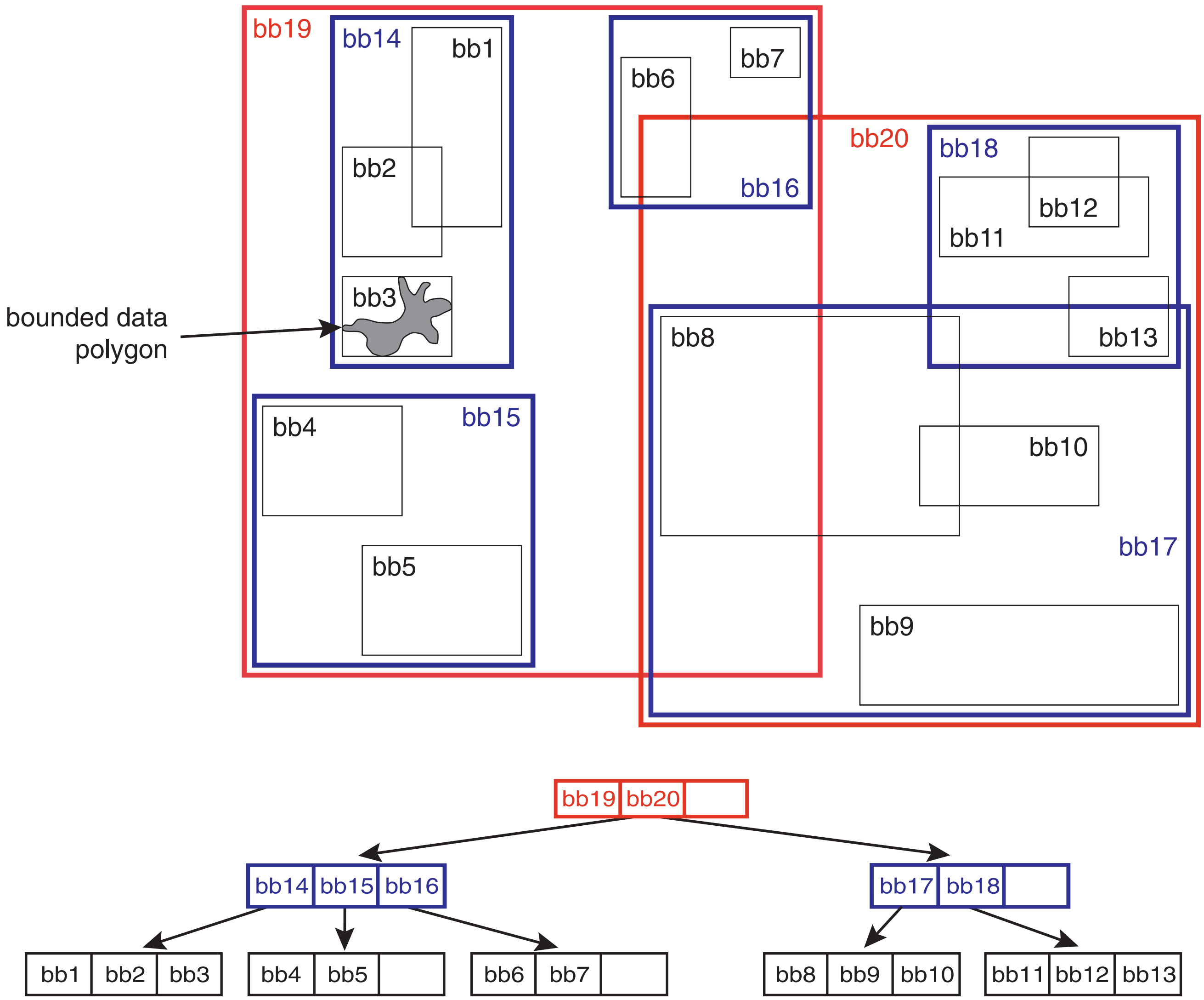


FIG. 230. THE R-TREE DATA MODEL. This spatial data model is based on an areal hierarchy of rectangles, with the lowest-level rectangle consisting of minimum bounding rectangles, or bounding box (bb). Each higher-level rectangle is also a bounding rectangle enclosing a set maximum number at the next lower level in the hierarchy. This translates into a balanced tree structure at the implementation level.

incorporation of time added a number of philosophical and implementational complexities relating to the nature of events, the differences and similarities of space and time, and the relative advantages of linear and cyclical views of time, among others.

Seeing the Theory for the Trees

The development of representational techniques within the GIS community progressed into the 1980s with a general emphasis on incremental improvements in spatial data models based on familiar methodologies and a bottom-up approach to database design that focused on implementational rather than conceptual advancements. This strategy reflected a proliferation of GIS and a heightened awareness of the young technology's capabilities and capacities.

The spatial data–handling systems of the 1980s could generally be described as monolithic in their database design insofar as the typical system was based upon either a vector or a raster data model. As an example of the degree of separation in the use of raster and vector data models, ESRI marketed two types of GIS, called PIOS and GRID, which were vector based and grid based, respectively.

The topological vector format, and particularly the hierarchical topological vector format, became the dominant spatial data model for geographic software designed to support urban and regional planning. The spatial configuration of essential geographic features such as streets and census blocks could be described in detail on the basis of points, lines, and polygons. The grid or raster format was found more effective for applications in forestry and natural resource management, which focus on overall spatial pattern rather than individual features. This format was also used for image processing applications, for which data were typically provided in raster format.

As computing hardware, electronic data, and geospatial software became more widely available, an increased range of applications and research questions not only exposed the functional limitations of various database representations but also raised the issue of how to broaden the individual GIS's functional capabilities. Because of a monolithic GIS database design philosophy as well as the speed and capacity constraints of computing technology at that time, the solution was interpreted as hinging on which of the two basic types of representation—raster or vector—could best handle the complete potential range of functions. This was also seen as a means of avoiding the overhead of converting data from one data model to another.

The often heated raster-versus-vector debate that arose in the late 1970s lasted through most of the 1980s. A popular phrase described the tradeoff: "Raster is faster but vector is correct(er)." Raster representations were viewed as easy to implement and fast to use, but significantly less precise. Unless a very fine grid or other spatial tiling was used, lines and feature boundaries would appear jagged when plotted, and the coarse representation would provide a very coarse data representation. To reduce the cell size would result in an extremely redundant storage method, with many pixels recording the same data values. The vector-type model was seen as the means for recording much more precise locational information—a false claim by vector-mode proponents insofar as already existing grid-compaction schemes could effectively eliminate data redundancy and thus obviate overly coarse grids. These claims, regardless of their validity at the time, became moot with rapid advances in electronic memory and processing speed.

Development of an overall taxonomy of existing geographic data models, which required putting known approaches into a cohesive framework, was the next phase in the development of geographic representation. These conceptual frameworks gained much attention as practical guides (e.g., Peuquet 1984), but the basic representational choices viewed geographic space as either cells or a complex of points, lines, and areas.

Early attempts to address digital spatial and space-time representation on a fundamental/theoretical level were sporadic and had little practical impact on databases or software. David F. Sinton (1978) interpreted within a GIS context Berry's geographic matrix (1964), which more than a decade earlier had provided a framework linking positional, temporal, and attribute data. Chrisman (1978) examined the implications for geographic databases of absolute- and relative-space representations. Michael F. Dacey (1970) anticipated the need for a spatial query and manipulation language based on fundamental geometric principles.

Hybrid models with characteristics of both raster and vector data models were also developed, but these were primarily attempts to extend the standard raster/vector framework. The strip-tree (Ballard 1981) and the vaster (Peuquet 1983) models are two examples. Commercial GIS increasingly acquired the ability to handle both raster and vector data, simply out of functional necessity. Not until the late 1980s was the dual nature of raster and vector data models, and the intrinsic need for both, generally acknowledged and described in the literature from a theoretical perspective (Peuquet 1988).

Using a dual raster-vector framework, the basic logical component of a vector model is seen as a spatial entity, which may be identifiable on the ground or created with the context of a particular application. The spatial organization of these objects is explicitly stored as attributes of these objects. Conversely, the basic logical component of a tessellation model is a location in space. Each of the basic vector and tessellation data model types can be seen as object based (or entity based) and location based respectively. Each is therefore also intrinsically more effective for answering one of two fundamental spatial queries, which themselves can be viewed as logical duals of each other. From the object-based view, the question is: Given a specific entity or entities, what are its associated properties (one of these properties may be its location)? The query from the location-based view is: What entity or entities are present at a given location?

It was Helen Couclelis (1992) who couched the duality of GIS data models in cognitive/theoretical terms, renaming the two basic approaches of geographic data representation as objects (instead of vectors) and fields (instead of rasters). Drawing upon philosophy, Couclelis linked the field-based vs. object-based dichotomy of geographic database models to the cognitive distinction of location-based and object-based views of the world. From a database design, the renaming of these basic model types also serves to emphasize the focus on the external (i.e., logical/cognitive) view.

This development coincided with the more general recognition that a coherent theoretical foundation for geographic representation was lacking, and that such a theory is needed to interrelate all forms of representation—cognitive, graphical, and database. This was highlighted in the call for development of geographic information science as an interdisciplinary field to address geographic representation and related issues on a theoretical level (Goodchild 1992). This general recognition suggested that research in GIS in general, and in geographic database representation in particular, had reached a state of maturation in accord with the normal progressive development of any methodology or science. The field that had been evolving for over two decades acquired the new name GIScience (GISci), in which science replaced systems, to emphasize a fundamental shift from a focus on implementation to a focus on concepts and a coherent theoretical framework.

By the late 1990s, most current commercial GISs utilized a multirepresentational database design, incorporating both raster- and vector-type representations for coordinate data as well as links to a database management system (DBMS) for storing attribute data. This allowed procedures to be linked to the most suitable representation for performing a given task. From the perspective of the representation and capture of observed information, researchers now recognized the need to model *human concepts* of reality instead of merely modeling cartographic representation. Corresponding to human problem solving, each type of model, or view of reality, is a form of representation that is particularly useful for addressing certain types of problems and answering certain types of questions.

Geographic Data Models Based on Cognitive Structure

In the 1990s researchers paid increased attention to ontological and high-level conceptual issues, as evidenced by the series of international COSIT (Conference on Spatial Information Theory) meetings, held biennially starting in 1993. As important as these efforts were, they revealed a disconnect in the research on geographic representation. Research in the realm of high-level abstraction grew directly out of the spatial cognition and philosophy traditions focused on theory. By contrast, implementational efforts remained largely focused on technical issues and were largely framed by a worldview of points, lines, polygons, and pixels.

Jonathan Raper and David Livingstone (1995) recognized this deficiency and offered an example of an implementable data structure for observational geomorphologic data that was based on a high-order and more natural cognitive worldview. They demonstrated how object-oriented data modeling techniques, with intrinsic mechanisms for representing conceptual taxonomic and partonomic hierarchies, would provide greater representational power. Jeremy L. Mennis, Donna J. Peuquet, and Liujian Qian (2000) offered a general-purpose framework based on this perspective in what they called the "pyramid framework."

At the end of the twentieth century, geographic information science in general and geographic representation in particular had taken a major step beyond solutions merely automating or imitating manual methods and models. New perspectives promised a fuller exploitation of computing technology and its unique capabilities as well as an enhanced human understanding of both abstract, higher-level knowledge and observational data. However reliant on earlier ideas and techniques, whatever new frameworks and strategies were to evolve could now benefit from a firm theoretical foundation.

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SEE ALSO: Canada Geographic Information System; Geocoding

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Data Capture and Data Conversion. Data capture is defined simply as how mapmakers make and record observations of real world features. By contrast, data conversion is the process of transforming existing data and information to a form that can be used directly by a cartographer or, later in the century, a geographic information system (GIS). Data capture and data conversion are discussed together here because they both depend on the scale and type of mapping being performed. For example, data collection for a small-scale mapping project is often a process of converting data developed for a large-scale base map. Similarly, data for thematic mapping typically requires that existing data be converted. Thus, for the cartographer, data collection implies data conversion.

To understand developments in cartographic data capture and their implications, it is useful to categorize the phenomena of interest. Three broad classes of phenomena are relevant: (1) the physical environment, most importantly topography, bathymetry, geology, and the atmosphere; (2) the biosphere, including biotic land cover, ocean species, and wildlife; and (3) the socioeconomic landscape, including population distribution, epidemiology, and economic activity. All three categories depend on data capture and conversion, but the methods and requirements typically differ from category to category. For example, direct observation is appropriate in topographic mapping, while inference is required when mapping consumer behavior or vegetation health. Consequently, a wide range of data capture methods and technologies evolved over the course of the century, each with its own development trajectory, impact, and implications. The principal approaches, discussed below, are land surveying, overhead imaging, the Global Positioning System (GPS), and collection of socioeconomic data.

Land surveying is the process of collecting essential measurements to determine the relative position of points or physical and cultural details above, on, or beneath the land surface. For much of the century, land surveying involved manually recording measurements of horizontal and vertical angles from known control points using a surveyor's compass or theodolite. These measurements were reduced using mathematical methods and a set of three-dimensional vectors and control points established in a local coordinate system. Control points in an absolute coordinate system were used to convert local observations to data for use in systematic mapping. Phototheodolites—metrically stable cameras combined with a theodolite—supported terrestrial photography used for indirect measurements of a landscape. One of the better-known instruments was the Zeiss Field Phototheodolite developed by Carl Pulfrich in 1906 (Blachut and Burkhardt 1989, 23–24). These methods of data capture were labor intensive and required specialized equipment and knowledge and thus were typically employed by government organizations to support military activities and basic mapping programs. Despite the resources required, this type of land survey produced highly accurate topographic data. Optical survey instruments developed in the mid-1920s led eventually to electronic-optical devices (e.g., the total station), and by the 1980s instrumentmakers had combined electronic distance measurement with data storage and an internal processor for converting observations to coordinates. These systems were refined through the early 1990s, when global navigation satellite systems (GNSS) such as the well-known Navstar GPS offered a more efficient solution for many survey applications.

Throughout the twentieth century, land surveying was an important method for capturing highly accurate spatial data, and while the theoretical foundations remained the same, significant advances occurred in the automation of data capture and conversion. In particular, the ability to transfer data directly to computers greatly increased the efficiency of land surveying and subsequent mapping. Nevertheless, the need to make a large number of measurements and the emergence of overhead imaging as a viable option diminished the relative utility of land surveying for many mapping applications.

Developments in overhead imaging, including aerial photography, satellite remote sensing, and lidar (light detection and ranging), revolutionized spatial data capture and conversion in the twentieth century and had a wide range of scientific and societal impacts. Aerial photography, the earliest of these developments, played an important role in reconnaissance, surveillance, surveying, and mapping throughout the entire century. Its adoption reflects several clear advantages over traditional land survey techniques. Among these are the establishment of an improved vantage point that supports a complete survey across large areas of the earth's surface; the creation of a permanent, versatile record of an instant in time for use in historical studies and change detection; the ability to record phenomena not visible by the human eye using specialized film; and the ability to measure landscape features (Lillesand and Kiefer 1994, 49–50). The balloons and kites used as aerial platforms in the latter part of the nineteenth century were quickly replaced following the invention of the fixed-wing aircraft (airplane) in 1903. The first aerial images taken from an airplane were captured in 1908. The reconnaissance and surveillance requirements of World War I drove advances in aerial survey techniques (Finnegan 2006). Following the war, civilian applications used the knowledge and experience of military pilots and interpreters, and new applications in mining, soils, forestry, and agriculture emerged. World War II resulted in further developments including the use of color-infrared film for camouflage detection. Since then, aerial photographic surveys have provided the foundation for much national, topographic, and thematic mapping. Clearly, warfare and military applications had a significant impact on the development of aerial surveying and its subsequent use in the civilian domain.

FIG. 231. THE WILD HEERBRUGG LTD. AUTOGRAPH A7 STEREOPLOTTER. Optical stereoplotters were used to extract geographic data and plot maps from aerial photograph stereo pairs. Proficient operation of the device required extensive training and experience. As indicated by the photograph, the plotter was a large machine relative to the size of the stereo pairs that it processed (ca. 9″ × 9″, or 23 cm × 23 cm).
From Blachut and Burkhardt 1989, 121 (fig. 73). Copyright by the American Society for Photogrammetry and Remote Sensing.

FIG. 232. DIGITAL PHOTOGRAMMETRIC WORKSTATION. These stations made optical and analytical photogrammetric devices effectively obsolete by the end of the century. The combination of high accuracy, small size, relatively low cost, and ease of use gave the new systems a competitive advantage.
From Lillesand and Kiefer 1994, 350 (fig. 4.30). Permission courtesy of John Wiley & Sons, Inc.

Developments in image capture were paralleled by developments in image processing and related data conversion methods and instrumentation. Photogrammetry is the technique of using photographs to perform indirect measurements of the terrain. Based on the early work of Theodor Scheimpflug in 1897 and Édouard Deville in 1902, simple measurement and manual calculations gave way to the manufacture of instruments such as the stereoplotter (fig. 231). The geometry of overlapping photos (stereo pairs) support the extraction of three-dimensional data, and thus the plotting of topographic and thematic mapping from photographs. In turn, manual-optical collection gave way to electronic image correlators, which greatly expedited the plotting process. The advent of digital computers in the 1950s provided the platform needed to develop fully analytical stereoplotters, which used a mathematical model to assist and automate much of the set-up and data-collection processes. While more accurate, versatile, and efficient than stereoplotters, these systems continued to use analog, hard-copy photographs. In the 1990s soft-copy or digital photogrammetric workstations (fig. 232) that used digital raster images rather than photographs rapidly replaced both optical-mechanical and analytical stereoplotters. Although the electronic scanning of photographic film or prints initially provided the data for digital photogrammetry, advances in digital cameras streamlined the process by providing "born-digital" data—data captured originally in digital form. At the end of the century, the ability to combine accurate positioning and orientation data collected during flight with digital photography and soft-copy photogrammetry enabled rapid, near-real-time mapping (Lithopoulos, Reid, and Hutton 1999). Increased efficiency and reduced costs led to a greater commercialization of aerial survey and data conversion as government mapping agencies replaced their own survey teams with outside contractors and competitive bidding.

The launch of Sputnik in 1957 inaugurated the era of space-borne remote sensing, and the rapidly escalating Cold War drove a variety of early innovations. Perhaps the most noteworthy system—but known at the time only to a small number of people with high-level security clearances—was the American Corona spy satellite, developed primarily for reconnaissance and surveillance of Soviet activities. The first mission to successfully return images launched on 18 August 1960 following a string of frustrating failures (Wheelon 1997, 29). Able to acquire high-resolution images (for pixels as small as 1.5 m) on photographic film delivered back to earth in a capsule, Corona was a significant innovation in overhead imaging. Although the imagery remained classified until 1995, the program advanced remote-sensing through experience and innovation over the course of launching 145 satellites with progressively improved sensors. Corona is another example of the link between geographic data capture and military applications that had a marked impact in the latter decades of the twentieth century and beyond on civilian mapping, spatial analysis, and change detection (Galiatsatos, Donoghue, and Philip 2008).

Remote sensing for earth resource monitoring moved forward with the launch of the Earth Resources Technology Satellite (later renamed Landsat) by the National Aeronautics and Space Administration (NASA) in 1972. Landsat 1 used a digital sensor that scanned the earth's surface in multispectral mode—in visible as well as infrared portions of the electromagnetic spectrum—at a ground resolution of approximately eighty meters. The Landsat series continued until the launch of Landsat 7 in 1999, with Landsat 5 continuing to deliver high-quality data in 2009. Many other remote sensing satellites were launched in the 1980s and 1990s, including the first Indian Remote Sensing Satellite (IRS-1A) in 1988; the Japanese Earth Resources Satellite (JERS) in 1992; and Canada's Radarsat in 1995. All of these systems produced digital data for direct processing by computers. Radarsat and JERS used an active sensing process that recorded the reflection of a microwave signal transmitted downward. Although microwave radar can penetrate cloud cover and allows scanning at night, these advantages increased the tension between military officials concerned with secrecy and security and civilian scientists and mapmakers focused on research needs and commercial applications. As with conventional aerial photography decades earlier, national defense was the primary force behind developments in remote sensing, but civilian applications tended to benefit, albeit somewhat later and with lower resolution.

Remote sensing had many impacts on mapping and cartography. Early in the century, creating small-scale maps necessarily involved compiling the map from larger-scale base maps. The ability to image very large portions of the earth while providing base data much closer to the desired publication scale had a huge practical impact on small-scale mapping of regions and continents. Moreover, faster digital processing methods with a time lag on the order of days or weeks, rather than months or years, meant that frequently updated maps could support a variety of monitoring applications.

GPS accurately locates a receiver using the travel times of signals from several satellites in a larger constellation of GPS satellites. Originally developed by the U.S. Department of Defense to support military activities, including cruise missiles and so-called smart bombs, the system was made available for civilian use in 1983 and was considered fully operational in 1995. The latitude and longitude coordinates calculated by the receiver can be converted to any popular coordinate or projection system, either with the receiving unit or with a GIS. Due to its low cost, portability, data logging capabilities, ease of use, and compatibility with computers, GPS had become by the late 1990s a dominant tool for capturing data for scientific, industrial, and land survey applications. A notable institutional breakthrough occurred in May 2000, when civilian users were given access to an unblurred signal previously available only to the military. GPS redefined how spatial data are captured and how maps are made. For example, in the early twenty-first century the OpenStreetMap project began using GPS to develop copyright-free digital street maps. While clearly an important data capture tool, the increasing ubiquity of GPS and related interfaces also raised the issue of "locational privacy" and the ethics of involuntary satellite-based tracking (Monmonier 2002, 132–39, 175–76).

The second half of the twentieth century also saw a major transformation in the capture and conversion of socioeconomic data (Martin 1991). In general, this change was facilitated by the emergence of the computer and the Internet as the dominant methods, respectively, of data capture and data transfer. Data capture for socioeconomic thematic mapping moved from manual, hard-copy survey techniques to more fully automated digital techniques that supported powerful analytical methods and data integration. A specific example is the Topologically Integrated Geographic Encoding and Referencing (TIGER) system developed by the U.S. Census Bureau (Cooke 1998, 54–55). Building on the Dual Independent Map Encoding (DIME; originally Dual Incidence Matrix Encoding) format (see fig. 227) developed in 1967, TIGER was a technical solution for modeling the topology of the boundary and street networks as well as for converting census data to maps and supporting spatial analysis. This innovation ultimately created a foundation layer for the U.S. Spatial Data Infrastructure and spawned what Donald F. Cooke labeled the "business geographics" industry (Cooke 1998, 49). A member of the original DIME development team, Cooke founded the firm Geographic Data Technology, Inc. (GDT) in 1980. GDT went on to become a major international data vendor. As more and more socioeconomic data became available in digital form, analysts learned to use location as a link for integrating geocoded data sets—examples include credit card purchases, real estate transactions, and magazine subscriptions, all recorded by household, and census data aggregated by block or census tract. Harnessing innovations in data capture and conversion, business geographics provided a strategy for more efficiently marketing products but also raised questions about the impact of these techniques on personal privacy (Monmonier 2002, 140–53).

Starting in 1962 with the development of the first GIS, data conversion became more integrally linked with data capture. A GIS work environment required digital data, and before born-digital data became prevalent in the 1990s, information was made electronically readable by typing it onto punch cards (through the mid-1970s) or magnetic media, by digitizing existing maps with a digitizing tablet to create vector data, or by scanning maps or photographs to generate raster data. Vector data are characterized by the use of coordinates to create geometric elements (points, lines, polygons) in contrast to raster data, which record a phenomenon's presence or intensity at grid cells or pixels arrayed in rows and columns. Each data model has advantages and disadvantages, and most early systems were based on a single model. Because some analytical tasks required both models, more mature systems not only supported both vector and raster data but included algorithms for data conversion. Raster-to-vector conversion computationally creates lines by following similar cells across the array, while vector-to-raster conversion relates the rectangular coordinates of points and lines to the rows and columns of the array, fills in intermediate cells as appropriate, and assigns grid values from an attribute table. Because of the prevalence of multiple data models, a system's capacity for data conversion was a defining issue in geographic information processing through the last four decades of the twentieth century (Montgomery and Schuch 1993).

Data capture and conversion can be categorized into three general eras, with 1900 to approximately 1950 characterized by a relatively small number of highly trained specialists applying time-consuming manual methods to capture primary data focused on local areas and used to produce hard copy printed or one-off products, mostly maps. A transition era from the 1950s to the early 1970 witnessed the advent of digital data, automated cartography, and the analytical processing of geographic information. Although digital computers were used to process data, collection and conversion were primarily based on analog-to-digital conversion. Around the early 1970s, new sensor and information technologies initiated a move to more fully digital processes of data collection and conversion, and the century concluded with the digital transition well under way.

Within this overall pattern the three eras saw several specific transitions, including shifts from analog to digital representation; from manual to automatic processing; from local- to global-scale data capture; from a focus on military and basic mapping to a range of applications including business geographics, environmental monitoring, and location based services (LBS); and from government-driven data capture and dissemination to wide-ranging private-sector programs of data capture and conversion. Indeed, the broad commercialization of geographic data capture and conversion was an important development in the last quarter of the twentieth century and the first decade of the twenty-first. Corporations like Space Imaging (later GeoEye), EOSAT, and RADARSAT International became major data vendors. WorldView Imaging (subsequently EarthWatch) became the first company licensed in the United States to build and operate a high-resolution satellite, ultimately launching the QuickBird satellites. Other companies, notably Navteq and Tele Atlas, built international corporations through the sale of cartographic and other geospatial data. While commercialization added choice and value to the market for geographic data, open-source activities like the OpenStreetMap project challenged the model of spatial data as a commodity by treating it as a public good.

The twentieth century also saw significant technological and methodological advancements, often related to combat and other military applications, while broader technological innovations such as digital computing and the Internet resulted in greater efficiency, new data sources, and the ability of the private sector and individuals to readily capture and convert data. The much-expanded supply of data supported a broad range of applications, including topographic mapping, resource monitoring, socioeconomic analysis, and vehicle routing and tracking, and these applications stimulated new commercial opportunities. Despite the appearance of progress, these applications also raised questions about the consequences of new forms of data capture as a tool for surveillance as well as the implications of a commercially driven spatial-data enterprise.

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SEE ALSO: Canada Geographic Information System; Marketing Cartographic and Spatial Data

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Display Hardware. Computer hardware able to produce a cartographic image, permanent or ephemeral, led the emergence of computer-aided cartography (Monmonier 1985, 145–71) and more generally computer graphics as a form of artistic creativity (Spalter 1999). Electronic digital computers, first developed in the early 1940s for military applications, were used from the mid-1950s onward for operational numerical weather prediction, which generated large amounts of spatial data, which became an incentive for plotting geographic data on line printers in the mid-1950s and for using computer-controlled plotting machines to add isotherms and pressure-surface contours to preprinted base maps in the early 1960s (Harper et al. 2007, 642–44). Meteorology's role in the development of computer-assisted mapping included map-like displays of precipitable moisture on radar scopes in the late 1940s and cartographically enhanced overhead images of clouds captured by TIROS (Television Infrared Observation Satellite) weather satellites, first launched in 1960.

Waldo R. Tobler introduced academic cartographers to computer-generated maps in his short but seminal 1959 article that called attention to the electronic computer's emerging prowess for coping with the mathematical complexities of map projection as well as for drawing maps with a cathode-ray tube (CRT), "much like the tube used in a television set" (529), and with hard-copy devices ranging from the simple computer-controlled typewriter to comparatively expensive hardware for plotting images on film and printing plates. Tobler also identified the distinctly different strategies for making hard-copy maps that came to be known as raster-based and vector-based mapping. Adding symbols to a printed base map could compensate for the poor graphic-arts quality of fast, widely available raster-mode devices like the line printer, which produced a display row by row, like a typewriter. By contrast, the slower and comparatively scarce vector-mode pen plotter could produce reliably more intricate images of boundaries and coastlines represented by strings of x, y coordinates.

The cartographic literature is rich in studies of the uses and limitations of display hardware, which confirm a progression in generally available technology from line printers in the 1960s to color monitors (including laptop computers), color inkjet printers, and high-resolution black-and-white laser printers by century's end. In the 1960s and 1970s display hardware was comparatively expensive and available largely at centralized computing centers, which by the early 1970s usually included a pen plotter. David P. Bickmore, who assessed the state of the art in a short 1979 article, observed that line printers were "very widely available" and drum plotters were "widely available," while storage tubes (CRTs that did not require constant refreshing) were "increasingly" available, refresh CRTs and flatbed plotters had "limited availability," and color displays and high-resolution film writers were comparatively scarce (115–17). Personal computers (PCs), which became increasingly common in homes and offices from the early 1980s onward, were typically accompanied by an inkjet or dot matrix printer, adept at first mostly for printing text or photographs. The PC included a CRT monitor, or later a flat LCD (liquid crystal diode) screen, which fostered interactive graphics, mostly in color since the early 1990s, when sales of inexpensive color inkjet printers and laser printers increased markedly. Although color laser printers were not yet common in university and home offices by 2000, interactive mapping—in color, of course—was widely available to researchers and the public on desktop and laptop computers.

Display hardware for making maps at government offices and universities advanced steadily, albeit fitfully, through several parallel development sequences, which included the replacement of inked ribbons with electrically charged droplets of ink fired at the paper by tiny inkjet nozzles, and replaced in turn by fine particles of black-and-white (and later colored) powder called toner, which was attracted to electrically charged areas on the photosensitive drum of a laser printer, transferred electrostatically to a sheet of paper, and fused into the paper by heat. Geometric positioning of the ink or toner progressed from the computer-controlled striking of the print ribbon by the appropriate letters or other type symbols at each position in a coarse grid of character locations, to the computer-controlled movement of an ink pen or light source across a two-dimensional sheet of paper or photographic film, to the construction of the image, row by row, by laser light on a photosensitive medium with a high-resolution (2400 ppi or better) large-format imagesetter (for producing a film negative or photographic proof) or platesetter (for producing an offset printing plate). Because relatively infrequent use did not justify buying an imagesetter or platesetter, cartographic publishers typically depended on a service bureau or commercial printing house. Labels on maps advanced abruptly from the relatively small characters of the typewriter and line printer to the larger but crude vector-mode lettering of the pen plotter and eventually to comparatively refined high-resolution type reconstructed from stored fonts at any desired typeface, size, style, angle, and spacing. Because of integrated advances in display hardware, mapping software, and cartographic databases, mapmaking without any manual touch-up or other interventions had become the norm by the 1990s in applied geography as well as commercial and government cartography.

MARK MONMONIER

SEE ALSO: Color and Cartography; Geographic Information System (GIS): GIS as a Tool for Map Production; Interactive Map; Reproduction of Maps: Reproduction of Maps by One-Off Processes; Virtual Reality; Wayfinding and Travel Maps: In-Vehicle Navigation System

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Electronic Map Generalization. In its simplest form, cartographic generalization is the graphical modification of features so that their symbols are appropriate for a given scale. It is unlikely, for example, that delineations suitable for 1:50,000 can be displayed at a scale of 1:500,000 without eliminating some features and simplifying, moving, or merging others. Although cartographers have been generalizing spatial information since the first maps were created, efforts to formalize the process have roots in the nineteenth century, well before the digital computer enabled a transition to electronic solutions. In fact, it was the German cartographer Max Eckert who argued in his seminal two-volume work *Die Kartenwissenschaft* (1921–25) that cartographic generalization bridged the artistic and scientific aspects of this process. Eckert realized the intrinsic subjectivity of the process and the key role of human geographical knowledge in understanding how information content changes with map scale. In this vein, he asserted that generalized maps should be treated as products of art clarified by science (Eckert 1921–25, esp. 1:330–39).

Erwin Raisz and Arthur H. Robinson made early contributions to the overall philosophy of map generalization. Raisz, in many of his writings, proposed that generalization had no absolute rules but could be defined as a series of discrete processes, including combination, omission, and simplification. This first attempt to isolate the various steps of generalization would later assist in developing automated approaches. Most of Raisz's examples were remarkable generalizations of the landscape derived by interpreting aerial photographs. Robinson extended the conceptual framework. By the fourth edition of his seminal textbook *Elements of Cartography* (Robinson, Sale, and Morrison 1978), he had identified the major components of the generalization process as simplification, classification, symbolization, and induction.

In the European literature, Lech Ratajski (1967) proposed two different types of generalization: quantitative generalization, defined as a gradual reduction in map content depending on scale change, and qualitative generalization, which results from the transformation of symbolization types, as when two or more point features are aggregated to an areal polygon. Later, Robert B. McMaster and K. Stuart Shea (1992) created a comprehensive model of the process that included philosophical objectives (why generalize), cartometric evaluation (when to generalize), and spatial and attribute transformations (how to generalize) applicable to both manual and digital generalization. Their model included the identification of six theoretical elements that influenced the process: reducing complexity, maintaining spatial accuracy, maintaining attribute accuracy, maintaining aesthetic quality, maintaining a logical hierarchy, and consistently applying the generalization rules.

McMaster and Shea (1992, 3) treated digital generalization as "the process of deriving, from a data source, a symbolically or digitally-encoded cartographic data set through the application of spatial and attribute transformations." A search for appropriate transformations began in the late 1950s and 1960s, when researchers interested in the use of computers for making maps began to explore specific "automated" approaches to map generalization. The most notable pioneer is Waldo R. Tobler (1964), who developed methods for filtering coordinate pairs (line simplification) as well as entire images. From the 1970s onward, much of the research on automated generalization focused on methods applicable to either vector (point-based) or raster (grid-based) data. A primary concern was the identification of the key operations, or discrete processes, amenable to an algorithmic solution. Because of its complexity, electronic generalization was one of the most complicated problems in digital cartography and was still unsolved at century's end.

Data Structures and Generalization Algorithms

During the 1970s and 1980s a number of researchers questioned the relative merits of raster and vector data models, which led to the so-called raster-versus-vector debate. Although the first computerized databases were raster in format and significant amounts of raster-based data had been acquired through remote sensing technologies, vector-based data were considered more map-like and visually appealing. The real debate concerned geoprocessing, in particular the efficiency of the raster data model, with which neighborhood searches such as assessing the relative proximity of geographic features are significantly easier. Determining relative proximity is inherently more complex with a vector model, which requires complex manipulations and many calculations to determine distance between two features. The generalization of raster data often involves the systematic application of kernels (moving windows of a given size such as three-by-three cells or five-by-five cells) in order to determine an average or modal characteristic of the window. This characteristic is then assigned to the center cell as a generalization. By century's end, the increased speed of modern computers as well as the enhanced ease of data storage and retrieval had shifted attention away from the relative benefits of the two data models, and efficient algorithms for conversion between models hastened the emergence of hybrid generalization strategies.

Although advances in computing defused the raster-versus-vector debate, most of the basic operations that emerged in the literature focused on strings of x, y coordinate pairs—vector data. These operations include simplification, smoothing, aggregation, amalgamation, collapse, merging, refinement, exaggeration, enhancement, and displacement (fig. 233). Each of these operations geometrically modifies a feature to enable an appropriate representation at the reduced scale. As noted in figure 233, generalization operations for vector data focus on different geometries—points, lines, and areas. Whereas simplification and smoothing operations focus on linear data, aggregation groups points and amalgamation groups areas. Certain types of operations, such as collapse and refinement, work on multiple geometries. Research has focused on developing algorithms for each of these operations (McMaster and Shea 1992), developing methods to analyze the effectiveness of the algorithms (McMaster 1986; João 1998), and determining the correct sequencing of the algorithms (Monmonier and McMaster 1990). Figure 234 illustrates the consecutive application of simplification and smoothing algorithms when a significant reduction in scale is required.

Perhaps the most energy in finding solutions to automated generalization was spent on line simplification, that is, the weeding out of unnecessary coordinate information. Line simplification algorithms vary significantly in complexity from what are called local independent approaches—for example, weeding out every 3d, 4th, or *n*th point—to those that look broadly at the entire line and seek to retain "critical" points that capture the essential geometry of the feature. This last method was developed by David H. Douglas and Thomas K. Peucker (1973) and has become the standard in field. Although computationally complex, mathematical analyses have demonstrated that the Douglas-Peucker algorithm does indeed retain those points with geometric significance. Many of the methods fall between local independent routines and global routines that eliminate coordinate pairs by evaluating sections of a line, a strategy called extended local processing.

Another area of research focused on the smoothing of coordinate data to remove small crenulations and to improve the aesthetic quality of the line. Algorithms for smoothing have used a variety of approaches, including moving averaging, splining (a curve-fitting approach), and Julian Perkal's rolling ball method (Brophy 1972). A rolling ball smoothes a line by rolling a circle of a given radius along the line and eliminating any portion of the line that is never within the circle (fig. 235). Another common smoothing technique applied a five-point moving average with the "smoothed" point being the middle (3d) point and decreasing weights toward the 1st and 5th in the sequence. Researchers also worked on ways to enhance or exaggerate features, which is equivalent to an inverse smoothing. One of the more interesting projects involved the application of fractal geometry (Dutton 1981) in order to add self-similar detail back into an already generalized feature.

One of the more difficult operations is feature displacement, whereby features that are close to each other are shifted apart in order to avoid overlapping symbols or graphic congestion when map scale is reduced. Consider, for example, three roughly parallel line features—a road, railroad, and river—all passing through a narrow opening between two mountains, as in a water gap in the Ridge and Valley Region of Appalachia. As the scale is reduced, the symbols for these three features would collide and need to be pulled apart (displaced) at the new scale. The problem has three parts: (1) establishing

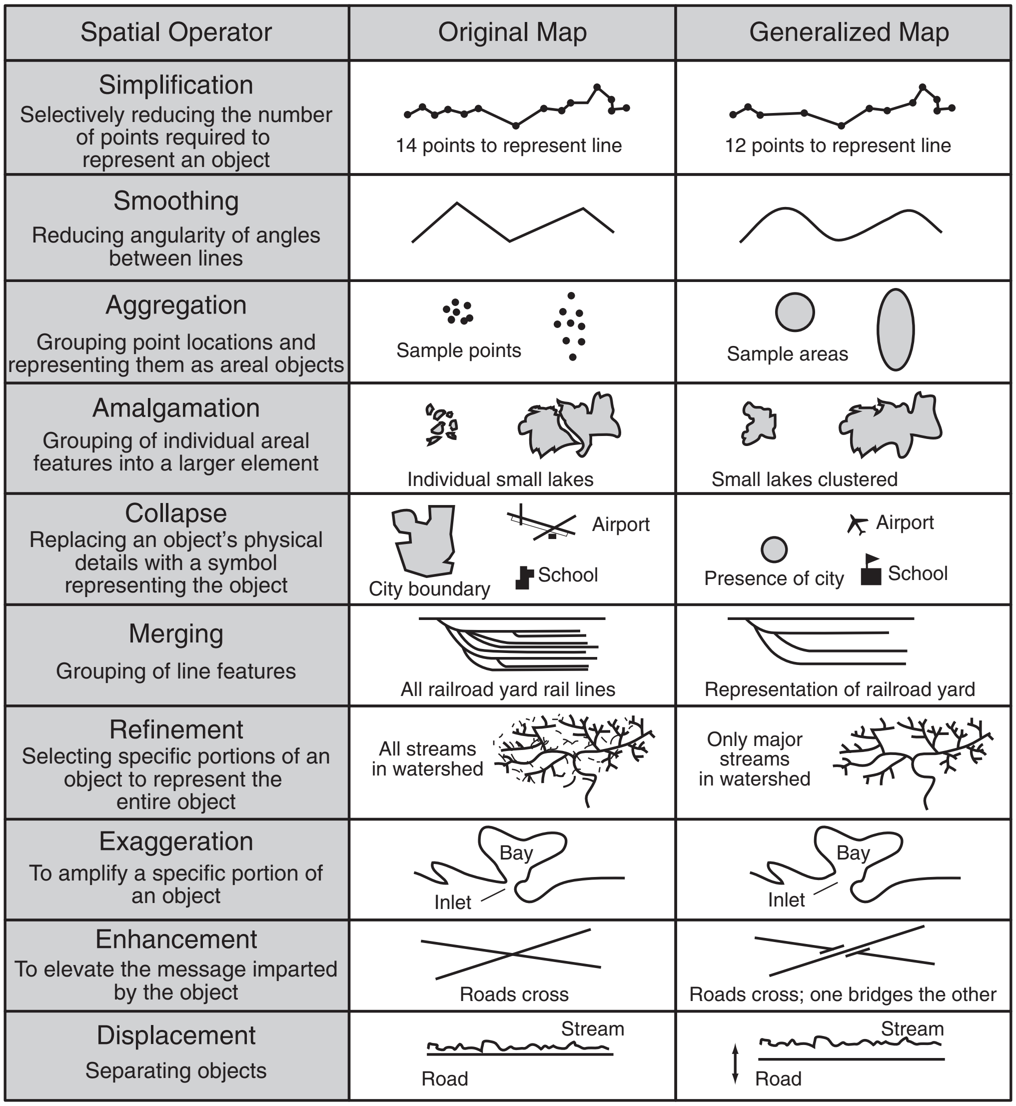

FIG. 233. TEN KEY OPERATIONS IN AUTOMATED CARTOGRAPHIC GENERALIZATION. Based on McMaster and Shea 1992, 55–64.

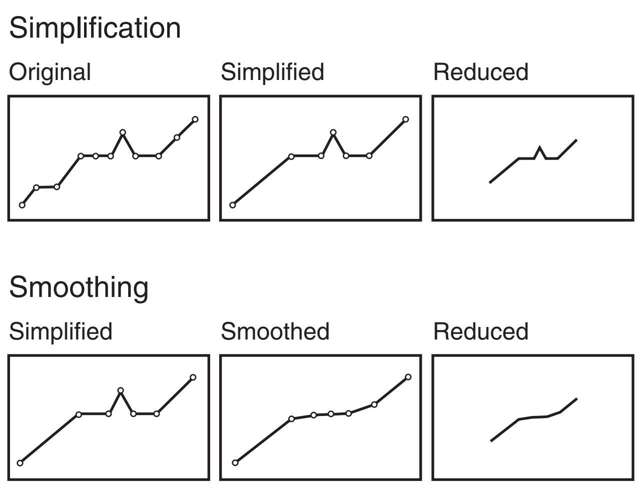

FIG. 234. SIMPLIFICATION AND SMOOTHING. Successive simplification and smoothing operators provide appropriate generalization for a line reduced 50 percent.
Based on McMaster and Shea 1992, 56–57.

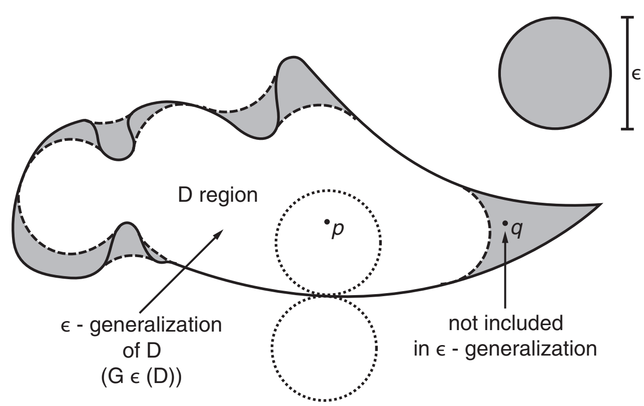

FIG. 235. PERKAL'S ROLLING BALL GENERALIZATION. A circle with diameter epsilon is rolled along both sides of the line in this example. Shaded areas indicate portions of the line never within the circle (point p falls within the circle and is retained; point q is not covered or touched and is eliminated). These portions of the line, which represent indentations into which the ball cannot fit, are replaced by the dashed line. The entire figure is called an epsilon generalization.
After McMaster 1987, 84 (fig. 6).

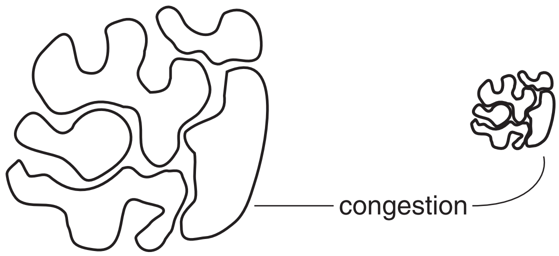

FIG. 236. EXAMPLES OF GRAPHIC CONGESTION WHEN A REDUCTION IN SCALE REDUCES THE SEPARATION OF CLOSE FEATURES.

a priority or displacement hierarchy among the features, (2) computing the distance between features, and (3) pulling the features apart. Figure 236 illustrates the spatial congestion that would occur if nearby features were not displaced. Because displacement is an intrinsically complex spatial process, it is one of the more difficult operations to capture in an algorithm (Christ 1978; Nickerson 1988; Nickerson and Freeman 1986).

Data Classification

Whereas generalization was typically considered a graphical or spatial problem, significant research focused on statistical generalization (also known as data classification), mostly in the context of choropleth mapping and mostly during the 1970s and 1980s. Much of the work involved developing new methods for classification, including a strategy for "optimal classification," and using a variety of metrics to evaluate these methods (Slocum et al. 2009, 57–75). Existing schemes such as equal intervals, quantiles, and natural breaks were scrutinized and new methods such as mean-standard deviation, maximum breaks, and optimal classification were developed and tested. This research suggested that the method of optimal classification, which attempts to model a natural-breaks classification, was most effective for many data sets.

The concept of natural breaks is straightforward. In classifying a data set (perhaps partitioning population density values for the fifty United States into five categories) the map author attempts to minimize variation within the classes and also to maximize the difference between the classes by finding the largest four natural breaks in the data set. Although homogeneous categories separated by prominent breaks are normally discerned by visually inspecting a histogram, the geographer George F. Jenks developed an optimal algorithm, based on the analysis of variance and a process of iterative approximation, to find the statistically ideal set of category breaks. Jenks's iterative algorithm used the goodness-of-variance fit (GVF) metric to assess the quality of the classification at each step and then searched for a better result by shifting the breaks slightly and recomputing GVF. The late 1970s and 1980s witnessed an intense debate over the relative benefits of classed choropleth maps and so-called unclassed maps, in which data values were portrayed by a continuous series of gray tones, believed to obviate the need for a formal classification because data values no longer had to be aggregated to accommodate a small number of discrete gray tones.

Expert Systems and Object Orientation

Work on line generalization algorithms continued into the 1990s, when research endeavors broadened to include the application of rule bases and expert systems to map generalization (Mackaness, Fisher, and Wilkinson 1986; Buttenfield and McMaster 1991). These strategies, mostly applied to topographic maps, brought together researchers from North America and Europe (Muller, Lagrange, and Weibel 1995), who looked at ways to design rules for the process (Buttenfield 1991); apply principles of amplified intelligence, whereby the map author still maintained some control (Weibel 1991); and treat cartographic features as objects with rich attributes, or knowledge, that would enable more efficient, more meaningful electronic generalization. For example, in a "smart" database designed to expedite generalization, a line object could be coded to "know" the level of simplification needed at a reduced scale as well as "know" which other features were so close that graphic congestion might result.

David M. Mark (1991) identified the concepts of entities, cartographic symbols, and digital objects as they pertained to map generalization and also devised a set of rules for object generalization based on, for instance, the area and depth of a bay and the possible social importance of these features. In this example, the decision to eliminate or retain a small bay might consider its relative importance as a coastal feature and whether its area and depth exceeded minimum thresholds for bays on maps of the intended scale. This area of research ultimately developed into agent-based approaches whereby more advanced objects known as agents could trigger even more complicated interactions among cartographic objects.

Although significant progress had been made in map generalization by century's end, the process was still not completely automated, and manual intervention continued to be necessary. Most of the success had been in the area of algorithm development and the generalization of specific topographic maps series, such as France's BD Carto and BD Topo series. Here the problem was made more tractable by standardized methods that considered requirements for a small number of specific scales. Later developments included web-based generalization, which exploited the remarkable speed of computers and enhanced capacity for data exchange to allow the swift delivery of pregeneralized maps, selected from an archive of pregeneralized cartographic databases—maps already generalized for display at a specific scale and delivered rapidly for nearly instantaneous display on a mobile device or vehicle navigation system.

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SEE ALSO: Cartometry; Fractal Representation; Geographic Information System (GIS): GIS as a Tool for Map Production

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Electronic Map Labeling. During the 1970s, as automated cartography became ever more adept at the application of computer graphics technology to the artistic rendering of linework and terrain, attention was increasingly given to the less well-defined problems. One of these, electronic map labeling (also called automated name placement) remained a challenging area of research through the end of the century. Like so many other interesting problems in automated cartography, the aesthetic placement of labels is determined by guidelines rather than rules. Succeeding generations of systems have dealt with various aspects of the problem from the creation of rule bases, data structures, and methodologies to the purely artistic application of the labels themselves.

In both concept and practice, electronic map labeling refers to procedures for fully automatic map-feature annotation. Although numerous digital illustration and map-composition tools offer functions that facilitate the manual placement of map labels, this article focuses on general trends in the development of rule bases, algorithms, approaches, and implementations for fully automated systems. Among various online bibliographies that have helped coordinate research on automated name placement, the Map-Labeling Bibliography maintained by Alexander Wolff, a computer scientist at Karlsruhe University, has been a notably valuable resource.

Most early papers on electronic map labeling relied on an article by Eduard Imhof for their methodological underpinnings. Originally published in 1962 in the *International Yearbook of Cartography* as "Die Anordnung der Namen in der Karte," the article was later translated into English (Imhof 1975). Drawing upon his lecture materials for a course offered on cartography in 1957 at Eidgenössische Technische Hochschule Zürich, Imhof presented a set of rules for placing names for point, line, and area features. Each rule is presented succinctly and is accompanied by one or more clear illustrations of good and bad practices. Without anticipating later work on automated name placement, Imhof presented many of his rules in a way that made them eminently suitable for implementation in an expert system rule base. Directions are given for the placement of labels next to point references, with somewhat flexible preferences given to certain positions of the label relative to its referent symbol and its distance from it. Other types of rules are helpful at a systematic level. One such rule suggests beginning work at the center of the composition and working toward the edges to limit undesirable clustering of labels. Another suggests that placing the names of large areas on the map before placing those for point features will minimize label overlap.

Cartographic guidelines of governmental agencies are another source of rules for electronic labeling systems. One document established numerous labeling rules that have been adopted in various automated systems (U.S. Geological Survey 1980). On the subject of positions for lettering, it suggests prioritized label positions for point features comparable to Imhof's. Similarly detailed instructions are provided for labeling line and area features, with attention given to specific examples of features in each category.

Not until the work of Pinhas Yoeli in 1972 were such rules implemented in electronic labeling systems, and he was one of the earliest to propose an algorithm for automated placement and present a testable implementation (Yoeli 1972). Arguing that 50 percent or more of manual map production involved text placement, Yoeli identified two primary tasks of an automated system: the selection of names from a database and their subsequent placement. Believing the creation of a "universal" geographical name data bank to be beyond the scope of his paper, he focused instead on the second task, the development of label placement algorithms for area and point features.

Yoeli believed that aesthetic solutions for area name placement were more constrained than those for point name placement. As a result, his system processed area names first, using variable letter spacing to expand a name across its referent region. The subsequent placement of names of point features followed, with ordered preferences given to label positions relative to the referent symbol (fig. 237). The system made one pass through the name lists without guaranteeing to place all labels. Those left unplaced were identified for later manual positioning.

Yoeli referred to the placement rules of Imhof and others but chose to implement only those that were practical for the mainframe computing and printing environments of the early 1970s. Other characteristics of his algorithm suggest further deference to the computing realities of the time. Although much of the methodology for his system seems to be drawn from the human cartographic experience, he did not provide a mechanism for repositioning placed labels as commonly practiced in manual cartography. Apart from Lisp or other list-processing languages of the day, few programming languages then supported the recursive mechanisms that simplify those types of backtracking solutions. It would have been possible, though awkward, to do so in FORTRAN. Because Yoeli did not mention the programming language he used, this effect on his implementation is not clear.

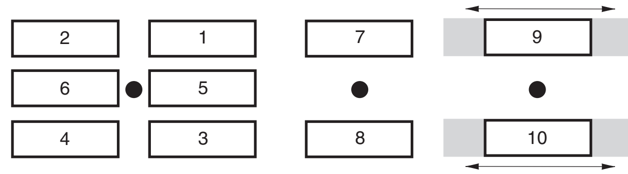

FIG. 237. OPTIMUM POSITIONING OF LABELS FOR POINT FEATURES. Yoeli (1972, 103 [fig. 17]) used the integers 1 to 10 to prioritized label positions for point features: 1 for the most desirable and 10 for the least. Positions 1 through 8 are fixed. Positions 9 and 10 are bands; a label in either position can be nudged along the band to avoid conflicts with other symbols.

During the 1980s, as work in automated cartography migrated from mainframe computers to minicomputers, languages such as C and Pascal became popular development tools for automated name placement. Compared to previous FORTRAN and Basic implementations, C and Pascal offered sophisticated built-in tools for data structure design and recursive function calls. During that period a number of projects concerned with labeling point, line, and area features made extensive use of such programming tools to apply backtracking and other techniques borrowed from work in artificial intelligence.

Constraint propagation, one of the more popular of those techniques, saw the map document as a bounded plane upon which labels competed for space. Stephen A. Hirsch's (1982) point feature placement algorithm used an iterative approach that followed an initial first-approximation placement of labels with a search for overlap. Labeling conflicts were resolved by repositioning an overlapping label along a vector pointing toward an unoccupied position weighted by placement desirability (fig. 238). The procedure ran until no further conflicts were found or until a maximum number of iterations had been reached. Hirsch's approach followed a gradient descent model, characterized by the choice of an operation that provides the greatest improvement at each step. His work foreshadowed the optimization paradigm that came to dominate automated-name-placement research from the 1990s onward.

Herbert Freeman and John Ahn (1984) attempted to localize competition for map space by modeling neighborhoods of labels as a mathematical graph of connected

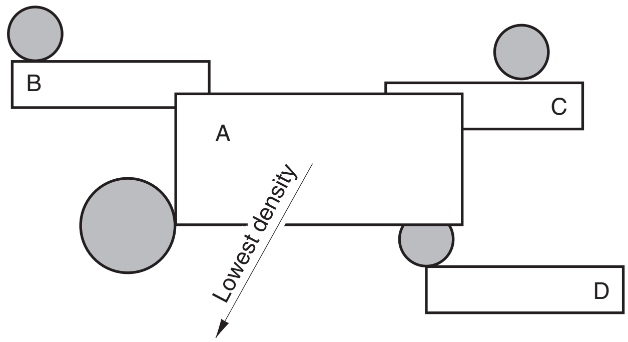

FIG. 238. POSITIONING OF OVERLAPPING LABELS. Rather than using discrete label positions, Hirsch (1982) computed conflict resolution vectors to assign new positions for overlapping labels. For the point symbols represented here, label A overlaps labels B and C as well as the point symbol for label D. The computed conflict resolution vector points to the area below and somewhat left of symbol A as having the lowest local density of labels, and thus providing the best opportunity for a nonconflicting placement.

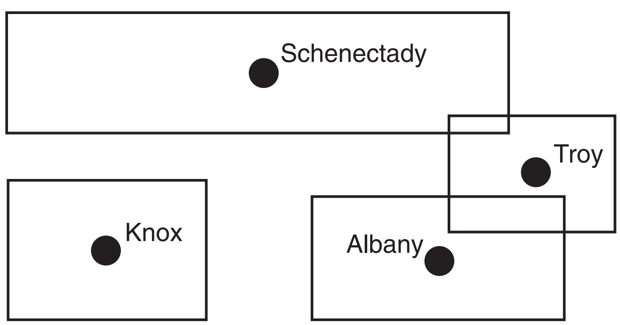

FIG. 239. REGIONS FOR POSITIONING LABELS FOR POINT FEATURES. Freeman and Ahn (1984, 556–60) have modeled overlapping point feature label regions as a graph of connected components. A rectangle around a point feature represents the region of all possible placements for that feature's label. Overlapping regions are noted as connected components and investigated for possible overlaps. In this example, movement of Troy's label must be checked against the positions of those for Albany and Schenectady. The label for Knox is never in conflict and thus never requires checking or repositioning.

components. Two features were identified as neighbors if their regions of possible label placements intersected (fig. 239). Starting with any unplaced point feature label, the procedure chose a position for it and then considered label positions for its neighbors in a "breadth-first" manner by comparing its position with those of "neighboring" labels. Placement within a given neighborhood ended once a suitable position was found for each of the features within it, preventing unnecessary processing in map regions beyond the local neighborhood.

When a fully annotated, finite map space is progressively reduced to a smaller scale, labels begin to overlap with one another, inevitably forcing the cartographer to delete some of the labels and their referent features from the map composition. Practical name placement systems are obliged to perform feature selection as well, through manual intervention or procedural mechanisms. James E. Mower (1986) introduced the use of ancillary data for making selection decisions for populated place features (such as cities and towns) based on their population. Using an object-oriented approach, map entities competed with each other for map space based on their relative importance. Using population as the ancillary-importance criterion, each feature adjusted its label position to avoid conflict with a more important feature. If none could be found, the feature deleted itself, thereby integrating label placement with feature selection, a key task in map generalization. Upon deletion, all of its remaining neighbors would reset their positions to the best possible placement and the competition would begin anew. Since a reset could occur only after the deletion of a feature, placements could not oscillate forever, guaranteeing that the procedure would finish. Mower later adapted this object-oriented system to a single instruction stream/multiple data stream (SIMD) parallel-computing environment in which each processor represented a competing feature and its label.

Rather than work with localized constraint propagation procedures, Robert G. Cromley (1985) proposed a linear-programming relaxation method that modeled the problem as a weight-minimization function. Weights were defined as a ranked placement desirability index from 1 to 6, with 1 indicating the best placement position for a label and 6 indicating the worst. Although not purely automatic in its original form—some user interaction was allowed—he showed that an iterative-relaxation approach to linear programming could provide an efficient solution to the label placement problem. Steven Zoraster (1986) constrained Cromley's linear programming approach to a 0–1 integer-programming problem and, like Cromley, made provisions for human intervention in his prototype.

Jon Christensen, Joe Marks, and Stuart M. Shieber (1992) provided a classification of earlier work in automated name placement that encouraged the introduction of two new methods, the first based on gradient descent and the second on simulated annealing. A simulated-annealing approach provides an optimized solution through the minimization of a system's total energy. Arguing that many earlier techniques required solution times that increased exponentially with the number of data elements, they were among the first to compare implementations of their approaches to those of others, in this case with Zoraster's integer-programming solution and Hirsch's gradient descent approach. They also provided a summary of the algorithmic complexity analysis of the name placement problem, first suggested by the work of Robert J. Fowler, Michael S. Paterson, and Steven L. Tanimoto (1981) on the packing of the plane with rectangles. Their work made a convincing argument for the efficiency of a simulated-annealing approach in particular and for optimization approaches in general.

Hirsch inspired another line of research in automated name placement that developed in the late 1990s. Related to his use of vector-determined placement solutions, this strategy is sometimes called the "slider model." Most of the earlier point feature placement techniques used a discrete-position model, allowing only a finite number of placement positions surrounding a point feature. By contrast, Gunnar W. Klau and Petra Mutzel (2000) adapted Hirsch's continuous-position model to aspects of Zoraster's 0–1 integer-programming approach to create an optimal point feature placement algorithm.

In conjunction with the academic exploration of label placement algorithms, several geographic information system (GIS) manufacturers, most notably Environmental Systems Research Institute (ESRI) and MapInfo, have marketed their own automated placement packages. Maplex, ESRI's in-house offering, was developed from the work of Christopher B. Jones when he was at the University of Glamorgan in Wales. Maptext, an independent company, offered several automated name placement products for specific mapping domains including topographic, bathymetric, and aeronautical applications.

As the 1990s came to a close, the exploration of automated name placement had begun to move beyond the bounds of traditional applications and analyses. Several teams were investigating label placement in virtual and augmented-reality systems while others were finding uses for automated name placement in illustrative work for texts. Name placement research seems certain to grow into new, unanticipated areas with the proliferation of handheld and other mobile platforms offering sophisticated, multiuse graphic displays.

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SEE ALSO: Atlas: Electronic Atlas; Reproduction of Maps: Reproduction, Design, and Aesthetics; Wayfinding and Travel Maps: Web-based Wayfinding

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Computer-Aided Boundary Drawing. Discussed in various contexts as *barriers*, *borders*, or *segments*, boundaries can be defined as the edges of homogeneous areas and regions or as zones of rapid change in a continuous spatial field such as elevation, soil category, or vegetation type. As cartographic features, boundaries are intended to reflect real-world areal entities of scientific or practical significance. From at least the nineteenth century the systematic partitioning of space into geographic regions has been an important undertaking for cartographers, geographers, and planners, and during the twentieth century boundaries were widely used in environmental science and urban management. Epidemiologists have demarcated zones of rapid change in cancer mortality, air pollution, and respiratory illnesses, and government ecologists concerned with wildlife conservation and environmental protection have delineated zones containing endangered species of plants and animals.

Boundary lines are a fundamental element of chorology, the study of causal relationships within geographic regions. Although it might have been introduced as early as the second century A.D. by Ptolemy, chorology languished until its rediscovery and development during the nineteenth century by German scholars, notably Carl Ritter and Siegfried Passarge, which led to wider application during the early twentieth century, when geographers were consulted to mediate political disputes and postwar reorganization, especially in America and Europe (Dickinson 1969). Systematic quantitative techniques for configuring boundaries are rooted in psychologist Robert C. Tryon's work on cluster analysis in the 1930s and statistician William H. Womble's use of composite variables and "differential systematics" to identity narrow zones of great change (Womble 1951). Geographers like William Bunge (1962), who linked regionalization with classification, laid the foundation for computer-based regionalization. Classical methods developed before the early 1960s had emerged mostly from discrete measurements of spatial fields, sometimes analyzed using manual overlays. The greatest advances occurred after the 1970s and reflected substantial progress in computer-aided scientific visualization, remotely sensed digital imagery, and geographic information systems (GIS).

Large spatial data sets inspired the development of numerous quantitative strategies for detecting boundaries (fig. 240). The choice of technique depends on the type of available data—quantitative or qualitative, and collected as regular or irregular points from ground measurements, as a contiguous array of pixels (as a lattice from raster images), or along transects—as well as the type of boundary of interest to the analyst (Jacquez, Maruca, and Fortin 2000). Boundaries that enclose an area are considered *closed*, whereas those that do not are *open*. Well-defined features or phenomena, such as administrative regions, land cover types, forest clear-cuts, and roads, typically have *crisp* boundaries, but when the edges or criteria are imprecise, the boundaries are naturally *fuzzy* (fig. 241). The choice of technique also reflects the analyst's primary interest in either the territory enclosed or the boundary's position. *Areal boundaries* delineate homogeneous areas within which a variable or set of variables has similar values, whereas *difference boundaries* are often open, disconnected, and fuzzy. Naturally occurring phenomena such as shorelines and rivers that flood frequently cannot be precisely defined and have vague or indeterminate boundaries.

These distinctions account for the development of two broad families of boundary detection methods: edge detector techniques and spatial clustering algorithms. Edge detectors are based on a very simple principle: the use of a moving window, or *kernel*, to compute the difference between adjacent locations over the entire raster data set. Difference boundaries become apparent as a chain of comparatively high dissimilarity values. These contact zones can be useful as surrogate boundaries, as when a dissimilarity boundary based on vegetation reflects a boundary between distinctly different soils. By contrast, spatial clustering algorithms group locations based on the similarity of their attributes and the spatial adjacency of the locations. Geographic regionalization is the partition of contiguous areas into a predefined number of regions using edge detectors based on one or more variables that vary across geographic space. (Typical data sets address demographic, socioeconomic, topographical, morphological, ecological, and biological phenomena.) Normative regions, also known as formal or uniform regions, are defined and aggregated according to the uniformity of attribute values, whereas functional regions, also called nodal or analytical regions, are constrained by the phenomena under examination. For example, labor market regions are defined in terms of travel-to-work areas. Analytical regionalization imposes spatial contiguity as a condition of aggregation but does not ensure spatial compactness. Regionalization is further constrained in a *location-allocation problem*, for example, when an area must be partitioned into hospital service districts that reflect both the potential demand

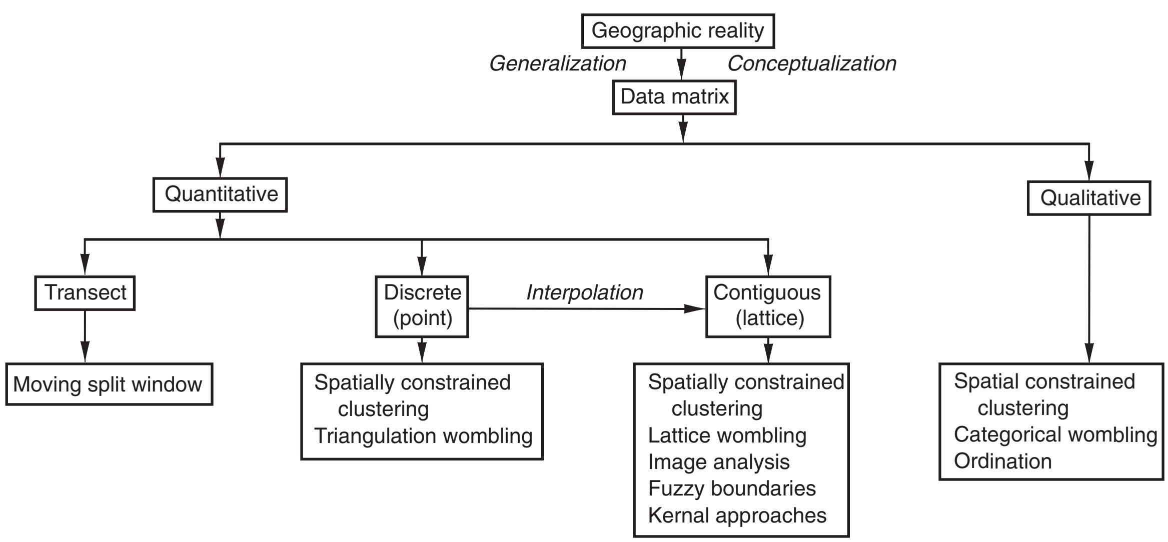

FIG. 240. CONCEPTUAL FRAMEWORK RELATING BOUNDARY DELINEATION TECHNIQUES SUITABLE FOR DIFFERENT TYPES OF SPATIAL DATA.

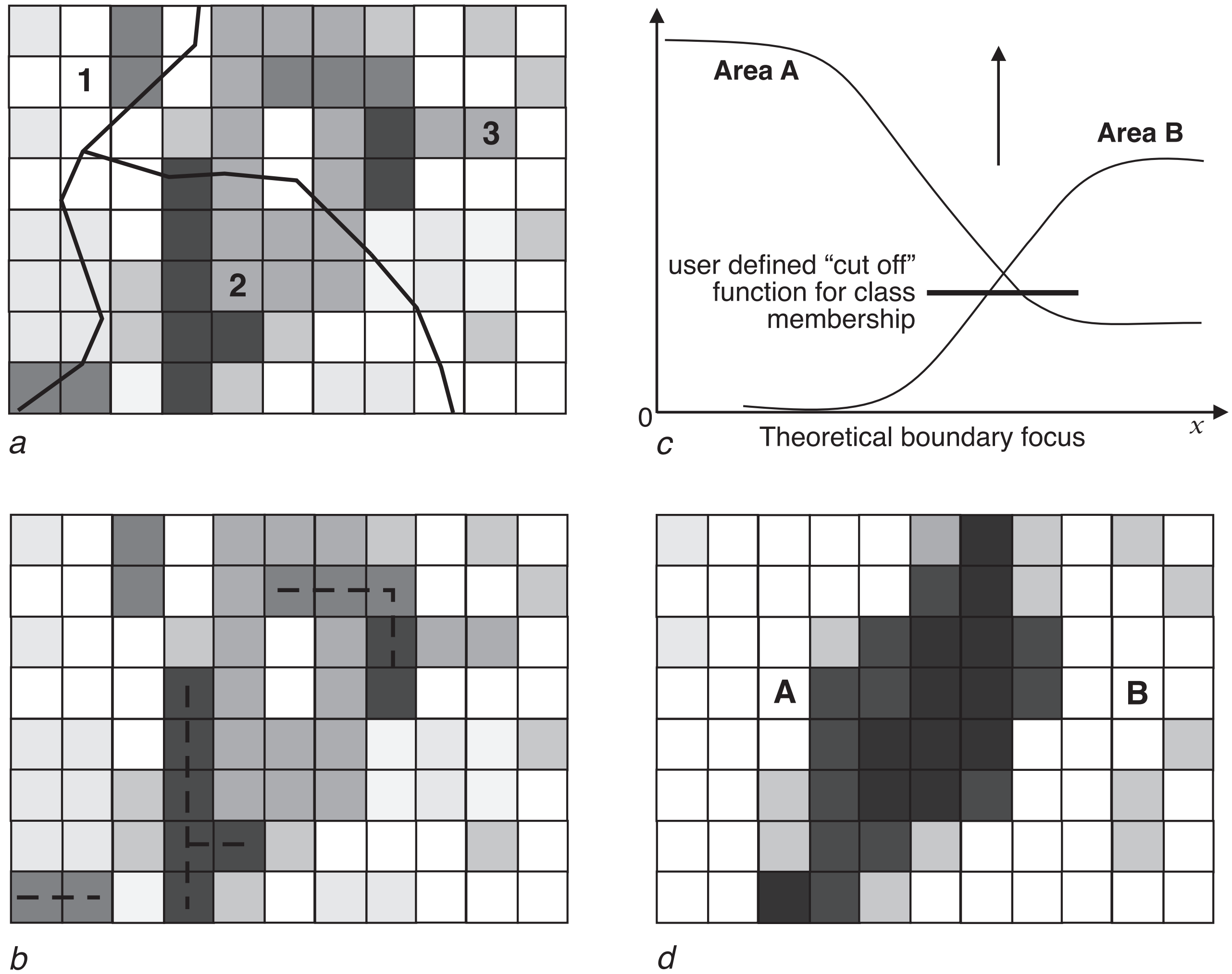

FIG. 241. TYPES OF BOUNDARIES. (*a*) Sharp areal (closed) boundaries separating and partitioning the study area, (*b*) sharp disconnected (open) difference boundaries, (*c*) two-dimensional representation of overlapping membership functions of a fuzzy boundary, (*d*) raster representation of the uncertainty in membership for pixel elements between areas *a* and *b*. The black areas are undefined pixels below the cut-off function shown in (*c*).

for service as well as the locations and capacities of individual hospitals (Ghosh and Rushton 1987). The aggregation criterion in location-allocation problems consists of maximizing regional compactness by minimizing the sum of the product of population density and the squared distance from the centroid of each area to the region center to which it was assigned. In some contexts the formulation also requires exactly equal populations in the regions. By contrast, the maximum-difference boundary method threads boundaries through an area by imposing a boundary between highly different areas (fig. 242).

In remote-sensing applications, image segmentation algorithms localize significant variations in gray level in order to reveal or isolate the underlying physical phenomena (Haralick and Shapiro 1985). Among the many types of operators (kernels) developed to detect the edge using windows of 2×2 or 3×3 pixels are the Sobel operator, the Kirsch operator, the Prewitt operator, the Roberts cross operator, and the Laplacian algorithm. Early methods were gradient-based in the sense of looking for maxima and minima in the first derivative for the image. These approaches were effective in capturing sharp edges but produced wide edges across which gray-scale values changed slowly. To overcome this kind of limitation the Laplacian algorithm searches for zero crossings in the second derivative of the image. Because kernel detectors are sensitive to local noise between adjacent sampling points, which can lead to irrelevant, potentially misleading boundaries, analysts have favored Canny's algorithm or wavelet analysis in such circumstances.

Another way to delimit spatially homogeneous areas on a digital image is to group pixels with similar characteristics into contiguous regions or to "grow" regions from predetermined "seeds" by joining pixels of similar characteristics until the regions meet at boundary zones. While normal clustering methods group data based on similarity in measured attributes, constrained spatial clustering algorithms group sampling locations into clusters based on geographic proximity and the similarity of attributes. Clustering is carried out hierarchically or heuristically, and boundaries are placed between the resulting clusters, thereby yielding a map of bounded areas of relative homogeneity. Hierarchical methods, which are not optimal, either merge *n* observations one at a time or split groups step-by-step, starting from a single group of *n* observations and, unless a stopping criterion is satisfied beforehand, ending with *n* groups. Heuristic methods, such as the *k*-means, seek an optimal partitioning into *k* groups. The *k*-means start with an initial partition of *n* observations into *k*-groups and then swap the individual observations experimentally, relying on an objective function to determine whether a new proposed grouping is better than the best grouping identified thus far.

Lattice delineation operates on lattice (regular) data drawn largely from image analysis (Lillesand and Kiefer 1979). It involves estimating first-derivative surface gradients and then using an arbitrary threshold, usually 10–20 percent of the highest rate, to identify as boundary elements those locations with the highest rate of change, or slope (Womble 1951; Barbujani, Oden, and Sokal 1989). After an initial phase focused on identifying boundary elements, the algorithm then merges adjacent boundary elements sloping in a similar direction. When quantitative data are irregularly spaced, a triangulation edge detector based on a Delaunay network has been used to compute the first derivative on a triangular window search (Fortin 1994). Another strategy, devised by Mark Monmonier (1973), computes the distance or difference across each edge of the Delaunay network and then builds growing barriers outward from the edge with the largest distance by always incorporating the adjacent edge with the largest distance (fig. 242). Monmonier's algorithm has also been used with discrete data to delineate genetic boundaries.

For qualitative data, a categorical edge occurs where a boundary reflects a mismatch, or marked discontinuity, between two adjacent sampling units. This boundary segment is then extended to provide a composite picture of barriers from several variables. A limitation of these edge detectors is their use of an arbitrary threshold to determine which rates of change qualify as boundaries. For this reason, spatial clustering and *k*-means techniques have been favored.

Boundaries are sometimes conceptualized as more gradual, comparatively fuzzy zones, rather than as crisp, sharp lines. Some researchers have proposed a so-called fuzzy classification strategy based on fuzzy set theory to overcome problems encountered in applying a deterministic approach to detecting or delineating real-world

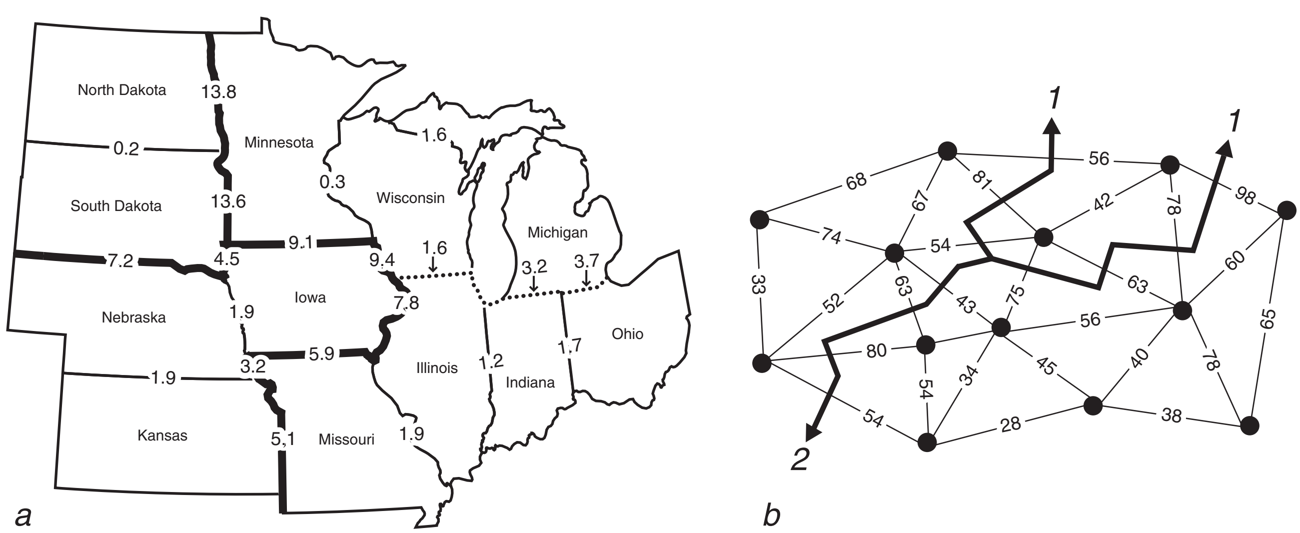

FIG. 242. CREATING MAXIMUM-DIFFERENCE BARRIERS USING MONMONIER'S ALGORITHM ON REGIONS AND IRREGULARLY SPACED POINT DATA. (*a*) North-central states barriers of the United States based on percentage population increase, 1960–70 (modified from Monmonier 1973). Numbers indicate the value differences between contiguous states. Different styled boundaries indicate partitions of the study area. (*b*) Once a triangulation between population (solid dots) is obtained (solid lines), the edges are associated with pairwise distance measures according to the distance matrix.

boundaries (Burrough and Frank 1996). These classifications seek to determine a membership function, which assigns a pixel to a particular land cover class by a numerical measure of likelihood or plausibility, defined to range between 0 and 1. Category membership is determined by general relationships, definition rules, or experimentation (fig. 241 *c* and *d*).

Development of algorithms for computer-aided boundary drawing reflects the concurrent emergence of quantitative spatial analysis and heuristic programming in the latter half of the twentieth century. Maps and aerial imagery provided basic data for boundary-drawing procedures, and maps were important in displaying, evaluating, and presenting the results.

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SEE ALSO: Administrative Cartography; Electoral Map; Exploratory Data Analysis; Planning, Urban and Regional; Software: Geographic Information System (GIS) Software; Statistics and Cartography

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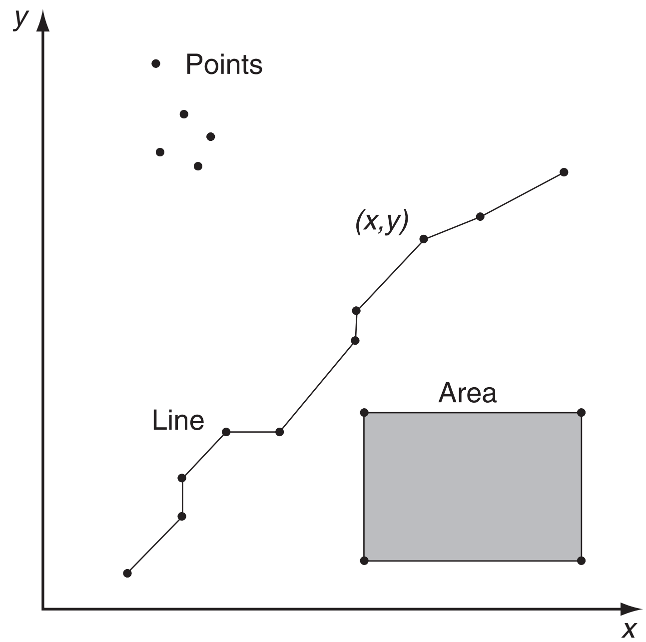
Intellectual Movements in Electronic Cartography. The term *electronic cartography* is synonymous with both digital and computer cartography, which emerged in the 1960s and 1970s, when mapmaking metamorphosed from a set of manual techniques to automated data capture, geoprocessing, and display technologies, the implementation of which inspired multiple streams of conceptual thinking. Many of the methods were developed for vector-based and raster-based modes of representation, which were sufficiently distinct to trigger a prolonged and often heated debate about workability and importance. The vector-based method represents a conventional, predigital map with separate *x, y* coordinate pairs for point features, strings of points for line features, and sets of linked strings that enclose area features. By contrast, the raster-based approach relies on images of picture elements or pixels organized as a matrix, in which each pixel represents one or more data values. Although hybrid methods eventually made this distinction less meaningful, much of the work from the early 1960s to the end of century focused on one of these two modes of representation.

Two significant advances for capturing digital cartographic data were digitizing and scanning. Digitizing used an electronic tablet to record discrete *x, y* coordinate pairs. A system of fine wires beneath the surface of the tablet that recorded coordinates as the operator followed a manually derived feature—normally on a paper map attached to the top of the tablet—with a puck, also called a cursor. Whenever the operator pressed a button, the digitizer recorded the puck's exact location. Digitizers often allowed both point-mode and stream-mode recording. In stream mode, the button was held down as the operator traced the map feature, and the digitizer recorded a string of coordinates. By contrast, the earliest digital scanners developed for capturing raster data consisted of a rotating drum and a scanning head. The map was attached to the drum, which rotated at a high speed while the scanning head, which measured the intensity of light reflected from the map, moved slowly along the top of the drum to record the image as lines of pixels. The result was a matrix of pixels, sometimes coded as 0s for blank parts of the map and 1s for pixels representing part of a line, label, or other symbol. Figure 243 depicts the two types of data.

Electronic digitizing and scanning not only revolutionized spatial data capture but established two basic models—vector and raster—for representing spatial data. The vector model, based on lists of *x, y* coordinates, could be enhanced by supplementary lists describing the topological structure of the digital map's constituent features. Nontopological vector data were often called spaghetti data because they consisted simply of unconnected strings of coordinates. Spaghetti files were easily and quickly plotted, but a list of coordinates describing a linear feature's position and shape says nothing about other map features it intersects or separates. By contrast, a topological data structure included informa-



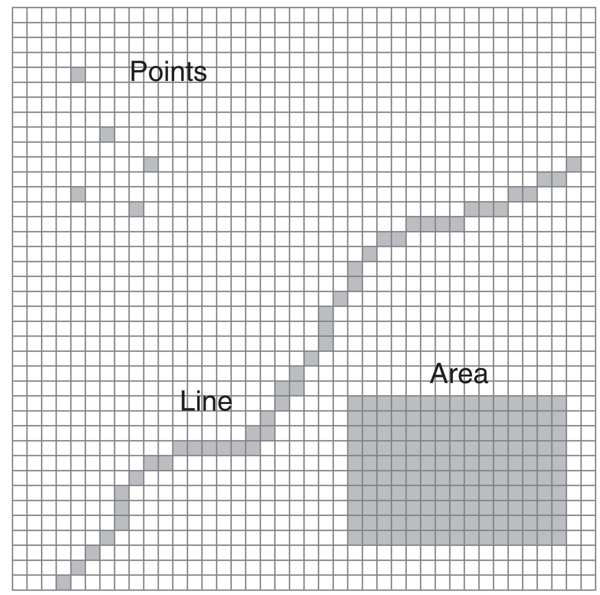


FIG. 243. EXAMPLE OF VECTOR (LEFT) AND RASTER (RIGHT) DATA.

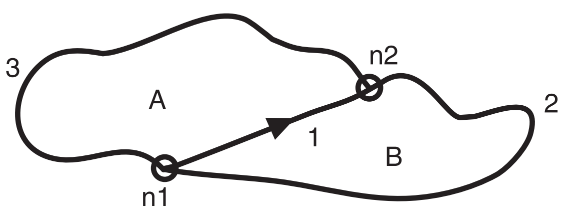


FIG. 244. TOPOLOGICAL DATA STRUCTURE.

tion about a feature's neighbors—the areas that adjoin along a common boundary, for instance, or the streets that meet at specific intersections.

Figure 244 depicts the fundamentals of a topological data structure, which consists of polygons (geographical areas) bounded by arcs (chains of straight-line segments that run in a specific direction from a beginning ["from"] node to an ending ["to"] node). In this example polygons A and B are separated by arc 1, which in turn is bounded by its end points, nodes n1 and n2. Direction is important insofar as when arc 1 is described as running from n1 to n2, A lies to its left and B lies to the right. A node is a single *x, y* coordinate pair representing the beginning or end of the linear feature, or arc. This information is represented in a database by an arc record that consists of "from" and "to" nodes (n1 and n2 in this example) as well as the "left" and "right" polygons (A and B). When software reconstructs a polygon's geometry, each of the individual arcs that surround the polygon are pulled from the file and chained together. In this example, software can also determined that polygons A and B share a common boundary (arc 1), and thus are neighbors. A typical spatial database would consist of thousands of similarly structured arc records.

A raster data structure is markedly more simplistic. Each of the pixels (cells) in the raster represents a certain area on the earth's surface, for example, a quadrilateral thirty meters on a side in a Thematic Mapper image. For some raster data, especially an image scanned from an existing map, each pixel might represent merely the presence of a feature, such as a road, boundary, or contour line (fig. 245). By contrast, for a raster consisting of categorical data, as with a land use/land cover map or satellite image, each pixel typically contains a number representing the corresponding data category. In a geographic information system (GIS), several raster maps might be stacked to produce a map overlay, whereby each pixel is defined for each of the superposed maps. For example, a single pixel representing a specific location in the region might contain values representing the location's census tract number, land cover, and political jurisdiction.

Vector and raster data structures each have distinct benefits and liabilities. Vector data better represents the map-like image that many readers expected, whereas a raster image is often easier to process and display. The verisimilitude of the raster image depends on its resolution: a coarse raster image can often seem grainy unless image processing techniques are used to smooth the image, but a fine-grained raster image can require

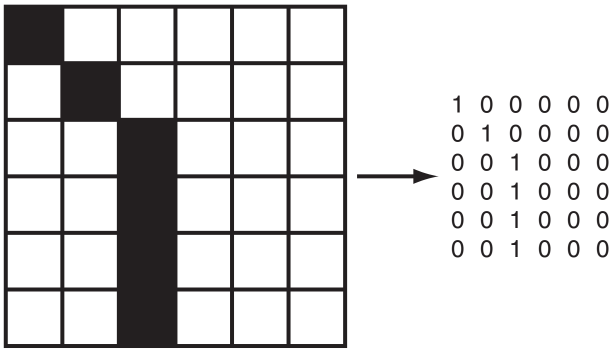


FIG. 245. TYPICAL RASTER IMAGE.

a huge amount of electronic memory. Vector structures are inherently more complicated and require significant processing time to chain the polygons in the topological data model. By contrast, the raster model has a straightforward, intrinsic topology in which the proximity of pixels is readily apparent.

One of the most difficult problems in the transition to electronic cartography was the generation of appropriate map symbols. Computer algorithms had to be devised for shading choropleth maps, creating graduated circles, placing dots on dot distribution maps, and threading contour lines and isarithms across maps representing three-dimensional surfaces. Much of the research in the 1970s and 1980s involved solving various problems related to computer-generated symbolization (Monmonier 1982, 45–52). When the principal display device was a pen plotter capable only of drawing thin, equally thick lines, the creation of choropleth shading was a complicated process. The basic choropleth-shading algorithm required filling a polygon with lines spaced to represent a gray value. The narrower the spacing between lines, the darker the gray value. Cross-hatched patterns, considered more visually pleasing, required the calculation of shading lines in two orthogonal directions, normally along the principal diagonals. Even so, the mathematical underpinnings were straightforward and required the calculation of intersection points between the polygon boundaries and shading lines.

In the late 1970s and 1980s the ability to vary the spacing of the shading lines led to a major philosophical debate over the efficacy of unclassed choropleth maps, whereby the choropleth shading—percentage of blackness—was made directly proportional to the data value, thus obviating the need for any formal data classification (Tobler 1973). Many cartographers believed that classification was a necessary form of generalization and made the geographical patterns understandable. Others (e.g., Brassel and Utano 1979) argued that a one-to-one relationship between data and symbolization was desirable and more accurate for the map reader. Although it was easy to judge which of two adjacent polygons on an unclassed map had the higher value, the need for a highly complex map key made it difficult to estimate the numerical value for a particular polygon.

A second major challenge was the electronic calculation of isarithmic symbols through a process of spatial interpolation, which typically involved overlaying a regular grid (raster) on a set of x, y, z values, each representing the location x, y on a plane of an elevation or statistical value z, such as rainfall. An interpolation algorithm would then estimate new values at the intersections of principal grid lines, perhaps by first determining the closest n data points for each grid intersection and then calculating an average z for these data points. The most common method, called distance-weighting interpolation, was to weight each z-value's contribution to the average according to the inverse of its distance from the grid intersection; closer data points thus had a greater influence than more distant ones. Some algorithms also considered local trends in data values and even allowed trend-based extrapolation above or below a local maximum or minimum. The SYMAP program, distributed by the Harvard Laboratory for Computer Graphics and Spatial Analysis, was noted for its comparatively sophisticated interpolation process (Shepard 1968). At the same time, significant research focused on developing and comparing different approaches for spatial interpolation and surface mapping (Davis 2002). Research also concentrated on other forms of symbolization, including graduated circles, cartograms, and dot distribution mapping.

Another intellectual challenge was automated label placement, which used computer software to replicate and thus replace a tedious manual process highly important to topographic and general reference maps. Solutions depended heavily on feature geometry. With point symbols, for instance, a set of rules could try out various preferred positions for labels and make suitable adjustments if overlapping labels resulted. If space were available and no overlap imminent, a label was typically placed to the upper right of the point symbol. For polygon features, the label was positioned within the feature and parallel to its principal orientation, for example, along a north-south axis for Lake Michigan and an east-west axis for Lake Superior. Automated label placement was comparatively difficult for linear features, especially geographically complicated streams or rivers. An acceptable solution normally required the computation of a set of vectors along the feature's axes so that a suitably offset label could be generated parallel to the feature's symbol.

One of the major research areas was automated generalization, whereby digital features were smoothed, merged, aggregated, amalgamated, displaced, and sim-

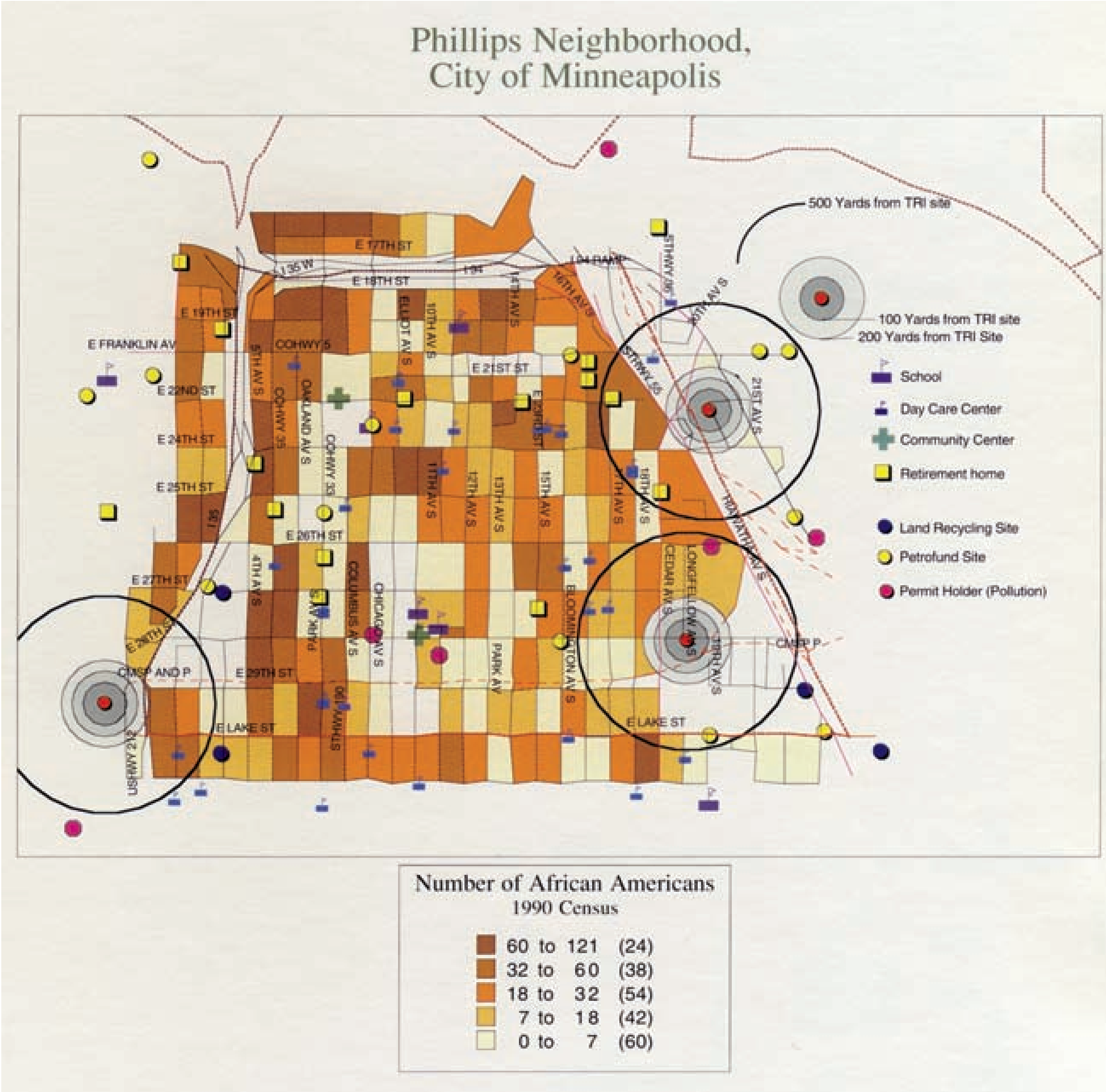


FIG. 246. ENVIRONMENTAL JUSTICE STUDY OF THE PHILLIPS NEIGHBORHOOD OF MINNEAPOLIS, MINNESOTA.
Size of the original: 15.1 × 15.4 cm. From Robert B. McMaster, Helga Leitner, and Eric S. Sheppard, "GIS-Based Environmental Equity and Risk Assessment: Methodological Problems and Prospects," *Cartography and Geographic Information Systems* 24 (1997): 172–89, esp. 187 (fig. 9). Permission courtesy of the Cartography and Geographic Information Society (CaGIS).

plified to accommodate display at a smaller map scale. Much of the work focused on line simplification, for which myriad methods were developed for eliminating unnecessary coordinates or crenulations. Some of these methods were quite straightforward, such as eliminating every second or third point. Others, such as the Douglas-Peucker technique, processed the line holistically and recursively identified critical points along sections of the feature (McMaster 1987, esp. 94–95). Algorithms were typically developed and tested separately for each generalization operation, such as simplification or smoothing, but later work attempted to look at the proper sequencing of multiple operations and use expert systems to guide the generalization process. Much of the research and implementation in electronic map generalization in the 1990s was completed by Europe's national mapping agencies, notably Britain's Ordnance Survey and France's Institut géographique national, both of which had research units to identify and solve the conceptual cartographic problems as well as production units able to implement the solutions.

During the 1990s it became clear that electronic cartography and GIS would have major effects on society. These systems were increasingly used for natural resources assessment, urban and transportation planning, and geodemographic analysis as well as for monitoring environmental pollution, regulating emissions, and evaluating public health and access to a broad range of medical and social services. As the intellectual center of electronic cartography shifted from algorithms to impacts, geographic information professionals as well as academic cartographers addressed issues involving public access, empowerment, intellectual property, privacy, and the ethical use of maps and spatial data.

Broadly defined, these issues inspired the "GIS and society" debates in which cartographers, geographic information scientists, and industry advocates argued for the benefits of these technologies and a group of self-identified critical human geographers and social theorists emphasized possible negative effects (McMaster and Harvey 2010). Although rhetoric was intense on both sides, one of the primary arguments against the increasing use of GIS was the persuasive power of electronically produced maps. Some asserted that such maps provided a false sense of authority since they were viewed as scientific and unbiased. Critics thought such representations would empower public officials at the expense of neighborhoods and disadvantaged groups. A positive direction of the debates about GIS and society led to the creation of public participation GIS/mapping as an academic specialty concerned with promoting a broader, more effective use of GIS by the general public as well as by community and grassroots groups. Figure 246, an example of the use of electronic cartography and GIS by community organizers, depicts the relationship between the distribution of toxic sites, the African-American population, and major public institutions in the Phillips neighborhood of Minneapolis, Minnesota. Such maps raised questions of social justice insofar as racial minorities often endure unusually high exposure to toxic materials.

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SEE ALSO: Academic Paradigms in Cartography; Map: Electronic Map; National Center for Geographic Information and Analysis (U.S.); Public Access to Cartographic Information

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Conferences on Computer-Aided Mapping in North America and Europe. Cartographic conferences held in the United States and Europe during the 1970s and 1980s played a key role in disseminating information about existing and potential uses of computing technology in mapmaking. In bringing together researchers and users from academia, the geospatial industry, and government at all levels, these conferences were inspirational as well as educational, promoted networking across disciplinary boundaries, and provided a more cartographically focused alternative to the meetings of professional organizations focused on computer science, geography, photogrammetry and remote sensing, regional planning, and surveying and mapping. Conference proceedings, typically available for distribution at the meeting, were an expeditious outlet for academic researchers as well as a supportive publishing opportunity for developers and government employees intimidated by refereed journals favoring theory or systematic analysis. With hundreds, if not thousands, of attendees, these conferences were also a magnet for exhibitors, who paid handsomely for the opportunity.

The most prominent cartographic conference was the Auto-Carto series, the first two of which were convened in Reston, Virginia, home of the U.S. Geological Survey (USGS), in 1974 and 1975. USGS helped organize the meetings and publish their proceedings. The venue moved to San Francisco in 1978, returned to Reston in 1979, and shifted in 1982 to nearby Crystal City, which had more adequate hotel accommodations. After Auto-Carto 6, held in Ottawa in 1983, the conference returned to Washington, D.C., in 1985, and continued as a biennial event sponsored jointly by the American Congress on Surveying and Mapping (ACSM) and the American Society for Photogrammetry and Remote Sensing (ASPRS). Auto-Cartos 9, 10, and 11 were held in Baltimore, about thirty miles north of Washington, D.C., but not far from the center of federal mapping operations, and Auto-Cartos 11 through 13 were convened in Minneapolis (1993), Charlotte (1995), and Seattle (1997). The Auto-Carto label had lost luster by the early 1990s, when cartography and geographic information systems (GIS) were undeniably "auto," and most of the Auto-Carto meetings during the 1990s were additions to a regular ACSM/ASPRS meeting, albeit with a separate program and an extra registration fee. (A decade and a half later, the Cartography and Geographic Information Society, which split off from the ACSM in 2004, revived the brand by holding the 2014 AutoCarto International Symposium on Automated Cartography in Pittsburg.)

Auto-Carto attracted presenters and participants from outside North America, principally from the British Isles, where the organizers of Auto Carto London, who borrowed the brand in 1986, drew large numbers of presenters from North America and Continental Europe. By contrast, the first and fifth European GIS (EGIS) conferences, held in Amsterdam in 1990 and Paris in 1994, had a distinctively European audience, with comparatively few North Americans (Rhind 1998, 302). Auto Carto London was a more ambitious but less durable venture than the Euro-Carto conferences, initiated by David P. Bickmore, founder of the Experimental Cartography Unit at the Royal College of Art, and convened at Oxford in 1982, Oslo in 1983, Graz in 1984, Frankfurt am Main in 1985, Paris in 1986, Brno in 1987, Mallorca in 1990, Warsaw in 1991, Oxford again in 1992, Kiruna in 1993, Copenhagen in 1994, and Ispra in 1995. By the late 1990s cartographic conferences had become frequent worldwide because of enterprising national organizing committees as well as the International Cartographic Association and the United Nations, which sponsored regional cartographic conferences in Africa and Asia.

This proliferation of conferences on computer-aided cartography (and later, on GIS) is apparent in the success of the biennial International Spatial Data Handling Symposia, initiated in Zurich in 1984, and the GIS/LIS series—LIS means land information systems—held annually between 1987 and 1998 (Samborski 2008). Other groups with agendas related to computer-aided cartography met regularly in the 1980s and 1990s; particularly noteworthy are AM/FM (Automated Mapping/Facilities Management) International and ACM SIGGRAPH, the Association for Computing Machinery's special interest group concerned with graphics.

Although the computer-aided mapping conferences of the 1970s and 1980s were distinctive in their impact on the emerging technology, they had several noteworthy precursors, including the twice-yearly meetings of the ACSM and the ASPRS, the yearly meetings of the Urban and Regional Information Systems Association (URISA), and the International Geographical Union's Commission on Geographical Information and Processing, active for twenty years, starting in 1968, under the direction of Roger F. Tomlinson (Foresman 1998).

The most prominent forebear was the SYMAP training conference held at Harvard University's Laboratory for Computer Graphics on 8–19 May 1967 (Horton and Tiedemann 1967). From 1977 into the late 1980s the Harvard laboratory held its own cartographic conferences and related symposia, which focused on the concerns of users, who were more numerous (and collectively more lucrative) than researchers. Attesting to the value of a large audience of software users, the most prominent successor to Auto-Carto is the annual ESRI User Conference, initiated in 1981 and held in San Diego, California, about 100 miles from company headquarters in Redlands.

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SEE ALSO: *International Journal for Geographical Information Systems/Science*; Journals, Cartographic; Societies, Cartographic; Societies, Geographical: Geographical Societies in Canada and the United States; Societies, Map Librarianship; Societies, Photogrammetric and Remote Sensing

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Conferences on Computer-Aided Mapping in Latin America. The widespread diffusion of digital mapping in Latin America is closely linked to the introduction of geographic information systems (GIS) to the continent in 1987, when the first Latin American conference on computers in geography, now known as Conferencia Iberoamericana de Sistemas de Información Geográfica (CONFIBSIG), took place at the Universidad Nacional de Costa Rica, under the auspices of the International Geographical Union. This meeting triggered the transfer of GIS technology to the countries of the region, which, as figure 247 shows, had been lagging behind the more developed world. Twenty-three years had elapsed between the emergence of the Canada Geographic Information System (CGIS), arguably the first GIS, in 1964, and the first donation of GIS software to academic insti-

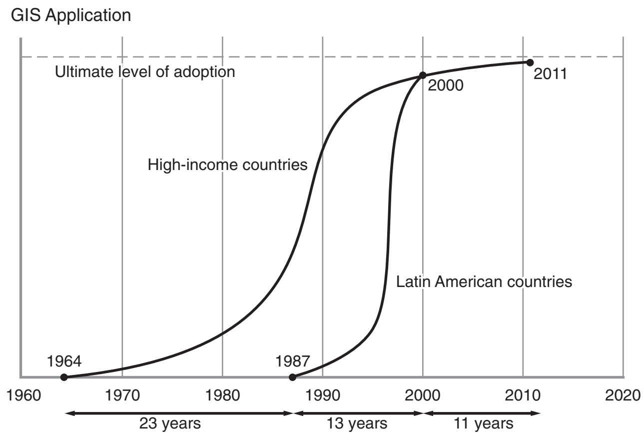

FIG. 247. CUMULATIVE FREQUENCY CHART COMPARING THE RELATIVELY EARLY ADOPTION OF GIS TECHNOLOGY BY HIGHER-INCOME WESTERN COUNTRIES WITH ITS LAGGING ADOPTION IN LATIN AMERICA. Vertical axis represents the proportion of adoptions as the adoption rate converged on an ultimate level. Intersection of the two curves shows that Latin American countries caught up with the West around 2000.
After Gustavo D. Buzai, *La exploración geodigital* (Buenos Aires: Lugar Editorial, 2000), 12.

tutions in Latin America in 1987, when Ohio State University offered its OSU MAP-for-the-PC map analysis package to several Latin American universities. Because of accelerated adoption during the 1990s, by the end of the century Latin America had almost attained the level of sophistication in geospatial hardware and software common throughout the global north.

The short history of GIS and digital mapping in Latin America is best reflected by the increasing maturity of technical and scientific presentations and vendor exhibits at the biennial CONFIBSIG as well as the meeting's diverse venues (table 13). Unlike those in North America, all of these meetings were hosted by universities.

Major Latin American academic and government institutions involved in map production participated in CONFIBSIG. The resulting publications reflect two broad themes, each encompassing slightly more than a decade. From 1987 to 1999, a period of accelerated adoption, technical papers focused on the implementation of hardware and software as well as the training of technical and professional workers. By contrast, from 2000 to 2011, CONFIBSIG publications reflect a shift toward a broadened range of applications and a growing use of mapping software. During this period, Brazil emerged as a leading regional developer of software and also achieved prominence for its undergraduate and graduate programs in GIS.

National meetings on GIS emerged in the 1990s, most notably the Simposio Argentino de Sistemas de Información Geográfica (1990); the Simposio Brasileiro de

TABLE 13. Locations of CONFIBSIG biennial conferences

1987	Universidad Nacional de Costa Rica, San José
1989	Universidad de Los Andes, Mérida, Venezuela
1991	Pontificia Universidad Católica de Chile, Viña del Mar
1993	Universidade de São Paulo, Brazil
1995	Universidad Nacional de Cuyo, Mendoza, Argentina
1997	Universidad Nacional Mayor de San Marcos, Lima, Peru
1999	Universidad de Los Andes, Mérida, Venezuela
2001	Centro Universitario La Salle, Porto Alegre, Brazil
2003	Universidad de Extremadura, Cáceres, Spain
2005	Universidad de Puerto Rico, San Juan
2007	Universidad Nacional de Luján, Buenos Aires, Argentina
2009	Universidad Nacional de Costa Rica, Heredia
2011	Universidad Autónoma del Estado de México, Toluca
2013	Universidad Nacional Autónoma de Honduras, Tegucigalpa
2015	Pontificia Universidad Católica de Valparaiso, Chile [planned]

Buzai and Robinson 2010, 13.

Geoprocessamento (1990–97); the GIS Brazil conference (1994–2004); GEO Brazil (2000–2010); and the Semana Geomática, in Colombia (2005–9). GIS Day, supported by local and regional offices of Environmental Systems Research Institute (ESRI) around the world, also was adopted in Latin America.

Like other cartographic conferences, these meetings typically discussed and adopted resolutions on professional priorities. Until 2000 these conference resolutions were relatively specific and focused mainly on systems operation, but after century's end they became more general with a focus on increased cooperation to promote the diffusion and application of GIS within Latin America.

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SEE ALSO: *International Journal for Geographical Information Systems/Science*; Journals, Cartographic; Societies, Cartographic; Societies, Map Librarianship; Societies, Photogrammetric and Remote Sensing

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Electronic Map. See Map: Electronic Map

Emergency Planning. Population movement from rural areas into cities during the twentieth century created a need for disaster planning by national, regional, and local governments. The resulting field of emergency management has been defined by homeland security expert Claire B. Rubin as "the management of the governmental and nongovernmental preparedness and response at federal, state, and local levels, including non-governmental organizations (NGOs) to unplanned events that affect public health and safety and that destroy property" (Rubin and Colle 2005, 2). Typically framed as a sequence of four key phases—prevention, preparedness, response, and recovery—emergency management also includes mitigation efforts to reduce the severity of an extreme event as well as to make recovery more rapid and effective. Although this entry focuses on emergency planning in the United States, the principles and products discussed can be found throughout the world, albeit more commonly in economically advanced nations.

Planning evacuations or otherwise shielding citizens from extreme natural events, technological hazards, or terrorist attacks is impossible without maps. Key emergency planning tasks that depend upon maps include delimitation of the affected area; coordination among local, state, and federal officials; communication among responding agencies; evacuation and sheltering, with appropriate attention to schools, hospitals, nursing homes, and other special-needs facilities; modeling the potential impact of geographic phenomena such as earthquakes, severe coastal storms, and nuclear accidents; positioning supplies and other resources; law enforcement communications; and risk communication with the public. In mitigating or responding to a disaster, any maps held by local governments, from road maps to sewer system diagrams, may prove useful (Dymon 1994). Private-sector data, most notably the site plans of large industrial plants using potentially explosive materials and the facilities maps of gas, electric, and telecommunications companies, can also be useful.

At the turn of the twentieth century, the fire insurance map was the most focused cartographic approach to disaster planning. Compiled principally for use by insurance underwriters in distant cities, fire insurance maps were city plans drawn at scales of 50 to 100 feet to an inch. The most prominent producer was the Sanborn Map Company, which mapped more than 12,000 U.S. cities between 1870 and 1950. Maps were updated regularly and provided detailed information about buildings and their surroundings, including construction material (e.g., wood, brick, stone); height; number of stories; locations of doors, windows, chimneys, and elevators; use of the structure; street address; lot lines; street width; and water sources, including water pipes, hydrants, and cisterns. Because the maps represented diverse factors affecting relative risk, a local fire insurance firm could share its liability and premiums with insurers elsewhere and thus avoid being wiped out by a major conflagration.

Chemicals stored on site or dispersed across a wide area were originally considered a hazard only if they were explosive or readily combustible. In the latter half of the century, biologist Rachel Carson described the threat of DDT and similar pesticides in her best seller *Silent Spring* (1962) and awakened citizens to a range of environmental hazards. Public awareness of the deteriorating conditions of land, air, water, and biota peaked in 1970, when the first Earth Day created an impetus for important federal environmental laws. The National Environmental Policy Act (NEPA), an overarching law passed that same year, expressed lofty goals for environmental regulators. The Emergency Planning and Community Right-to-Know Act (EPCRA), passed two years after a 1984 chemical plant accident killed at least 3,000 residents of Bhopal, India, helped communities gather data and map existing chemical hazards. The National Flood Insurance Program (NFIP), established in 1968, eventually produced a comprehensive program of emergency planning maps, nationwide in scope (U.S. FEMA 1992). Originally available only on paper, federal flood insurance maps were converted to a digital format in the early twenty-first century.

The Environmental Protection Agency (EPA), established in 1970, and the Federal Emergency Management Agency (FEMA), created in 1979, advanced the cause of emergency management not only through their mandated regulatory and monitoring activities but also by providing data useful to state and local emergency management agencies. Both agencies implemented regional programs for emergency planning, and EPA regional offices offered training to local jurisdictions. The advent of the EPA inextricably linked emergency management to environmental concerns insofar as the monitoring and gathering of environmental data also served to enhance emergency planning. Mapping intended specifically for emergency planning was often improved by existing geospatial data, readily available in the locality's geographic information system (GIS). In addition, the EPA distributed copies of CAMEO (Computer-Aided Management of Emergency Operations), a software application that local governments could use in conjunction

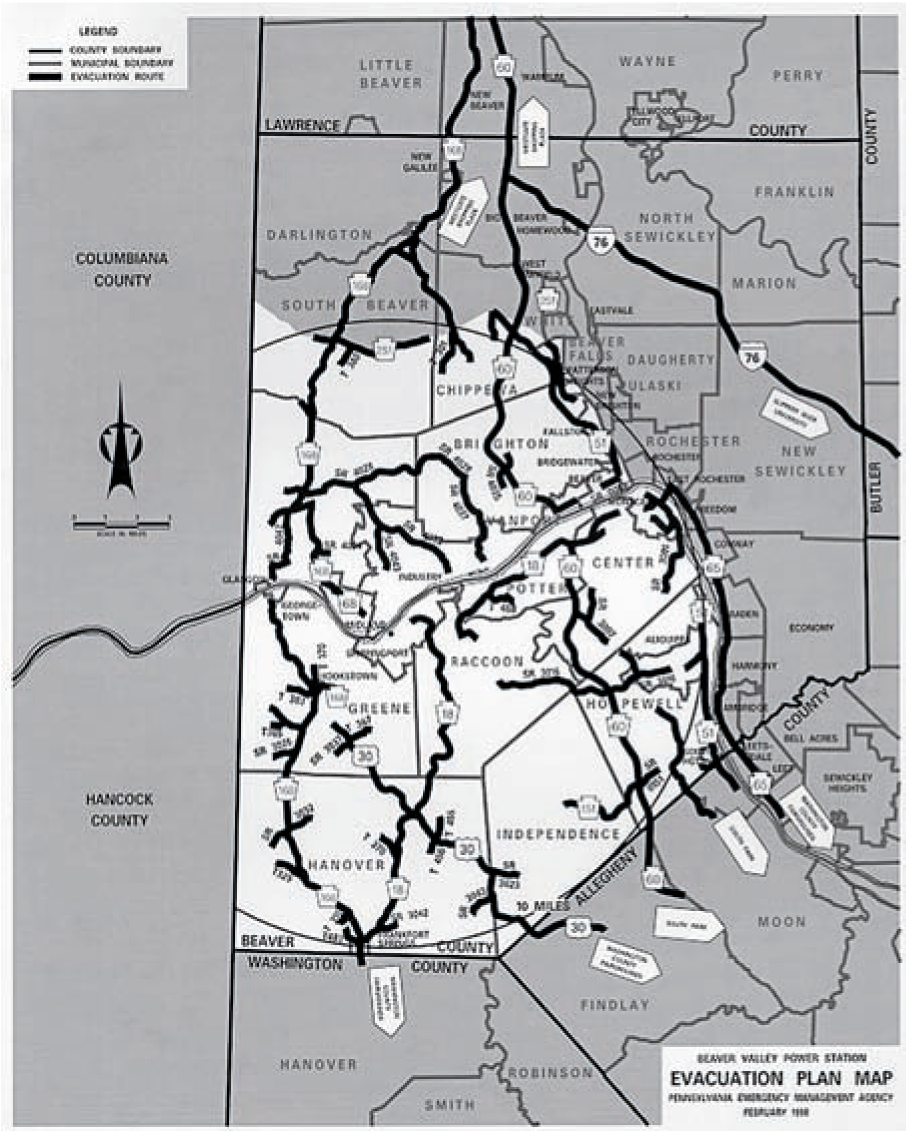

FIG. 248. NUCLEAR POWER PLANT EVACUATION PLAN MAP, BEAVER VALLEY POWER STATION, PENNSYLVANIA, 1998. Ten-mile radius of area potentially requiring evacuation in a nuclear incident. The wide black lines indicate evacuation routes.
Image courtesy of the Pennsylvania Emergency Management Agency, Harrisburg.

with Community Right-to-Know data to map the locations of hazardous materials.

Local evacuation planning became one of FEMA's foci. In addition, the U.S. Nuclear Regulatory Commission (1980), which provided federal oversight of more than 100 nuclear power plants, required detailed evacuation plans covering a ten-mile radius around each plant (Holt and Andrews 2006, 4). To reduce possible confusion, these emergency planning zones (EPZs) were often expanded somewhat to accommodate topographic obstacles or encompass whole towns. Each nuclear plant was required to distribute evacuation planning maps throughout its more or less circular EPZ (fig. 248).

Emergency mapping at all levels of government proceeded apace with the increased sophistication of computer technology during the twentieth century. The usefulness of GIS for real-time disaster response was demonstrated in the aftermath of Hurricane Andrew, which devastated southern Florida in 1992. FEMA had learned that a GIS armed with local data was valuable for immediate response, including maps for rescue teams and other field personnel, as well as for later mitigation efforts (Winter 1997). In addition, forest fires in Yellowstone National Park in 1988 and extensive flooding in the Midwest in 1993 proved that aerial photography and satellite imagery were essential ingredients in wildland fire management planning, wetlands protection, and other mitigation efforts. FEMA established a Mitigation Directorate in 1993, and where state or local funding allowed, Local Emergency Planning Committees (LEPCs)—a key provision of EPCRA, passed in 1986 but poorly supported—began to collect geospatial data and make maps required for emergency planning. Many LEPCs found that local first responders (principally police and firefighters) could capture much of the necessary data themselves using Global Positioning System (GPS) technology.

Focused on implementing new technology, emergency management officials occasionally neglected the visual effectiveness of computer-generated maps. Traditional map symbols and aesthetic standards were far less relevant than clarity and accuracy when maps had to be made on the spot to help first responders, emergency managers, and local public officials cope with an extreme event (Dymon and Winter 1991). The hurried manner in which crisis maps were generated from crude data often rendered common cartographic practices unworkable, especially for unusual or unprecedented emergencies, which mapmakers could not easily anticipate. For instance, a potential chemical explosion from a train derailment in a steep ravine in 1991 was avoided by the fire chief going up in a helicopter to hand draw a simple crisis map on cardboard (fig. 249). In 2003, the breakup of the Columbia space shuttle upon its return from space required a unique sort of crisis mapping (Chien 2006). Based on GPS and a massive data coordination effort requiring cooperation of all levels of government, GPS technology was crucial to retrieving debris and mapping the debris path across the Southwest.

The 11 September 2001 terrorist attack on the World Trade Center in New York City, which led to a massive reorganization of federal agencies, was perhaps the foremost catalyst for improving cartographic support for emergency planning. By 2003, the newly created Department of Homeland Security (DHS) had absorbed FEMA into its Emergency Preparedness and Response Directorate. Ground data collected with diverse overhead imaging strategies, including lidar, thermal imaging, and aerial photography, proved valuable in disaster recovery activities (fig. 250), especially when used to drive simulation models and dynamic three-dimensional visualizations, including fly-throughs and flyovers.

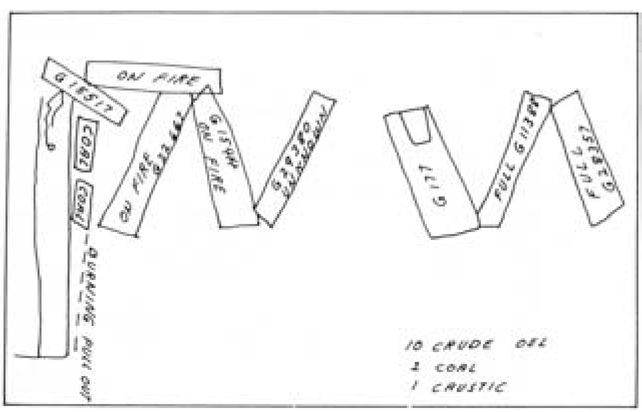

FIG. 249. RAILROAD DERAILMENT CRISIS MAP. Drawn from a helicopter by the fire chief to locate lingering hot spots in the wreckage.
From Dymon and Winter 1991, 385 (fig. 4). Copyright 1991, with permission from Elsevier.

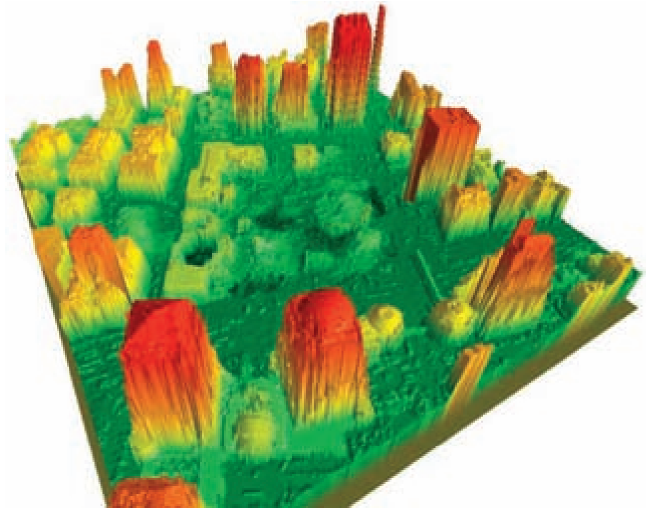

FIG. 250. WORLD TRADE CENTER POST-9/11/2001 LIDAR IMAGE. Frequent lidar images were an essential aid in the recovery work on the debris pile.
Image courtesy of the National Oceanic and Atmospheric Administration, Washington, D.C.

Examination of 9/11 emergency response efforts exposed disparities in the emergency maps used by first responders. Concern over miscommunication and confusion led to an investigation that revealed a plethora of emergency map symbols in use for diverse purposes at different levels of government (Dymon 2003). A canvass of existing emergency map symbols revealed that in the United States alone at least forty-four different symbols were being used to represent a hospital or medical facility. Standardization was considered important because a map viewer familiar with one symbol for a specific type of facility might assume that an identical facility portrayed with a subtly different symbol was something else. To promote standardization, a set of traditional and newly designed point symbols was screened by emergency responders and submitted in 2006 to the American National Standards Institute (ANSI), which adopted it as *Homeland Security Mapping Standard: Point Symbology for Emergency Management* (ANSI INCITS 415-2006).

By the early twenty-first century, every extreme event was followed by study reports, executive directives, preparedness plans and exercises, statutes, and federal reorganization plans that called for additional emergency planning maps (Rubin & Associates 2006). In 2004 alone, four Florida hurricanes and the lingering aftermath of the 2001 World Trade Center attack inspired a major RAND Corporation report on how to safeguard emergency responders during disasters and terrorist attacks (Jackson et al. 2004). In addition, Congress enacted four disaster preparedness statutes, including the Department of Homeland Security Appropriations Act, which provided critical funding for states and localities, and the White House issued Homeland Security Presidential Directive 10, titled “Biodefense for the Twenty-First Century.” Preparedness measures developed that year include the National Emergency Management Plan, prepared by the Occupational Safety and Health Administration (OSHA); the final version of the National Incident Management System (NIMS), prepared by the DHS; and the Hurricane Pam Exercise, a five-day FEMA emergency planning scenario focused on southern Louisiana. In addition three new organizations were created: the National Interagency Coordination Center (NICC), to mobilize resources related to wildland fire; the Homeland Security Operations Center (HSOC); and the EPA’s Office of Emergency Management (OEM). Emergency planning maps were essential to all of these initiatives.

Emergency mapping has a long-standing connection to military mapping. In a sense, all military maps are emergency planning maps, and emergency management agencies in many state and local governments function as paramilitary organizations, much like police and fire departments. Moreover, emergency planning in the United States was an outgrowth of civil defense initiatives during World War II and the Cold War, and through the 1980s, emergency planners typically had a military background. These connections have been particularly apparent in the development and implementation of advanced technology, insofar as military uses were often forerunners of civil applications. For example, the invention of radar in Britain just before World War II led eventually to weather radar systems, modified and reconfigured in the late 1970s and 1980s to provide an integrated storm warning system. And space technology and remote sensing, closely tied to post–World War II guided missile and military intelligence programs, have become invaluable sources of emergency response information.

By the end of the twentieth century, emergency planners were looking beyond the traditional notion of disasters as low-frequency, high-consequence, rapid-onset events. Earth scientists worldwide, public officials at the national and international levels, and long-range military planners recognized drought and sea level rise as slow-onset disasters that could not only inflict misery on the populations immediately affected but also trigger mass migrations with wider geopolitical consequences. The cause was global climate change, principally a steady rise in atmospheric temperature resulting from greenhouse gasses produced by burning fossil fuels. Reducing energy consumption seemed an obvious response, but its effectiveness as a mitigation strategy was undermined by the conflicting interests of less-developed nations with large populations and expanding economies, more-developed nations reluctant to consume less, and energy producers that persistently disputed both the forecast models and their underlying science. While planners typically considered an unprecedented disaster of some sort imminent—probably not in their own lifetime, though, or even their children’s lifetime—uncertainty about the timing and mechanisms of climate change resulted in a diversity of forecast maps, usually with red danger zones and vague or distant dates. In this environment, simulation models served not only as scientific instruments but also as persuasive maps, useful in promoting awareness of consumers’ ethical responsibilities to future generations. But because even small amounts of sea level rise could increase the destructiveness of tropical storms, planners also called for more precise elevation data for coastal areas. As with more typical rapid-onset disasters, the future effectiveness of emergency planning maps was linked to advances in information technology.

UTE JANIK DYMON AND
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SEE ALSO: Administrative Cartography; Geographic Information System (GIS): GIS as a Tool for Map Analysis and Spatial Modeling; Hazards and Risk, Mapping of

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Engraving. See Reproduction of Maps: Engraving

Environmental Protection. Whereas the modern environmental movement had its roots in the nineteenth-century works of naturalists and writers such as Ralph Waldo Emerson, George P. Marsh, John Muir, and Henry David Thoreau, the concept of environmental protection is largely a twentieth-century development. For most of the first two centuries of the Industrial Revolution, contaminants were released into the environment with little, if any, concern for the consequences. When thought was given to the human and environmental effects of the release of contaminants into the air, water, or soil, dilution was perceived to be the solution to air and water pollution, and burial—assuming that anyone bothered to bury toxic waste—was considered perfectly acceptable for less volatile or mobile materials.

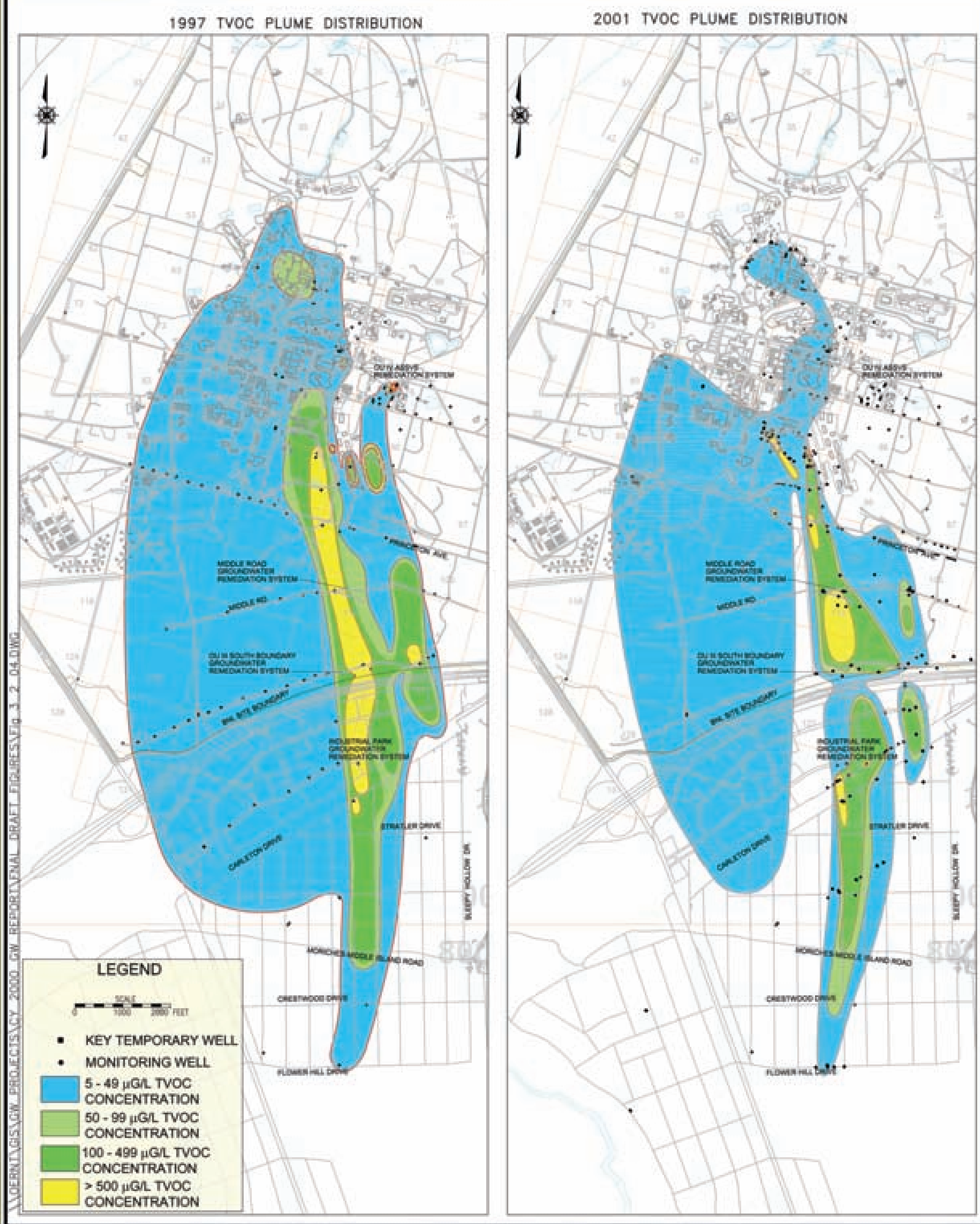
Attitudes began to change radically in the years following World War II. Development overran natural landscapes. Characteristic species, such as the bald eagle, were pushed to or over the edge of extinction. Radiation spread from open-air nuclear weapons tests. Deadly smog stalked residents of large cities. Rivers caught fire. And clusters of mysterious illnesses appeared near toxic waste sites. This onslaught of calamity captured the consciousness of those living in industrial societies and helped fuel demand for stronger laws to protect the environment. With the demand for better regulation came the need for better maps—for the environmental managers implementing the regulations, and for the public who theoretically benefits from those regulations.

What constitutes environmental protection? The question is not merely rhetorical. A review of the regulatory activities of state and local agencies with environmental protection in their name or somewhere in their mandate reveals a wide range of phenomena that are encompassed by the term. Environmental protection may be narrowly focused on protecting human health, such as ensuring safe drinking water or clean air, or aimed at minimizing pollution and the adverse effects of pollution from human activities (fig. 251). It may also focus on the protection of natural ecosystems and threatened and endangered species. Regardless of the specific agenda, access to accurate and appropriate spatial data is vital to ensure prudent policy and a well informed public.

Arguably Dr. John Snow's fabled "ghost map" of 1854—a proto-geographic information system consisting of the street grid of the London neighborhood of Soho as a base, with "overlays" of the number of cholera cases at each address and the location of publicly available water pumps in the neighborhood (Johnson 2006)—was the ancestral effort to modern mapping for environmental protection. In Snow's case, the clustering of cholera cases around one pump, on Broad Street, helped cement his argument that the disease was spread through contaminated water. Much has changed since Snow's time, including acceptance of the theory that germs like *Vibrio cholerae* caused disease, but in many ways his approach is still used to identify as well as avoid exposure to potential threats to environmental and human health.

Despite improvements in public health and growth of a nascent environmental movement in the late nineteenth century, much work remained at the turn of the twentieth century. The need to protect and conserve natural resources had been recognized, and much mapping effort was devoted to identifying and delineating lands deemed of some value to society at large. Many types of maps in wide use at the beginning of the century, such as topographic maps and nautical charts, had multiple purposes: inventory and navigation, of course, but also environmental management. Even more specialized products, such as Sanborn fire insurance maps (made from 1867 to 1970), contained information vital to anyone interested in environmental hazards such as the location of flammable and hazardous substances.

In the early twentieth century, these maps were compiled in the traditional manner, using ground-based surveys. The Wright brothers' invention of the airplane, along with the rapid development of aircraft and photographic technology during and after World War I, led to a revolution in mapping. Aerial photography and the development of photogrammetry made it easier to identify, delineate, and measure potential environmental hazards as well as areas that might be sensitive to or affected by specific environmental hazards. Aside from the ability to survey broader areas faster and more accurately than is usually possible with ground-based surveys alone, the bird's-eye view of the landscape enabled authorities to quickly see the spatial relationships of objects on the landscape. Potential environmental threats, such as close proximity of fuel storage tanks to water supplies, wetlands, or residential neighborhoods, can be



BROOKHAVEN NATIONAL LABORATORY	TITLE: OU III/ OU IV/NORTH STREET TVOC PLUME DISTRIBUTION 1997 – 2001	DWN: KCK	VT:HZ.: –	DATE: 06/13/02	PROJECT NO.: 07176
		CHKD: WRD	APPD: WRD	REV.: –	NOTES: –
ENVIRONMENTAL SERVICES DIVISION	2001 BNL GROUNDWATER STATUS REPORT	FIGURE NO.: 3.2–4			

spotted much more easily from the air than from the ground.

The advent of film emulsions sensitive to electromagnetic radiation outside the visible spectrum, particularly in the infrared and ultraviolet bands, as well as other technologies such as radar and sonar, expanded the range of environmental hazards that could be efficiently mapped from aerial platforms. Infrared imaging proved useful for a number of environmental purposes, from monitoring the health of vegetation to detecting impaired waters. Sonar, which was developed from sounding technology designed to detect icebergs following the sinking of the RMS *Titanic*, enabled researchers to visualize structures beneath the surface of bodies of water, such as shipwrecks leaking oil into the sea. Radar, developed to detect enemy aircraft and surface ships during World War II, has been useful in spotting natural and human structures beneath the land surface, such as underground storage tanks or buried drums containing hazardous waste.

The final big development in imaging technology was satellite-based remote sensing. Satellite platforms often carry a variety of sensors that detect multiple bands of electromagnetic energy. These multispectral scanners collect digital data that can be combined and mathematically manipulated with data from other bands to reveal specific phenomena of interest, such as changes in vegetation communities stressed by air pollution or climate change. Depending on the type of orbit, most remote sensing satellites, while not as flexible as aircraft in their ability to fly over a specific region on a moment's notice, offer the advantages of either repeated overhead scanning of a particular location every few days or weeks, or continuous coverage of one region by a geostationary satellite.

Much of the current aircraft- and satellite-based imaging technology began its development prior to the widespread availability of computers. But as computer technology developed, a new technology for spatial analysis rose to prominence. That technology is embedded in the geographic information system (GIS), which is capable of capturing, storing, retrieving, analyzing, and displaying spatial data. The modern GIS is computer based, but like Snow's map, it facilitates comparisons of data from different data layers. Unlike Snow's map, the data in the layers can be manipulated graphically or mathematically to make it easier to detect phenomena of interest or to improve the readability, usability, or esthetics of the final product.

Geographic information systems have revolutionized environmental protection efforts, both scientific and regulatory. For example, they can incorporate data from diverse sources (groundwater monitoring and modeling, air quality monitoring and modeling, geological surveys, surveys, land use/land cover maps, and topographic maps) and predict areas unsuitable for some land uses, such as residential development or schools because of potential exposure to chemical agents that pose particular health risks to children. Spatial modeling and spatial statistical techniques, such as various forms of kriging (spatial interpolation), can help reveal patterns in contaminant concentrations despite sparse or unevenly distributed monitoring data.

Environmental sensor networks, such as weather station networks, have allowed continuous monitoring of environmental conditions for more than a century. The sensor networks originally required manual reading or downloading of the data, but improved computer and communications technology provided automatic measurement and, thanks to the Internet, real-time display and analysis of environmental data. One such sensor network is the Chesapeake Bay Observing System (CBOS), created in 1989 as a network of buoys with instruments for measuring a range of meteorological and oceanographic variables so that interested parties can monitor the health of the troubled Chesapeake ecosystem.

Risk assessment methodology, which was largely developed in the final three decades of the twentieth century, is frequently used by environmental managers to determine the potential harm to humans or, in the case of ecological risk assessments, other organisms resulting from exposure to an environmental stressor, such as a chemical agent. Risk assessment methodology serves as an organizing principle for the use of spatial data in environmental management and planning; likewise, spatial data play a vital role in every step of a risk assessment, except dose/response assessment, which is based on toxicological data alone. Human health risk assessments consist of four steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization. Ecological risk assessments consist of three steps: (1) problem formulation, (2) analysis, and (3) risk characterization. Problem formulation is analogous to hazard identification in human health risk assessment, whereas analysis is essentially a combination of dose-response assessment and exposure assessment for species potentially vulnerable to the stressors identified in the first step.

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FIG. 251. TOTAL VOLATILE ORGANIC COMPOUNDS (TVOC) PLUMES. Comparison of the extent of plumes of groundwater contaminated with volatile organic compounds in the vicinity of Brookhaven National Laboratory (BNL) in New York, 1997 and 2001. BNL was placed on the Environmental Protection Agency's National Priority List in 1989. In 1996 over 3,000 wells were installed to monitor groundwater on and off the BNL site.

Size of the original: ca. 22.6 × 17 cm. From *2001 BNL Groundwater Status Report* (fig. 3.2–4).

FIG. 252. RADIATION HOTSPOTS, CHERNOBYL NUCLEAR POWER PLANT, 1996, SHOWING BELARUS, RUSSIA, AND UKRAINE.
Size of the original: ca. 18.4 × 17.2 cm. From Central Intelligence Agency, *Handbook of International Economic Statistics, 1996* (Washington, D.C.: Government Printing Office, 1996), 177 (fig. 31).

During hazard identification or problem formulation, spatial data have been used to determine the presence or absence of an environmental stressor at a site as well as the presence or absence of human populations (adult resident, child resident, worker, etc.) or species vulnerable to a specific stressor. During exposure assessment or analysis, spatial modeling might be used to calculate the concentration or magnitude of the stressor—that is, the dose—to which the population or species of interest may have been exposed. Modeling data are vital in some cases, such as when analysts must estimate inhalation exposures to volatile compounds emitted by contaminated groundwater. Spatial data and spatial models are likewise important in the risk characterization step, in which the analyst must estimate the probability of harm resulting from exposure to a given concentration or magnitude of a stressor. The steady emergence of new, ever more complex environmental threats during the twentieth century suggests an increased role in habitat protection and environmental health for spatial data, numerical modeling, and cartographic analysis (fig. 252).

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SEE ALSO: Administrative Cartography; Biogeography and Cartography; Community Mapping; Counter-Mapping; Forestry and Cartography; Geographic Information System (GIS): GIS as a Tool for Map Analysis and Spatial Modeling; Hazards and Risk, Mapping of; Public Access to Cartographic Information

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Environmental Systems Research Institute (ESRI; U.S.). By the end of the twentieth century, geographic information system (GIS) software produced by ESRI was used by more than 300,000 organizations worldwide and had more than a million individual users. Its substantial market share made ESRI formats de facto standards for spatial data production and handling in several fields. ESRI has had a tremendous impact on digital cartography and spatial analysis: how GIS software works and what questions it addresses often trace back to ESRI. The firm has also played a fundamental role in the development of the GIS community. The relationship has been reciprocal: ESRI has both shaped and been shaped by the GIS community.

ESRI software and outreach have also placed GIS tools and models in the hands of many people without formal cartographic or GIS education. Some observers saw this development as the democratization of cartographic practice, encouraging people to think spatially and control their own information and strengthening the presence of geography in academia. Others have warned of the risks of hidden assumptions embedded in GIS packages and of misuse (Goodchild 2000).

The story of the interplay between ESRI, GIS technology, and the GIS community has much to do with the background of founder and president Jack Dangermond, who has been a leading proponent not only of ESRI but also of the importance of geography for addressing global problems and of GIS as a common way of seeing. Dangermond described GIS as a way not only to synthesize heterogeneous data but also to bridge conflicting viewpoints. He has been able to impart this vision to remarkable effect.

Dangermond has cited Howard T. Fisher, John Kenneth Galbraith (Reed 2006), Hosni N. Iskander, Ian L. McHarg, and Philip H. Lewis as influences. Dangermond grew up working at a family-owned nursery, which gave him early exposure to the relationship between people and land. He received a bachelor's degree in landscape architecture from California State Polytechnic University Pomona and a master's degree in urban planning from the University of Minnesota. At Minnesota he was introduced to the theories of quantitative geography and social and landscape modeling by geographer John R. Borchert. Dangermond received a master of landscape architecture degree, Harvard Graduate School of Design, in 1969. At Harvard he spent late nights working in the Design School's Laboratory for Computer Graphics and Spatial Analysis, producing regional air pollution maps using SYMAP and becoming immersed in the intense experimental community surrounding automated cartography (Chrisman 2006, 34, 48).

At the same time, Dangermond became fascinated with how computers might help solve problems in which he was interested: first in landscape architecture, then in planning, and finally in a broad sense of understanding geography and supporting environmental planning (Reed 2006). Dangermond's background gave ESRI its early impetus and character, shaping the studies ESRI undertook and the way it approached those studies and therefore both the software it developed and the relationships it formed with software users.

In 1969 Jack Dangermond and his wife Laura Dangermond founded ESRI as a nonprofit organization in their hometown of Redlands, California. Backed by $1,000 in personal savings and run from their kitchen table, the new venture offered consulting services in environmental studies.

ESRI was created to apply a geographic approach to problem solving and from the beginning used computer software as part of its approach. Services offered included environmental and biological studies, land suitability and capability studies, and computer graphics displays. Early projects included planning for the development of a highway in Wisconsin, redevelopment planning for the city of Baltimore, and assisting Mobil Oil with site selection for the new town of Reston. ESRI had international clients from the beginning and helped plan new towns in Japan and Venezuela. By the mid-1970s, ESRI had helped develop land use planning systems and parcel map systems for several cities and counties.

The new environmental laws of the 1970s created a demand for environmental impact studies that treated large areas, which sometimes crossed state and county boundaries, as units. Studies for federal, state, and local government agencies became a mainstay of ESRI. In 1973, for example, ESRI began building the Maryland Automation Geographic Information (MAGI) system, its first statewide GIS. The system was used by Maryland to conduct environmental assessments and environmental suitability and capability analyses (Dangermond and Smith 1988, 306–7). These early projects pushed the development of in-house GIS software in the direction of analyzing land use and assessing environmental parameters and established many of ESRI's long-term relationships with users that would shape later software capabilities and the composition of the larger GIS community.

Dangermond continued to be involved in the early GIS community of researchers, scholars, and tinkerers, participating in the first Symposium on Geographical Information Systems in Ottawa, 1970, organized by Roger F. Tomlinson and Duane F. Marble. In 1973 the firm shed its nonprofit status, becoming Environmental Systems Research Institute, Inc. In its early years the company focused on consulting and developing software for its own in-house use at a time when the scarcity and cost of computing hardware meant that ESRI had to buy time on an IBM mainframe on the University of California's Riverside campus. The idea of selling software to clients as a separate product, rather than delivering it as part of a report, began to emerge in the late 1970s.

In 1970 San Diego County, California, hired ESRI to develop the Polygon Information Overlay System (PIOS) to map soil polygons. The software could be used to edit and update point, line, and polygon data. Despite its name, PIOS was less successful as a polygon overlay program than the GRID package that soon followed, but it could accommodate vector processing. GRID processed data for grid cells, digitized from a blueprint of a source map overlaid with a grid pattern. Later versions allowed rankings for up to three features to be assigned to each cell. AUTOMAP II, a program that was relatively simple to use and modestly priced, provided several mapping functions with line printer output (Dangermond and Smith 1988, 302).

These systems were originally written in FORTRAN for an IBM machine, but PIOS and GRID were eventually converted to several different hardware platforms. As minicomputers emerged as affordable alternatives to mainframe systems, users began to devote machines exclusively to spatial data processing. Turnkey systems (integrated, ready-to-go suites of hardware and software) began to appear in the marketplace, and ESRI joined the movement (Dangermond and Smith 1988, 304–5). Entering a joint agreement with Prime Computers, ESRI began to install turnkey GIS systems. The business model proved successful, especially after ARC/INFO entered the equation.

By 1980, ESRI clients included federal, state, and local government agencies, mostly dealing with land planning and management; two petroleum companies; and Southern California Edison. ESRI also began to develop international affiliates in Australia, Germany, Japan, and Venezuela. Of the nineteen user sites listed as having a continuing relationship with ESRI, almost all used ESRI software for environmental impact assessment and land use forecasting (fig. 253). Other common applications included land capability and suitability analysis, facility siting, urban and regional planning, agricultural development planning, and water resource analysis. These application needs shaped ESRI's early software functions and are still fundamental in its current products.

In 1981 ESRI hosted its first user conference at the suggestion of a user, with sixteen users from eleven sites attending. The meeting was so small that at one point participants stood in turn to tell their best jokes. The conference set a collaborative model in place between ESRI and its users regarding needs and general direction.

Soon afterward Scott Morehouse, who had developed the ODYSSEY software package at the Harvard Laboratory for Computer Graphics and Spatial Analysis, joined ESRI. He was responsible for the initial design and architecture of ARC/INFO, ESRI's first truly commercial software, released in 1982. ARC/INFO was a "complete departure" from PIOS, ESRI's earlier vector processing software (Dangermond and Smith 1988, 302), and from

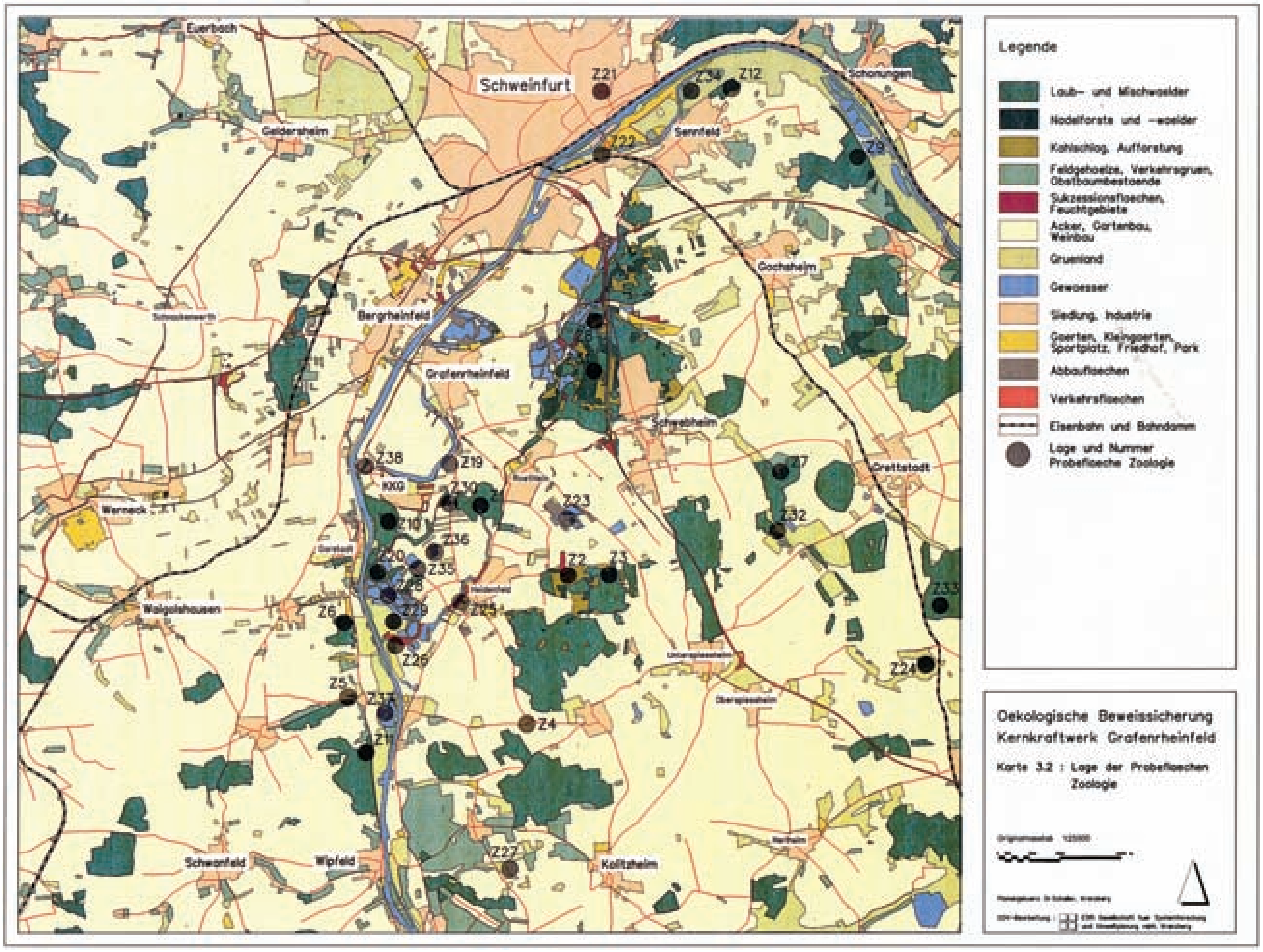


FIG. 253. LAND USE IMPACT ON NATURAL RESOURCES. This is one in a series of maps used to determine the impacts of different land uses on natural resources in a planning region in southern Bavaria (ESRI-Germany, Joerg Schaller).

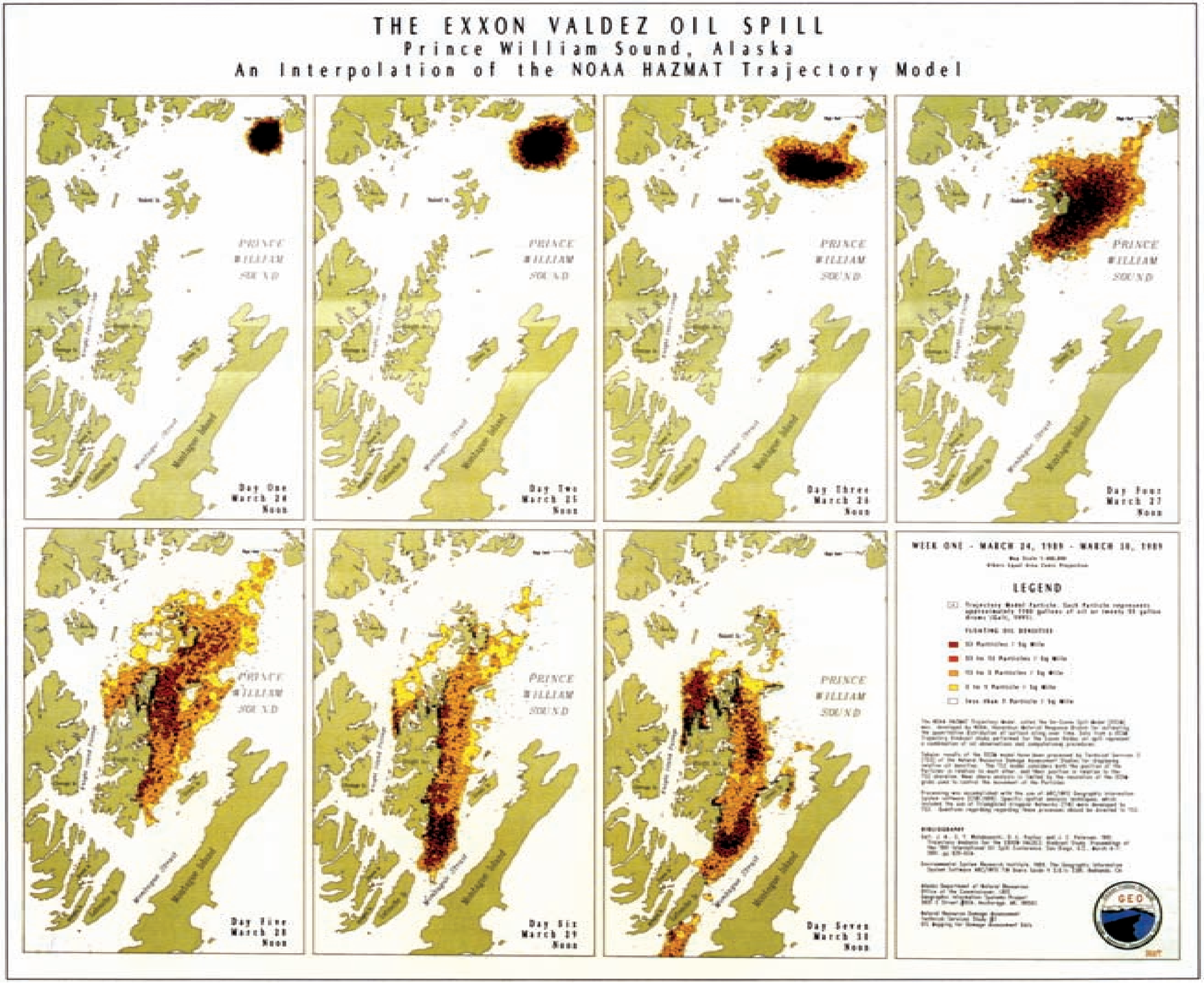
From *ARC/INFO Maps*, vol. 4 (1988), 33.

ODYSSEY as well. The command-line software linked a display component (ARC) that drew point, line, and polygon features on the screen with a relational database component (INFO) that stored and processed attributes for each feature in tables. ARC/INFO implemented two related ideas: separating map features and their attributes, and handling attributes using a relational database system. These ideas were not new. For example, the Canada Geographic Information System (CGIS) had separated map features and attributes. But ARC/INFO was so successful and widely influential that these methods became widely adopted, almost to the exclusion of other approaches.

For ESRI, the release of ARC/INFO represented a shift from services to products. ESRI kept its consulting emphasis on supporting clients in their decision making, but the relationship between ESRI and users was transformed.

ARC/INFO was often referred to as ESRI's flagship product and became the bulk of its software business (fig. 254). Its ascent was facilitated by falling hardware prices and a concurrent tendency in the 1980s among government agencies and large organizations to invest in databases for keeping updateable records. By the end of the decade, GIS began to seem less of a "technology in search of uses" (Dangermond and Smith 1988, 305) and more of a necessity to be specified in an organization's objectives.

This trend led eventually to a situation, well established by the end of the twentieth century, in which most geographic data were held in digital rather than print form. On the one hand, organizations could produce maps on the fly, update their information at will, and use new data immediately. On the other, as formal map artifacts became less common, the preservation of


THE EXXON VALDEZ OIL SPILL
Prince William Sound, Alaska
An Interpolation of the NOAA HAZMAT Trajectory Model
PRINCE WILLIAM SOUND
Day One
March 24
Noon
Day Two
March 25
Noon
Day Three
March 26
Noon
Day Four
March 27
Noon
Day Five
March 28
Noon
Day Six
March 29
Noon
Day Seven
March 30
Noon
WEEK ONE - MARCH 24, 1989 - MARCH 30, 1989
LEGEND
GEO

the historic record of geographic data was increasingly problematic.

As time went on, modules were added to ARC/INFO. By the late 1980s, these included COGO for coordinate geometry, TIN for dealing with triangulated irregular networks, and NETWORK for processing network data such as roads and streams. A language for writing macro programs, Arc Macro Language (AML), was made available to users as well. AML allowed users to build custom programs on top of ARC/INFO.

The idea of building software in response to user needs and requests remained embedded within ESRI. Many of the first user conference participants became beta users, long-standing user sites who tested new software versions and whose suggestions, complaints, and pressures greatly influenced benchmarks for ESRI software. The interaction between users and ESRI was seen as a synthesis, and individuals who began as users often ended as employees and vice versa.

ESRI continued to build larger applications for clients and in 1983 and 1984 worked on several projects for the United Nations Environment Programme, including a world inventory of desertification. In 1989 ESRI was awarded a contract from the Defense Mapping Agency (later the National Geospatial-Intelligence Agency) to build the Digital Chart of the World, a 1:1,000,000-scale global basemap, from aeronautical charts.

At the same time, ESRI began to formalize user training and education. The Technical Support and Educational Services departments, tellingly, were parts of the same division. Continuing the tradition set by early interactions with users, ESRI blended conceptual GIS education with software training.

ESRI also began to consciously pursue colleges and universities as users. ESRI has sustained strong ties to the academic discipline of geography, even in decades when geography was unsure it wanted a connection with GIS. Milestone events included cosponsoring the first GIS Day in 1999 as part of Geography Awareness Week, helping to fund a GIS program at the University of Redlands in 2001, and adding an Education User Conference to ESRI's annual International User Conference.

The proliferation of personal computers in the 1980s pushed ESRI software in a new direction. In 1986 ESRI released PC ARC/INFO, a relatively affordable version that was adopted by many smaller organizations. By the late 1980s, ESRI sold 1,000 systems per year (Dangermond and Smith 1988, 305), considered at the time a staggering number.

By the early 1990s the company was growing fast; staff watched in disbelief as the number of employees passed 600. GIS was finding its way into new applications, and ESRI products began to proliferate. ARC/INFO continued to be enhanced by new commands, and the ARCTOOLS graphical interface was developed to tame the multitude of options. In 1994 ArcSDE (Spatial Database Engine) was designed to allow large user organizations to store spatial and tabular data in commercial database management systems (DBMS).

In 1992 ESRI released ArcView 1.0, a relatively lightweight, display-only desktop tool with limited functionality and a graphic user interface (fig. 255). Although it crashed often, it was affordable and comparatively easy to learn. It was designed to be a tool for people who were not normally mapmakers. People in many fields could use it without needing a GIS specialist as an intermediary. This shift in perspective helped GIS find its way into new commercial markets and smaller organizations, even as subsequent versions of ArcView added functionality until it could accomplish most of the analysis tasks of ARC/INFO. Likewise, BusinessMAP and its related family of products, introduced in 1994, were designed to be lightweight tools for use out of the box by people with little or no cartographic or GIS expertise.

As the U.S. Geological Survey and the U.S. Census Bureau began producing digital data in quantity, they eventually adopted ESRI data formats as standard output. When the National Spatial Data Infrastructure was announced in 1994, a complicated process of digitizing and sharing data began to emerge throughout levels of government within the United States. ESRI output formats frequently became the default for various organizations.

ESRI software had always produced maps, but the power of the software resided in its analytical capability rather than its cartographic output. In the mid-1990s ESRI software took a step forward in its map production applications. The improved cartographic capability lured National Geographic Maps from manual to digital map production, and the 1999 *National Geographic Atlas of the World* (7th ed.) was built entirely using ArcInfo. (The name of the software changed from "ARC/INFO" to "ArcInfo" upon the release of ArcGIS in late 1998.) The ability of the software to provide visualization improved.

(*Facing page*)

FIG. 254. *THE EXXON VALDEZ OIL SPILL, PRINCE WILLIAM SOUND, ALASKA: AN INTERPOLATION OF THE NOAA HAZMAT TRAJECTORY MODEL*. This series of maps was produced using a model created by the National Oceanic and Atmospheric Administration–Hazardous Materials Response Branch (NOAA-HAZMAT) and ARC/INFO TIN extensions. The maps estimate the general flow and the relative concentration of surface oil from the first week after the spill, 24 March–30 March 1989. Alaska Department of Natural Resources, by Dorothy Mortenson et al.
From *ARC/INFO Maps*, vol. 8 (1992), 38.

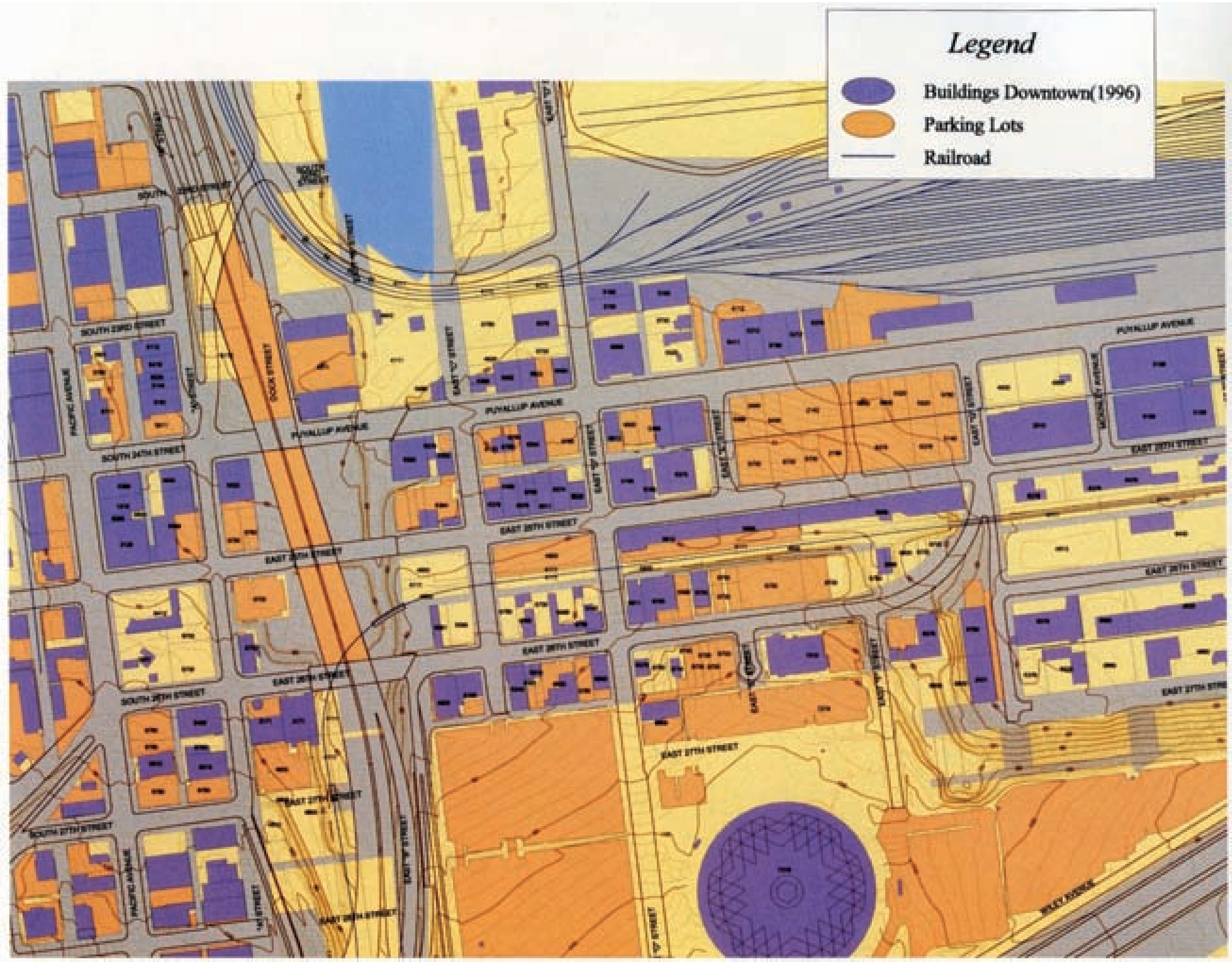


FIG. 255. DETAIL OF MAP FOR DEVELOPMENT OF LIGHT RAIL AND COMMUTER RAIL IN TACOMA, WASHINGTON. The Tacoma Dome Area Land Use map, by Mike Murnane and Donna Wendt, provides necessary background and neighborhood data to the Sound Transit project in its efforts to reduce traffic congestion in central Puget Sound. The map uses ARC/INFO, ArcView GIS, and ArcPress.
From *ESRI Map Book*, vol. 14 (1999), 70. Permission courtesy of the City of Tacoma.

As the twentieth century drew to a close, ESRI took up the new approach to software programming: building reusable components. The company began to reengineer its entire product line as a series of COMs (component object models). ArcInfo 8 was the first COM-based version of ArcInfo. In 1999 the release of ArcInfo for Windows NT recognized the growing hegemony of the Windows operating system among individual users. That year also saw the release of ArcIMS (Internet Map Server), which enabled users to integrate local data with data found on the Internet.

At the turn of the century, ESRI's array of products was somewhat dizzying. ESRI made an attempt to sort out and streamline its product portfolio. ArcGIS 8.1, released in 2001, reintroduced ESRI software products as an integrated, scalable, complete GIS spectrum of products with a number of different packages that could be stacked together according to user needs. ArcGIS subsumed both ArcInfo and ArcView, making them differentiated components. For example, the ArcView component had about 20 analysis tools, mostly for projection and conversion, and the ArcInfo component had 150 analysis tools. The situation remained rather confusing for users, who had to adapt to a new vocabulary and product structure. Geodatabases were introduced as a new data structure within a DBMS. The freely distributed ArcReader acted much as Adobe Acrobat Reader did, allowing people without GIS software to display and print spatial data published in the Reader format.

With the release of ArcGIS 9 in 2004, ESRI furthered its model of integrated software components. ArcGIS Server was introduced as a centrally managed server framework for enterprise GIS applications. GIS applications could be centrally managed on the server and large amounts of spatial data accessed from various repositories via browser software. This server model made data and mapping completely web based and was the next direction for ESRI products. In some ways this could be seen as a reversal of the move from services to products insofar as software and data, when distributed over the Internet, could be considered services.

ESRI remained privately held and personally run. Although the company had 2,900 employees in 2007, its telephone directory was still organized by first name. Even so, several regional offices and more than eighty international distributors extended the reach of the main site at Redlands. The annual user conference, attended by 12,000 users in 2006, was consistently the largest gathering of GIS practitioners in the world. In 2010 the company stopped using the "ESRI" acronym and switched to "Esri" as a proper name.

Clients included a substantial number of federal agencies, state and local governments, petroleum and forestry companies, universities, defense and intelligence agencies, corporations, and nongovernmental organizations. Applications in land planning and management, conservation, and natural resources have been joined by others in emergency management, homeland security, defense, real estate, banking, and earth science, among other fields.

ESRI continued to center itself around the discipline of geography. There is little doubt that GIS would be different if Dangermond had been a geologist or computer scientist. In fact, until the 1990s ESRI employed very few computer scientists. Clint Brown, who joined the company in 1983 and became director of software products, was trained as a statistician and held a degree in econometrics. D. J. Maguire, who became director of product planning, was a geographer who lectured at three universities in the United Kingdom before joining ESRI in 1990.

ESRI's history is not one of constant progress. The company sometimes seemed to be pulling in several directions at once. Software releases have never gone flawlessly, and some products have either quickly disappeared or never seen the light of day. Users were occasionally confronted with changed terms and definitions and the reuse of similar terms, such as the separate, concurrent products ArcExplorer, ArcExplorer Web, ArcGIS Explorer, and ArcWeb Explorer. Even so, ESRI has shown steady growth and has sustained relationships with its users as the technological landscape evolved. In some cases ESRI had sufficient weight to carry the user community along with it. But for the most part, ESRI fostered its connection with users that, at its best, was less about software releases than about helping users do their work.

SHELLY SOMMER

SEE ALSO: Geographic Information System (GIS): Computational Geography as a New Modality; Software: Geographic Information System (GIS) Software

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Epidemiological Map. The first disease maps were published beginning in the 1600s but during the twentieth century became a common way to communicate disease distributions. Maps can simply show the extent or magnitude of diseases or the results of sophisticated epidemiological analyses. The purpose of such maps is sometimes to promote public awareness, but they can also be used as research tools to investigate disease transmission, health threats, and access to health services. Relationships between diseases and the environment are often shown using epidemiological maps. Very few diseases are randomly distributed in space because environmental and population characteristics influence who gets a disease, and thus diseases vary spatially. Epidemiological maps often attempt to explain the complex relationships that influence heterogeneous disease occurrence. If diseases did not vary spatially they would not be mapped.

One of the grandfathers of twentieth-century epidemiology is English physician John Snow, who is well known for creating a map of a cholera outbreak in London in 1854. The map allowed Snow to test and communicate his theory that cholera was related to water and that pulling the handle off of the Broad Street pump would stop the epidemic because people living in the area would no longer drink its contaminated water (Snow 1855). In the 1930s the pioneering epidemiologist Wade Hampton Frost promoted Snow's cholera map as a cartographic emblem of bacteriological thinking.

Disease maps became commonplace during the twentieth century. In 1904, Scottish geographer and cartographer John George Bartholomew published *The Survey Gazetteer of the British Isles*, containing demographic and geographic data for both England and Wales. Based on 1901 census information, Bartholomew created maps displaying the average total death rate per 1,000 persons, as well as the death rate for children under age one. In addition, he included average death rates from phthisis, the term of the day for tuberculosis. Using a crude death rate as a measure, however, led to inaccurate conclusions about trends, especially considering the dependence of mortality upon the relative proportion of older people in the population. Physician Percy Stocks improved upon this in a description of mean cancer rates from 1919 to 1923. Correcting for differences in age, sex, and urban population, his published map implied that death rates "vary over such wide limits and the counties group themselves into such definite regions of high and low prevalence, that there can be no question that geographical influences are in some way concerned" (Stocks 1928, 518–19). By 1939, methods of comparing mortality had further advanced, allowing Stocks to produce a series of seventy-four maps illustrating standardized mortality ratios of cancer by type, age group, and gender in England and Wales.

During the late 1940s, physician Jacques M. May assumed the position of head of the Department of Medical Geography for the American Geographical Society in New York. Having witnessed disease outside of the United States in various cultures, May was interested in an ecological approach to understanding health and its relationship to social context and physical environment. Between 1950 and 1955, he created an *Atlas of Distribution of Diseases*, consisting of separate color maps that illustrated the distribution of polio from 1900 to 1950, cholera from 1816 to 1950 (fig. 256), and malaria vectors, as well as nutrition-related illustrations of dietary preferences and deficiency diseases. Geographer A. T. A. Learmonth, meanwhile, introduced a number of new methods for mapping health data. Aspiring to show the correlations between disease and environmental conditions, he used isolines to display contours of infant mortality, as well as matrixes representing variations among intensity and variability of disease incidence. His 1954 maps of cholera in India, using nine categories representing combined mortality and variability rates, identified epidemic and endemic areas. In 1957, Learmonth published a map of land types and malaria incidence, illustrating areas favorable for vector survival and thus more prone to malaria (Learmonth 1957). In Germany, doctors E. Rodenwaldt and Helmut J. Jusatz edited the three-volume *Welt-Seuchen-Atlas: Weltatlas der Seuchenverbreitung und Seuchenbewegung = World Atlas of Epidemic Diseases* (1952–61), which included both global and mostly European regional maps.

The majority of the aforementioned maps are small scale, displaying data by country or even continent. Of course, this did not properly display the subtler differences across regions, creating difficulty in interpreting relationships between disease prevalence and most geographical factors. In 1963, Welsh geographer G. Melvyn Howe published the *National Atlas of Disease Mortality in the United Kingdom*, using administrative units and data from the National Health Service that classified deaths by cause and by residence as opposed to the hospital in which the death occurred. He calculated standardized mortality ratios for thirteen different causes of death in Britain from 1954 to 1958, plotting them on a geographical base map across 320 administrative units. In 1970 he published a revised edition of the atlas, in which a demographic base map was included in order to compare disease ratios to at-risk local populations.

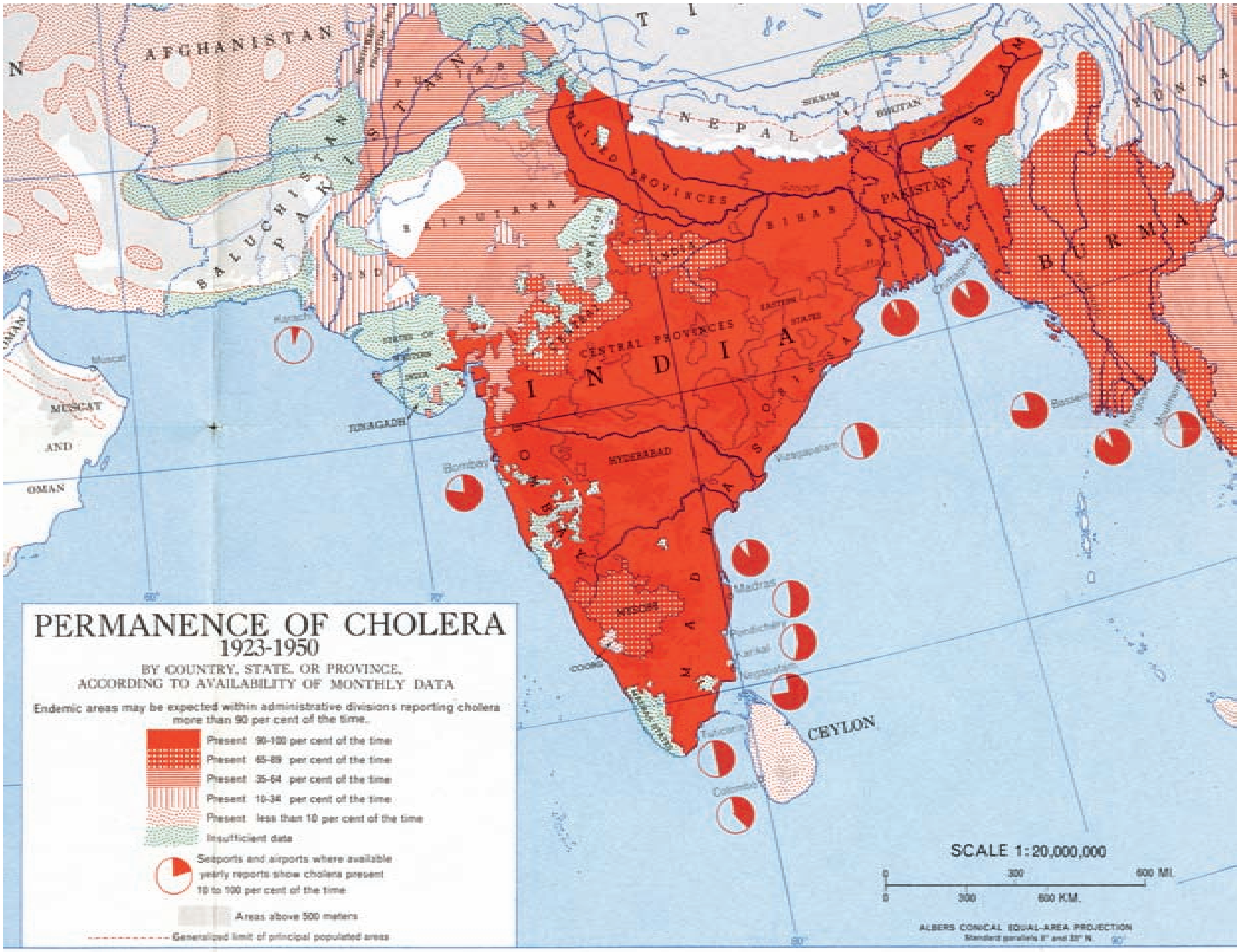
Beyond displaying point and distribution data related to health and disease outcomes, maps were also used to illustrate diffusion patterns. Cholera, for example, a disease with high epidemic potential, is a widely documented illness. Maps created during the 1900s often chronicled the diffusion of cholera in previous centuries, detailing the pattern of spread in Africa, Europe, and the United States. Geographer Gerald F. Pyle analyzed the disease as it spread throughout the United States during a 1910–11 epidemic, and Robert F. Stock identified four types of spatial diffusion patterns in Africa during the early 1970s, including riverine, coastal, urban hierarchical, and radial contact (Stock 1976, 91). A map of the Asian flu pandemic of 1957–58 showed how the disease began in Central Asia and then spread quickly to other areas, including Hong Kong, Taiwan, and Singapore. It later was discovered in certain European countries, the United States, and the Middle East. The map showed that by late 1957 every country in the world had been affected. Pyle mapped the diffusion of influenza within the United States during three consecutive seasons (1975–76, 1976–77, 1977–78) as well as three large-scale pandemics occurring in 1781–82, 1847–48, and 1889–90 (Pyle 1986). He classified four types of influenza diffusion, including explosive and rapid outbreaks as well as slower epidemics.

Mapping health and disease with the assistance of computers became common in the late 1960s and early 1970s, developing upon earlier methods that used plotters

(*Facing page*)

FIG. 256. DETAIL FROM JACQUES M. MAY'S MAP OF THE *PERMANENCE OF CHOLERA, 1923–1950*. A portion of one of the twelve maps and graphs on *Distribution of Cholera, 1816–1950*. See also fig. 36.

Size of the entire original: 61 × 91.5 cm; size of detail: 17.9 × 22.9 cm. From *Atlas of Distribution of Diseases* (New York: The Society, 1950–55), pl. 2. Permission courtesy of the American Geographical Society, New York.


PERMANENCE OF CHOLERA
1923-1950
BY COUNTRY, STATE, OR PROVINCE,
ACCORDING TO AVAILABILITY OF MONTHLY DATA
Endemic areas may be expected within administrative divisions reporting cholera more than 90 per cent of the time.
Present 90-100 per cent of the time
Present 65-89 per cent of the time
Present 35-64 per cent of the time
Present 10-34 per cent of the time
Present less than 10 per cent of the time
Insufficient data
Seaports and airports where available yearly reports show cholera present 10 to 100 per cent of the time
Areas above 500 meters
Generalized limit of principal populated areas
SCALE 1:20,000,000
0 300 600 MI.
0 300 600 K.M.
ALBERS CONICAL EQUAL-AREA PROJECTION
Standard parallels 8° and 32° N.
AFGHANISTAN
BALUCHISTAN
PAKISTAN
SIND
PUNJAB
RAJPUTANA
UNITED PROVINCES
NEPAL
SIKKIM
BHUTAN
BIHAR
BENGAL
ASSAM
BURMA
INDIA
CENTRAL PROVINCES
EASTERN STATES
ORISSA
HYDERABAD
BOMBAY
MADRAS
MYSORE
CEYLON
JUNAGADH
MUSCAT
AND
OMAN
Karachi
Bombay
Madras
Vizagapatam
Colombo
Bassein

for numerical output but lacked graphic representations. The ability to quickly calculate statistics on disease indexes and subsequently plot them directly on a map greatly advanced cartographic abilities, minimizing the amount of time spent producing the documents. The Laboratory for Computer Graphics and Spatial Analysis at Harvard University was a major facilitator in this process through its introduction of the SYMAP program. Improved resolution of the maps produced with this program was then made possible with the development of the pen plotter and the cathode ray tube. With these new techniques, the U.S. government published a series of national cancer atlases that featured color maps created using computers and mechanical plotters. Similar methods were used for maps of cancer mortality in England and Wales from 1968 to 1978.

Advances in computer technology led to much progress in the ability to map diseases, especially during the last two decades of the twentieth century. With computers, the map became more than a means to communicate spatial distributions; with the advent of geographic information systems (GIS) the map became a spatial database management and analysis system. The GIS map thus became a tool to integrate spatial data sets and analyze spatial patterns. Relationships between disease distributions and the environment and population characteristics could be explored through visualization techniques but also analyzed through simple descriptive overlay analysis or complex spatial statistical modeling. Specialized types of conventional statistical models such as regression analysis were developed to work with spatial distributions. These methods included local regression analysis that allowed the user to investigate how relationships vary in space.

In 1981, Environmental Systems Research Institute (ESRI) released the first commercial GIS software package, ARC/INFO. The program stored spatial data within binary files that could then be combined with attribute data that one could display. Common identifiers linked the two types of data, which were then transformed into a series of points, lines, and polygons. The ability to store topological relationships with demographic and health data and then project them in a specified format was highly useful for medical mapping. Additional developments in computer technology, complementary software packages, and the evolution of the Internet added to the ease with which one could download, store, and manipulate spatial data to present epidemiological phenomena in space (Koch 2005). The variety of programs and online data available by the end of the twentieth century made epidemiological mapping easier and far more accessible than it had been in past generations.

Epidemiological maps created using a GIS often display the results of sophisticated spatial analytical operations such as the work by geographer Stan Openshaw, which identified clusters of childhood cancer in Great Britain (Koch 2005, 265–67). Improbably large clusters of disease were mapped using hotspot or spatial cluster analysis. Because little was known about either the etiological factors behind childhood cancers or the spatial scale(s) at which they operate, iterative spatial statistics algorithms were developed to search for clusters across spatial scales (Kulldorff 1997). In England, geographer Peter Haggett and his student A. D. Cliff (1988; and with Ord 1986), and later Cliff's student Matthew Smallman-Raynor (1992; 1993; 1998), wrote a variety of books and atlases that used spatial analytical techniques to reveal patterns of infectious disease transmission. In the United States, geographer Peter Gould (1993) documented the progression of the AIDS epidemic in the United States during the 1980s. The World Wide Web can also facilitate interactive online mapping. For example, the U.S. National Cancer Institute created the Geographic Information System for Breast Cancer Studies on Long Island (LI GIS) as part of the Long Island Breast Cancer Study Project. The LI GIS website allows people to interactively map breast cancer incidence by ZIP code on Long Island as well as potential environmental risk factors such as hazardous waste sites (fig. 257).

During the twentieth century disease maps became an important epidemiological tool to investigate distributions of disease. The cartographic tools for displaying disease distributions have been integrated with the statistical methods needed to understand complex associations between diseases, population, and environment. With GIS, disease maps are more than just a way to communicate epidemiological information graphically; they are also a spatial integration and analysis tool. However, some major challenges still remain, and they are mostly not technological. Disease maps are only as good as the data that go into them, and most disease distributions are still collected through convenience samples such as passive hospital-based reporting systems. In order to truly understand the distribution of diseases in the future, epidemiologists will need to collect data through informed geographic sampling. In the twenty-first century epidemiologists will likely have more reliable disease maps and therefore will be able to more rigorously investigate the reasons behind their disease distributions.

MICHAEL EMCH AND SOPHIA GIEBULTOWICZ

SEE ALSO: Demographic Map; Exploratory Data Analysis; Hazards and Risks, Mapping of

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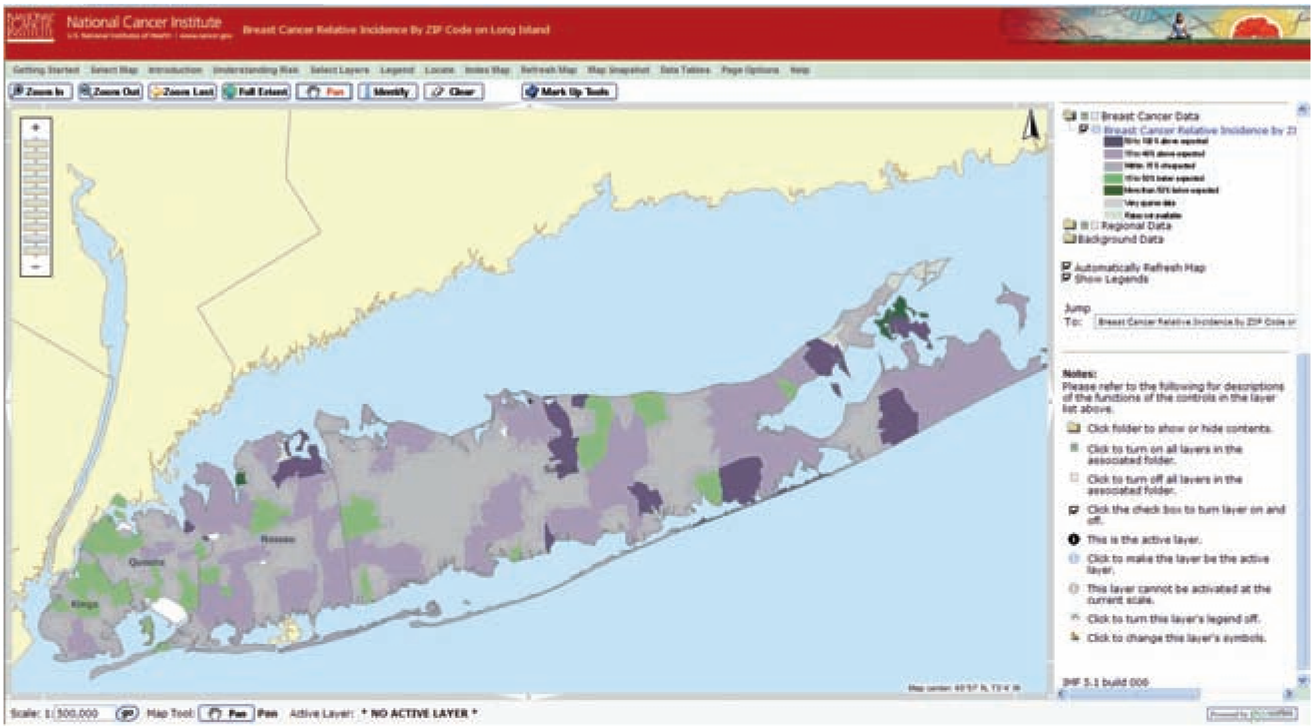

FIG. 257. MAPS OF BREAST CANCER RELATIVE INCIDENCE BY ZIP CODE ON LONG ISLAND. Screen capture, National Cancer Institute, LIGIS, with interactive mapping tools.

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ESRI (U.S.). See Environmental Systems Research Institute

Esselte Kartor AB (Sweden). Swedish map production in the twentieth century was strongly associated with the name Esselte, coined by pronouncing the initials of the holding company Sveriges litografiska tryckerier (SLT). The company name Esselte Kartor AB is comparatively recent and is part of a complex corporate history rooted in the mid-nineteenth-century origins of the mapping firm Generalstabens litografiska anstalt (GLA), which SLT (Esselte) absorbed in a merger of thirteen companies, in 1913.

The GLA was not the only mapmaker within SLT. In 1916, the cartographer Magnus Lundqvist founded AB Kartografiska institutet as a subsidiary of SLT and led the endeavor until 1957. Its product line included tourist maps and other thematic maps. The first national atlas of Sweden, *Atlas över Sverige*, produced by the Svenska sällskapet för antropologi och geografi from 1953 to 1971, stands out as the institute's most important cartographic contribution (fig. 258).

GLA was an atypical map publisher: a private company with a managing director appointed by the government. Its formation was closely connected to the development of military cartography in Sweden in the early nineteenth century. Topographical surveying had been carried out within the General Staff by a military unit known as the Topografiska corpsen. In 1833 the German Georg Leonard Dreyer, who brought modern

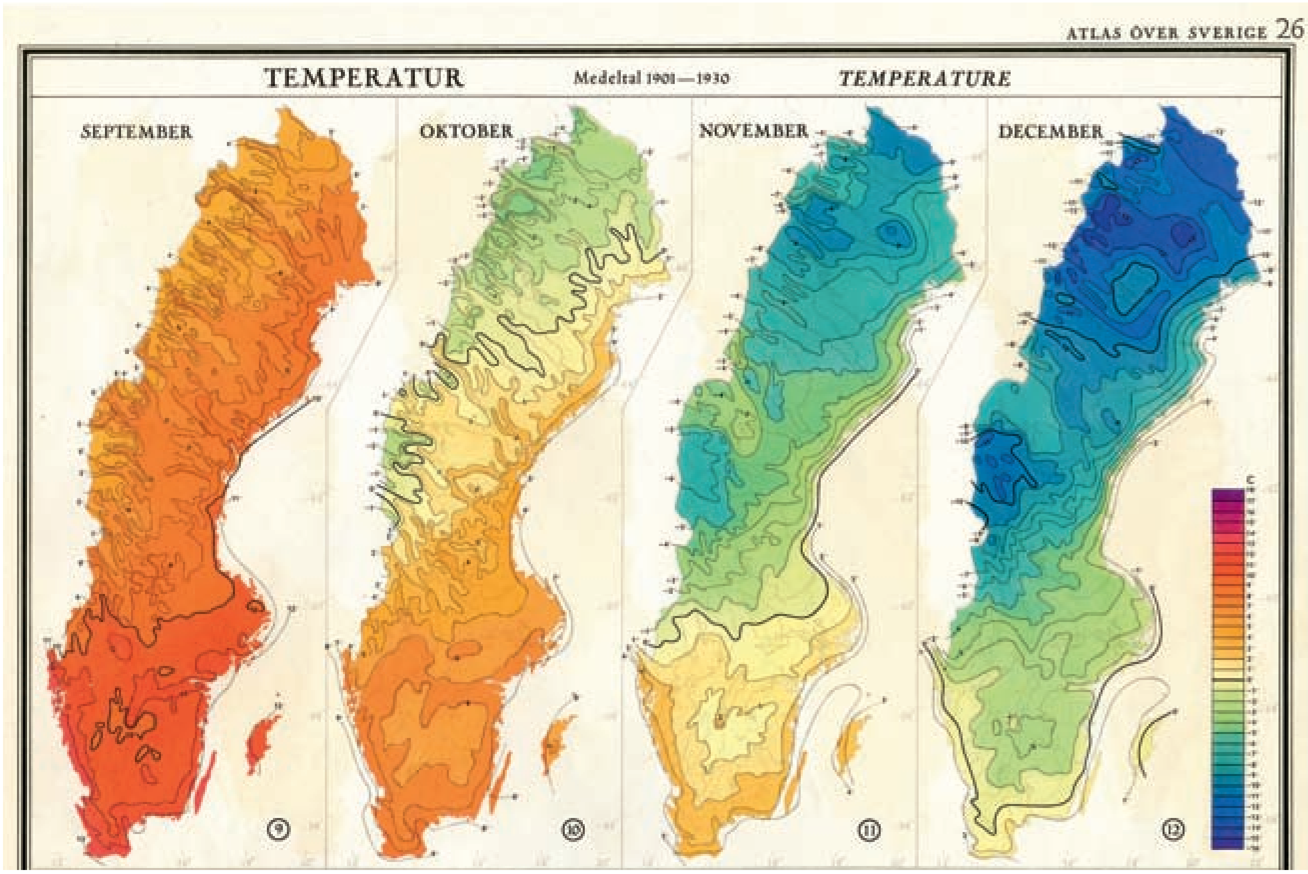

FIG. 258. MAPS OF AVERAGE TEMPERATURES IN SWEDEN, 1901–30. The months of September to December are shown. The first national atlas of Sweden was produced by AB Kartografiska Institutet, Esselte.

Size of the entire original: 40.6 × 32 cm; size of detail: 20.7 × 32 cm. From *Atlas över Sverige* (Stockholm: Generalstabens Litografiska Anstalts Förlag, 1953–71), pl. 26.

lithography to Sweden to replace costly copperplate engraving, was commissioned to print the map sheets surveyed by the Topografiska corpsen. His enterprise, initially called the Lithografiska tryckeriet vid generaladjutantens för armén expedition but renamed the Generalstabens litografiska inrättning in 1837, was a civil service department, outside the military chain of command. The demand for commercial maps began to grow after security restrictions were lifted from military mapmaking in 1857.

Johan Erik Algernon Börtzell, who succeeded Dreyer in 1872, added the printing of geologic maps to his government contract. In 1873 he renamed the operation Generalstabens litografiska anstalt, and in 1884 the government authorized the GLA to sell its geologic maps. The enterprise then formed a commercial division to produce and sell wall maps and a well-known school atlas (*Roths skolatlas*) along with other routine publishing activities.

To keep pace with technical developments Axel Lagrelius was sent to Germany to learn about photomechanical engraving and printing. The introduction of offset printing around 1900 radically reduced the cost of multicolor maps.

In 1903 the GLA's government contract was extended for another twenty years. The agreement required a total commitment to government work in times of war or military maneuvers and also obliged the GLA to use the best techniques available and to pioneer experiments.

The GLA had been organized as a corporate subsidiary of Börtzell's tryckerier AB, which in 1913 joined twelve other prominent printing and graphics businesses to form SLT, which was more like a loosely affiliated business group than a typical company inasmuch that its member companies were largely independent. The government contract was renewed again, in 1923, and the GLA successfully continued under the competent management of Lagrelius and Åke Wickman, to print and sell Swedish public-sector maps as well as produce a growing number of private-sector maps and atlases.

During World War II the GLA hired Carl M:son Mannerfelt to renew its cartography. While employed at the GLA, Mannerfelt worked on his doctoral thesis in physical geography, a pioneering study of air-photo interpretation, completed in 1945. There were close personal relations between Stockholm University geographers and Esselte. In 1959 Mannerfelt succeeded Wickman as managing director of the GLA and became the last head of operations appointed by the government.

Technical innovations in the postwar period included plastic engraving. Esselte's map division reached its peak with the completion of Sweden's first national atlas and widening international engagements. In 1959 Mannerfelt spearheaded the formation of the International Cartographic Association (ICA) and served as one of its vice-presidents until 1964. The ICA's highest award, the Carl Mannerfelt Gold Medal, commemorates his accomplishments.

In the early 1960s Sweden's Social Democratic leaders, who were strongly committed to state-owned industrial enterprises, decided to take over the printing of official maps. The government canceled its contract with the GLA, and on 1 January 1963 the Rikets allmänna kartverk (RAK) started publishing Sweden's official maps. The RAK, which carried out military surveying, had been removed from the General Staff in 1937 and made a civil service department. The government paid the GLA for the remaining stock of printed maps and called for bids on the government printing contract. Another state-run enterprise, Statens reproduktions anstalt, took over map distribution.

In 1962 Mannerfelt became managing director of the entire Esselte group. He reorganized the fragmented Esselte family of thirty subsidiaries into eight divisions, each with a specific focus. One of these eight was the map division, Esselte Kartor AB.

Under Mannerfelt and a leading cartographer, Olof W. Hedbom, the map division developed innovative and visually effective designs for atlases and wall maps. Its traditional geographical map, with a green-yellow-brown color sequence for lowland-to-highland hypsometric categories, was replaced by the *miljökartor* (environmental map), which used yellow for arable/open landscapes, green for forests, red for built-up areas, and relief shadowing in mountainous areas. These colors drew upon the user's visual experience with the landscape and were highly successful (fig. 259).

The Esselte map division also developed an export market, producing atlases for a number of countries. Products intended for export carried the name Esselte Map Service (EMS). Esselte as a whole developed into a purely graphic arts manufacturer specializing in office supplies. The company thrived during the 1970s, but this era ended in a partial sale of its subsidiaries. In 1990 Esselte sold its publishing division to the government-owned Liber, which in 1991 absorbed the EMS, known as GLA Kartor AB until 1993, when it was renamed Liber Kartor. Hedbom followed the maps and became managing director of Liber Kartor. Later, Liber Kartor was privatized and sold to the Dutch firm Wolters Kluwer, under which its long-standing map-production activities came to an end.

STAFFAN HELMFRID

SEE ALSO: Atlas: World Atlas; Marketing of Maps, Mass; Road Mapping: Road Mapping in Europe

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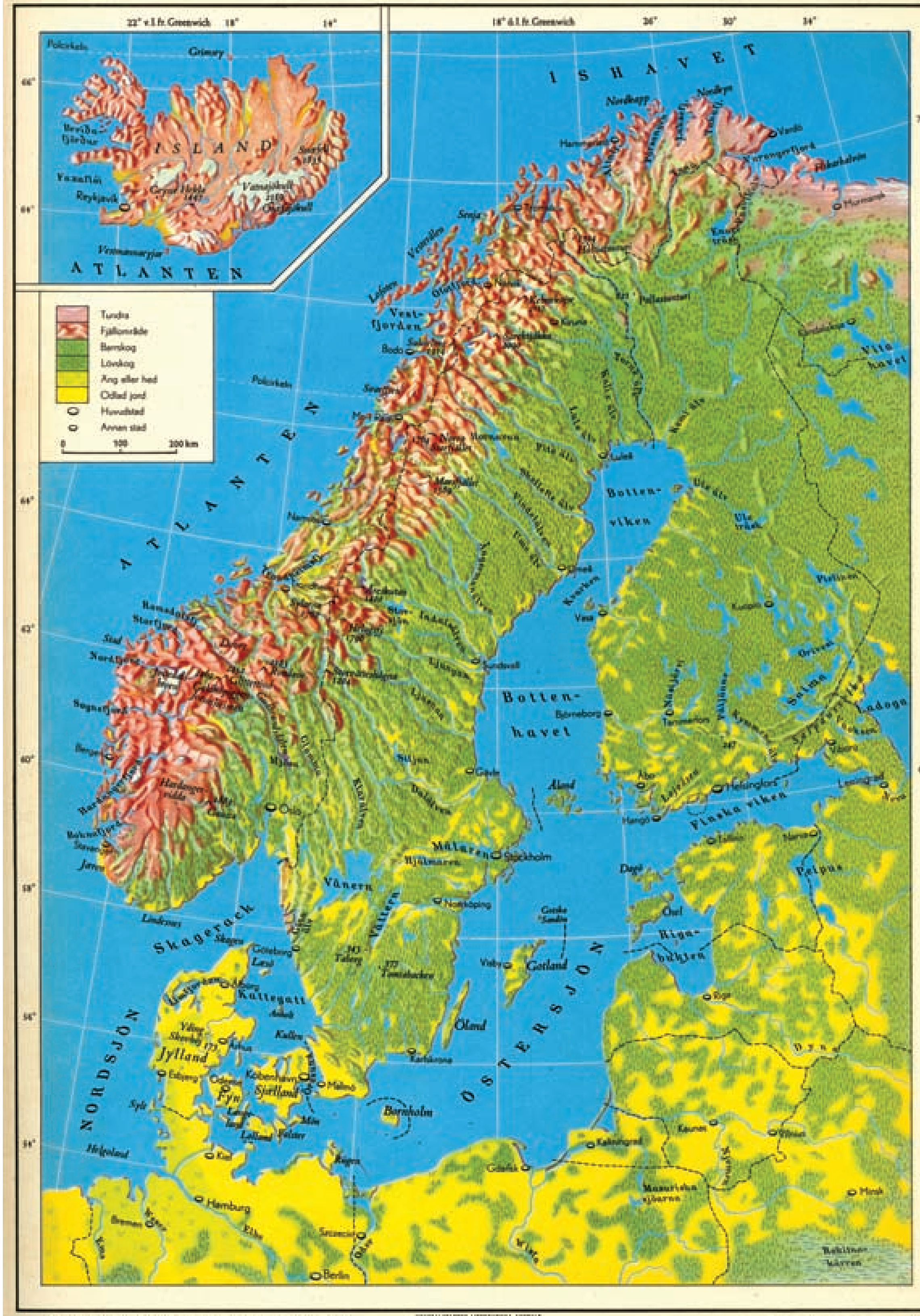
Ethnographic Map.

Ethnographic maps are a cartographic genre focused on creating, describing, and perpetuating the geography of ethnic groups. Because ethnicity is a tenuous concept, efforts to define and map ethnic groups are inherently political and potentially contentious. Used extensively after World War I to promote self-determination, ethnographic mapping became an established strategy for using biased cartographic arguments to claim territory or justify colonial or administrative control.

Few social science concepts are as complicated and as ardently debated as ethnicity. While some scholars continue to consider ethnicity as naturally occurring or primordial, it is more common today to treat ethnicity, along with race and culture, as social constructs that are fluid and contested. Based on real or imagined cultural, religious, linguistic, historical, geographical, or racial distinctions between groups of people (as identified by themselves or others), ethnicity inherently defines and categorizes groups of people by including some and excluding others. Race has often been implicated in defining ethnicity, and in the early twentieth century the terms were often used interchangeably (Crampton 2006, 739). In Euro-American contexts in particular, ethnic and racial groups are often defined as minorities that are not part of the white majority.

Maps have been instrumental in the creation and perpetuation of ethnic groupings, which occur at diverse



Normal konisk projektion med längdriktiga meridianer

Skala 1:7,5 milj.

scales ranging from the neighborhood to the transnational (Winlow 2006). Used to define and locate ethnic groups as well as establish boundaries of ethnic territory, ethnographic maps have often served as symbols of national identity, consciousness, and pride.

Although ethnographic maps predate the twentieth century, they became particularly prominent in post–World War I efforts to delineate ethnopolitical borders for nation-states. Influenced by environmental determinism, numerous Western academics and politicians devised maps that classified people racially and ethnically and then used these delineations to suggest national boundaries purported to separate homogeneous populations. Within a cartographic framework, place-names and diverse statistics based on language, religion, or biology helped create blocs of ethnically distinct groups. As political tools, these maps were manipulated to promote land claims as well as justify the inclusion or exclusion of certain groups. Colored areas with clearly defined borders thus erased diversity and created outsiders. In the early and mid-twentieth century, American and European politicians and scholars produced numerous maps for peace conferences and textbooks that equated ethnic groups with geographically contiguous nation-states, most notably in Germany, Hungary, and the ethnically diverse Balkans.

Following the fall of the Austro-Hungarian and Ottoman Empires in World War I, the territorial division of the Balkans became the subject of much debate in what Robert Shannan Peckham called "the ethnographic appropriation of the region" (2000, 79). Jovan Cvijić, an influential Serbian geographer, advanced the Serbian cause by documenting, classifying, and mapping ethnic groups in the Balkans (see figs. 194 and 779). Specifically, he used maps to depict Macedo-Slavs as a distinct ethnic group, thus rendering Macedonia as an ethnically natural part of Yugoslavia, rather than an extension of Bulgaria or Greece (Peckham 2000, 80). Cvijić's goal was to unify Yugoslavia, which meant ethnically classifying as Slavic the diverse peoples of Serbia, Croatia, Slovenia, and Montenegro. Geographer Jeremy W. Crampton (2006, 741), in his examination of post–World War I mapping of the Balkans, observed that even though Cvijić recognized a mix of people in the Balkans, he also believed that natural ethnic barriers could be mapped. Decades later his maps helped the leaders of post–World War II Yugoslavia argue that their country was a legitimate and coherent nation-state.

Ethnographic mapping was common throughout Central Europe. Guntram H. Herb's study of German mapping from 1918 to 1945 found an increased focus after World War I on the development and production of "more accurate ethnographic maps as documentary evidence for revision and the development of alternative concepts of national territory" (1997, 88). During the interwar years, the Nazis used language survey data to create highly "accurate" ethnographic maps that supported their territorial ambitions (Herb 1997, 142). Similarly, in 1953 Belarusian linguist John P. Stankievich used linguistic data to delineate the ethnographic boundaries of Belarus in his map *Whiteruthenia (Byelorussia) Ethnographical & Historical Boundaries*. New methods of mapping ethnographic populations emerged after World War II. Count Pál Teleki, a Hungarian geographer, member of Parliament, and premier during World War I, was an avid cartographer. His so-called *carte rouge* used population densities to show Hungary's multiple ethnic distributions (Kiss 1941; and see fig. 473). Another innovation was French geographer Emmanuel de Martonne's ethnographic map of Romania (see fig. 521), which separated urban and rural populations into ethnographic regions (Palsky 2002).

In addition to partitioning territory, ethnographic maps were also used in diverse ways to map economic, social, cultural, occupational, caste, and linguistic aspects of human geography. A noteworthy example is the *Ethnographic Atlas of Ifugao* (Conklin 1980), the compilers of which relied on fieldwork data and direct observation to map the economic, social, and cultural context of the rural northern Philippines as well as its ethnic diversity (see fig. 37). Similarly, the *Ethnographic Atlas of Rajasthan* (Mathur 1969) depicted ethnic breakdowns as well as traditional occupations of the province's castes system. A. L. Kroeber, an American anthropologist at Berkeley, devoted seventeen years to producing maps showing the linguistic diversity of Californian Indian tribes in his *Handbook of the Indians of California* (fig. 260).

Ethnographic mapping was also a tool of colonists. Eric Worby (1994) described how the British colonial administration used generalized ethnographic maps to help control northwestern Zimbabwe. Similarly, British colonists created maps of the 1963 Zambian census specifically showing population density and ethnic divisions (Kay 1967), which helped them to better understand the spatial distribution of the populations that they sought to control. At the end of the century ethnographic maps are still used in projects of simplification and control. Ethnolinguistic maps of Iraq were commonly used during and after the 2003 U.S. invasion to show where Sunni Arab, Shiite Arab, and Sunni Kurds lived (for

(*Facing page*)

FIG. 259. *NORDEN, RELIEF, VEGETATION OCH ODLING*, ENVIRONMENTAL MAP.
Size of the original: 32 × 21.7 cm. From *Nordisk Skolatlas: Läroverksupplagan*, ed. Hans W:son Ahlmann et al. (Stockholm: Svenska Bokförlaget, 1953), 9.

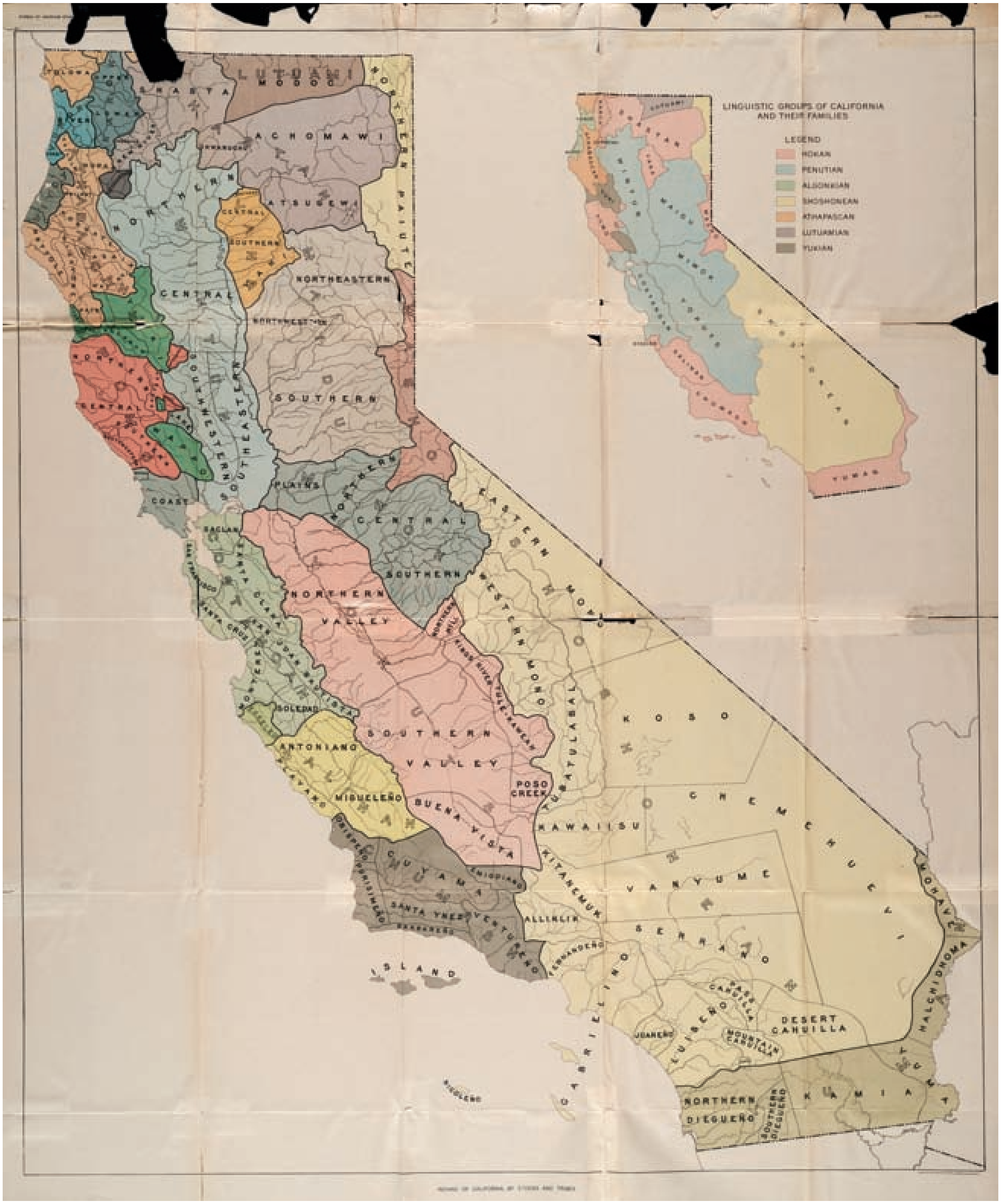


FIG. 260. A. L. KROEBER, ETHNOGRAPHIC MAP OF CALIFORNIA NATIVE PEOPLES.
Size of the original: 71.1 × 60.2 cm. From Kroeber's *Handbook of the Indians of California* (Washington, D.C.: Government Printing Office, 1925), pl. 1.

example, *Distribution of Ethnoreligious Groups and Major Tribes*, an inset to the Central Intelligence Agency's *Iraq: Country Profile*, 2003). Such maps were used to help to disseminate generalized information of a complex and multicultural place that Americans—including politicians and military leaders—knew very little about, even though this was their second military conflict there in just over a decade.

Despite (or perhaps because of) its scholarly overtones, ethnographic mapping is a political project involving choices and biases, and one for which there is no standard formula or approach. As the genre became more common in the twentieth century, these maps were based on diverse data and customized to serve distinct ends. Motivated at times by geopolitical and imperial ambitions, these maps often included poorly drawn boundaries, which triggered ethnic wars and resistance movements. As exemplified by cartographic portrayals of geopolitical and ethnic boundaries in Yugoslavia and linguistic groups in North America, mapping constructs ethnicity as much as it describes it.

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SEE ALSO: Cvijić, Jovan; Demographic Map; Geopolitics and Cartography; Linguistic Map

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Eurocentric Bias. Throughout history mapmakers have tended to place their own territory or some ideologically significant place—Jerusalem on medieval *mappaemundi*, Europe during the Cold War—at the center of the map. This ethnocentric tendency was well documented by Charles Wentworth Dilke, who in his *Great Britain* (1868) coined the term "omphalism" (based on the Greek word for navel) to describe a centralization of government or world interest, and by Yi-Fu Tuan in his classic text *Topophilia* (1974, 30–44), which provides a wide range of cross-cultural examples. A specifically Eurocentric bias in world mapping is a significant feature of twentieth-century mapping and has been a crucial part of the map's role in creating and maintaining Western political and economic hegemony within the global international system. Moreover, Eurocentric bias was still apparent at the end of the century despite a de facto shift in military and economic power to the United States after World War II. In J. B. Harley's words, Eurocentric maps, despite their apparent mathematical objectivity, reinforce "the manifest destiny of European overseas conquest and colonization" (Harley 1989, 10).

Eurocentric maps predominated in the early twentieth century, when major publishing houses in Europe supplied maps to metropolitan centers and colonial peripheries alike, and European educational models ensured the inculcation of a Eurocentric worldview in children across the globe. The centrality of metropolitan power was crucial to the myth of a benign, paternal imperialism. This "Euro-omphalism" was exemplified by the world map forming the frontispiece to *The Growth of the British Empire* (fig. 261)—"in the middle is tiny England, which is the Mother-country of them all" (Kerr and Kerr 1911, 2). Tuan (1974, 43) described such devices as "egregiously ethnocentric," and drew particular attention to the map in Sir Halford John Mackinder's classic study *Britain and the British Seas* (1902), *The Land Hemisphere* centered on Britain and designed to celebrate Britain's central position within the "Mediterranean Ocean" and the "Land Hemisphere." This and similar maps of empire emphasized the center's global reach and military power, often reinforced by lines of commerce—shipping lines, undersea cables, and, later, air routes—and exemplified by the map accompanying a 1943–44 article by Sir Edward L. Ellington (fig. 262).

These imperial images could also be subverted. For example, a World War II–era German propaganda map neatly turned a conventional Mercator map of the British Empire on its head by replacing the imperial pink with an acidic yellow and other countries in black, thereby treating Britain as a predatory power at the center of its worldwide empire (Murray 1987, 237). Equally important were maps deliberately designed to shift emphasis away from maritime Western Europe. Mackinder provided a classic example in his 1904 "Geographic Pivot of History" (see fig. 323), which illustrated "the natural seats of power" and his "pivot" region, centered

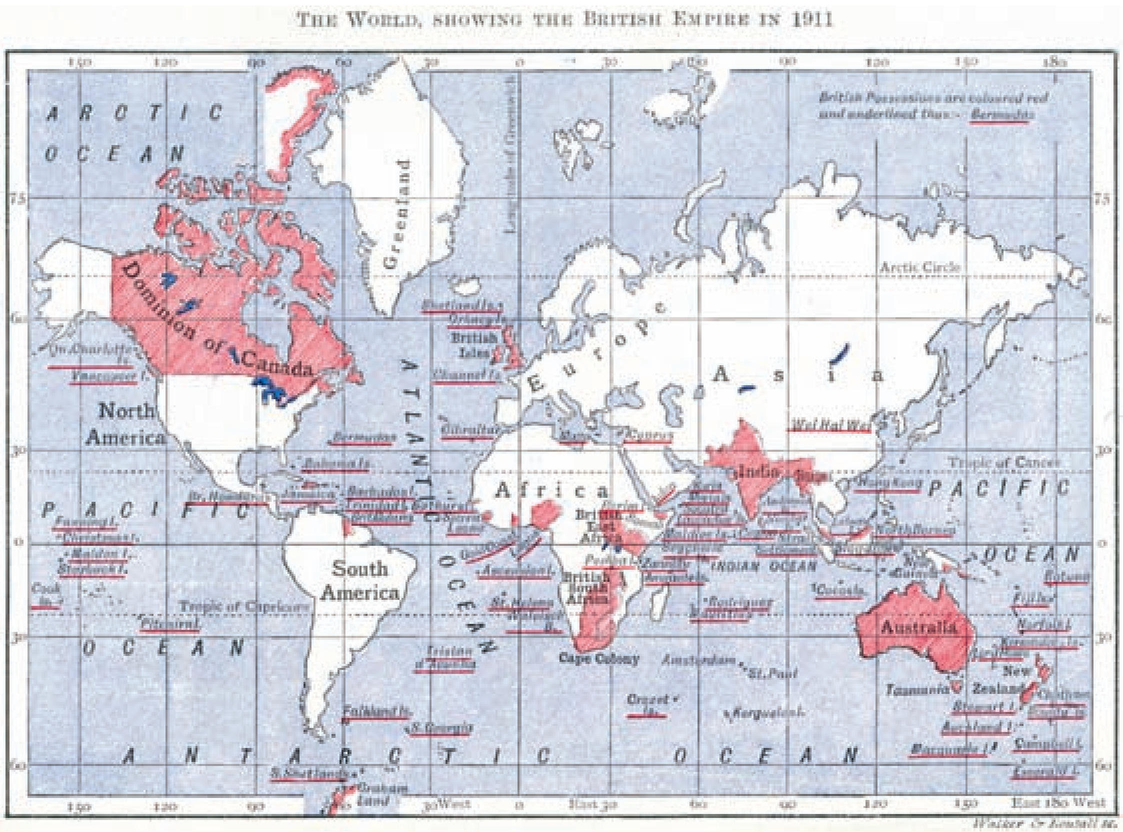

FIG. 261. *THE WORLD, SHOWING THE BRITISH EMPIRE IN 1911*, ENGRAVED BY WALKER & BOUTALL.
Size of the original: 11 × 14.8 cm. Frontispiece to Kerr and Kerr 1911.

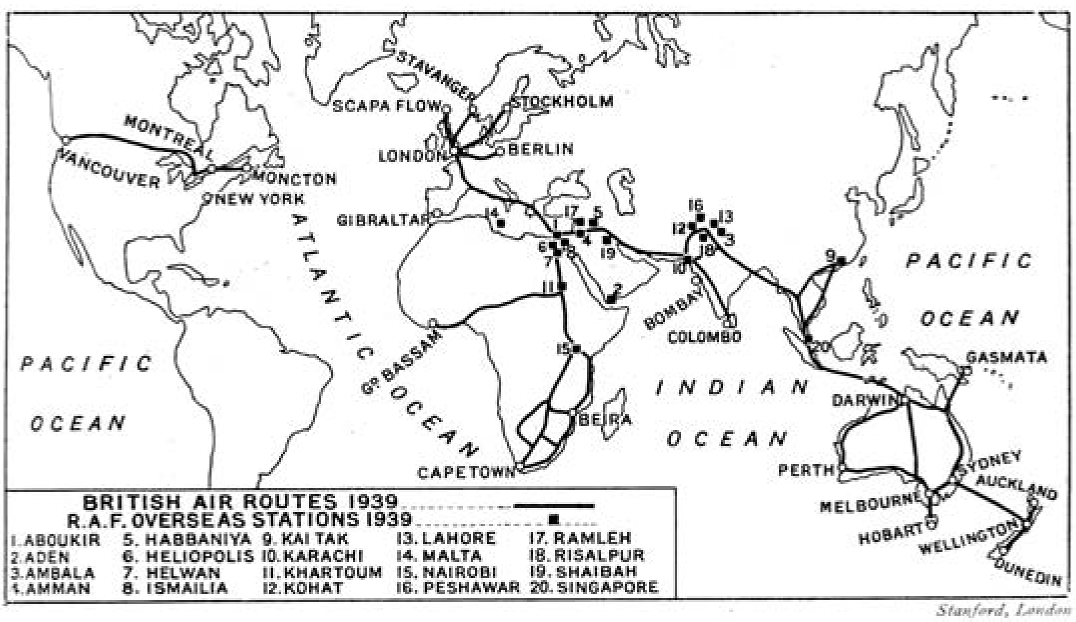

FIG. 262. MAP OF BRITISH AIR ROUTES AND RAF OVERSEAS STATIONS IN 1939.
Size of the original: 7.8 × 14.1 cm. From Edward L. Ellington, "Air Power and Geography," *Geographical Magazine* 16 (1943–44): 111–19, map on 111. Permission courtesy of Geographical Magazine Limited, Middlesex.

on Eurasia (a theme revisited by Zbigniew Brzezinski [1997], former assistant to the U.S. president for national security affairs [1977–81], nearly a century later). Resetting the center drew attention to key geopolitical themes, notably Mackinder's concerns with the relative balance between sea power and land power.

The imperial legacy remained potent and was evinced by a number of studies, the most important of which is Thomas F. Saarinen's (1988) analysis of 3,863 sketch maps drawn by students from forty-nine countries across the world. His findings confirmed the persistence of a Europe-centered worldview that "may be explained by a lingering colonial influence" (112). His examples from Anglo-America make this point clearly: overall 69 percent of students still produced Eurocentered maps, although far fewer than students in Europe (94 percent), as might be expected. Not surprisingly, U.S. students were less Eurocentric (65 percent) than their Canadian counterparts (81 percent). The only significant deviation from a Eurocentric worldview was exhibited by historically strong national cultures in Asia (Japan 5 percent, China 10 percent, and South Korea 3 percent) and by some states in Oceania (e.g., New Zealand, 6 percent) that tended to reject their "peripheral" status (see discussion of *McArthur's Universal Corrective Map* below). By contrast, "developing" states with a marked colonial heritage displayed high levels of Eurocentrism (e.g., India and Brazil, both 95 percent).

Eurocentric bias in world mapping clearly survived challenges that emerged during World War II. The United States had traditionally produced world maps centered on or near 90ºW, often on a standard Mercator projection, during the late nineteenth and early twentieth centuries. But even this local, Americentric worldview was sometimes challenged, for example, by J. Paul Goode's 1923 (Euro-centered) homolosine projection, described by historian Susan Schulten (2001, 187) as "one of the first to move the United States off center." Innovative and alternative worldviews emerged as the U.S. news media sought to explain the war to their audiences, following the lead of President Franklin D. Roosevelt, who had urged Americans to buy a world map so they could understand their nation's global strategy. Americans quickly recognized the importance of air power and the polar region to national defense, and graphic designers such as Richard Edes Harrison began to create maps that made sense of the new technological and strategic situation. As diplomatic historian Alan K. Henrikson (1997, 107) has pointed out, the old cylindrical projections failed to show the continuity of the "worldwide arena" and were replaced by more effective forms, notably North Pole–centered projections, of which Harrison's map *One World, One War* (1942) for *Fortune Magazine* provides the classic example (see fig. 20). It is worth noting that the United Nations emblem, approved in 1946, is based on a map of the world cast on an azimuthal equidistant projection centered on the North Pole (see fig. 22). Despite this challenge to the dominant worldview, traditional Eurocentric projections continued to be used across a wide range of media after World War II and into the twenty-first century (Vujakovic 2002).

A separate challenge to Eurocentric bias emerged in the late twentieth century, partly as a response to international development issues, and partly in defiance of negative characterizations associated with top-bottom connotations. A classic early example was Stuart McArthur's polemic *McArthur's Universal Corrective Map of the World*, published in 1979 (fig. 263), which placed south at the top and gave Australia a visually dominant position (Black 1997, 38–39, 52–53). Other turn-about maps, including Sinocentric or Americentric versions—the latter centered this time on Latin America, not the United States—were deliberately designed to challenge "northern" hegemony (Murray 1987). Another attempt to counter positional bias was the so-called "new cartography" of Arno Peters. His equal-area projection (also known as the Gall-Peters projection), with its instantly recognizable distinctive shapes of Africa and South America, was almost always published with Europe at top-center, and thus cannot be said to subvert the traditional Eurocentric representations that Peters attacked. But like any map centered conventionally at the intersection of the Greenwich Meridian and the equator, Peters' map was, strictly speaking, Afrocentric.

While many maps and related texts produced during the Cold War tended to reemphasize the central political and geographical position of Europe in the bipolar standoff between the U.S. and Soviet blocs, some publications have challenged this emphasis. For example, Saul Bernard Cohen, who used Eurocentered world maps in his *Geography and Politics in a World Divided* (1975 ed.), employed a Sinocentric map in a later work to represent the newly emerging world order (Cohen 1991). Similarly, Brzezinski chose a turn-about map for his article on geostrategy for Eurasia (1997, 54–55). Perhaps the most interesting of these new worldviews is Samuel P. Huntington's reconfiguration of world politics as a "clash of civilizations" along cultural lines (Huntington 1993, 1996). This involved representing the world map as a series of civilization groups—Western, Latin American, African, Islamic, Sinic, Hindu, Orthodox, Buddhist, and Japanese. John A. Agnew (1998, 121–22) literally portrays Huntington's clusters as discrete entities to visually convey their relative importance geopolitically. He depicts the groups as free-floating, continental fragments, with Europe (and Oceania) adhering to North America as the Western bloc, sundered from an

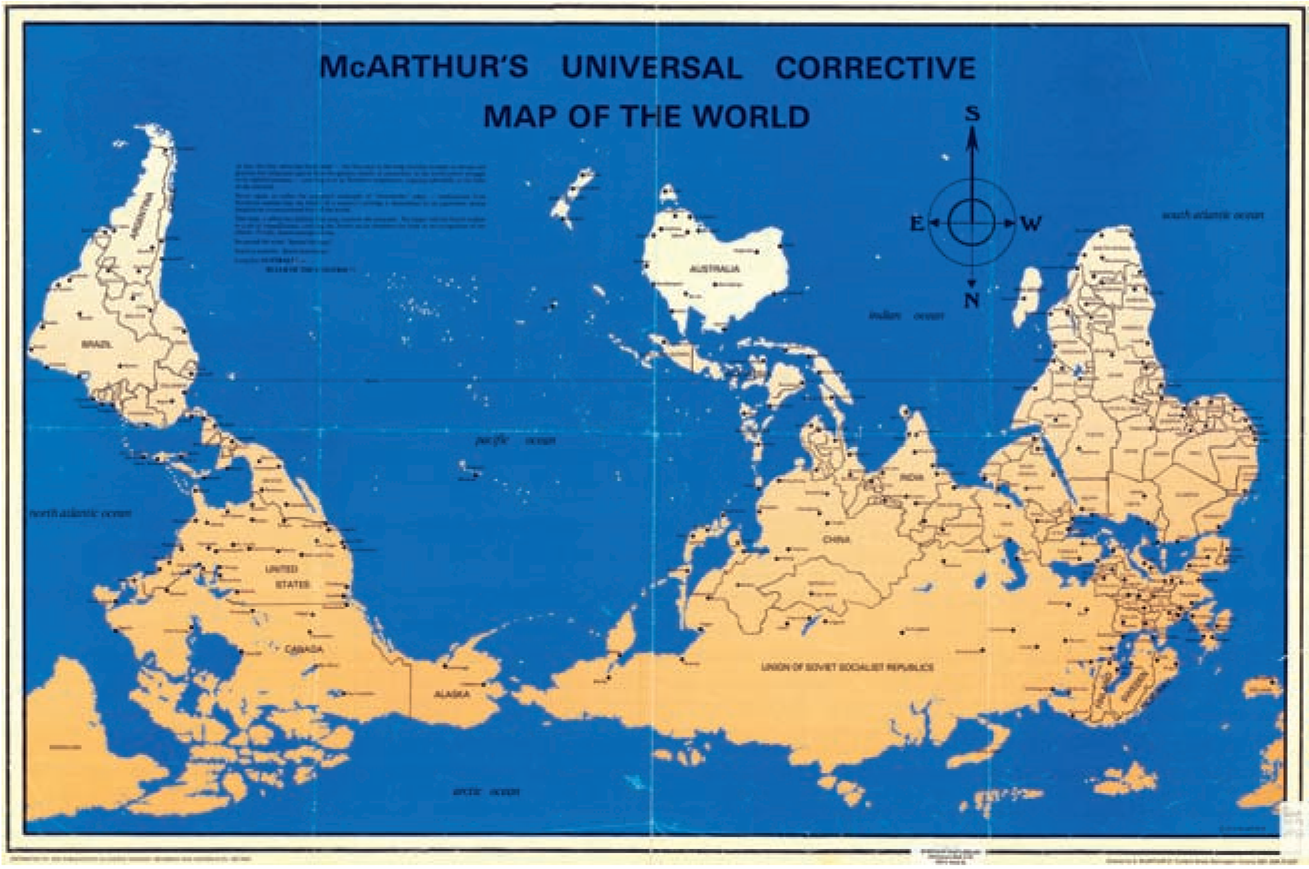

FIG. 263. *McARTHUR'S UNIVERSAL CORRECTIVE MAP OF THE WORLD*, 1979.
Size of the original: 57.5 × 86.7 cm. Image courtesy of the Arthur H. Robinson Map Library, University of Wisconsin–Madison.

Orthodox Eurasian bloc led by Russia. While Huntington's geopolitical analysis is debatable, his and Agnew's maps are emblematic of a postmodern sensibility that sometimes seeped into cartographic representations and spilled over into the world of art to challenge the viewer's sense of place.

PETER VUJAKOVIC

SEE ALSO: Atlas: World Atlas; Colonial and Imperial Cartography; Geopolitics and Cartography; Mercator Projection; Peters Projection; Projections: Cultural and Social Significance of Map Projections; Race, Maps and the Social Construction of

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European Union. After the destruction of World War II, the Western European countries founded the Council of Europe in 1949. Wanting even closer cooperation, six of them formed the European Coal and Steel Community (ECSC) in 1951. Treaties establishing the European Economic Community (EEC) and the European Atomic Energy Community (Euratom) were signed by the "six" (Belgium, France, West Germany, Italy, Luxembourg, and the Netherlands) in Rome in 1957. In 1967 the Merger Treaty, fusing the executive bodies of the ECSC, EEC, and Euratom into the European Communities (EC), unified them under a single executive commission and a single council. In 1973 Ireland, the United Kingdom, and Denmark joined the EC. Greece joined in 1981, Spain and Portugal in 1986. In 1993 the EC became the European Union (EU). Austria, Sweden, and Finland joined in 1995.

The gradual extension and limited sovereignty of the EU and also the handling of larger projects through tenders meant that the EU did not develop a single cartographic service. Initially, maps of the ECSC were produced by related organizations and external experts. For example, I. B. F. Kormoss from the Collège d'Europe in Brugge pioneered supranational statistical cartography under the auspices of the Konferenz für Raumordnung in Nordwesteuropa, a nongovernmental organization. He also authored *The European Community in Maps*, an atlas first published in 1962 by the European Communities in Brussels and based on data from its statistical bureau (Eurostat). Further atlases, such as the *Atlas vedr. regionaludvikling* (1979), published by the European Communities in Luxembourg, were produced under closer EU control. Gradually small cartographic units developed in Brussels and Luxembourg to support the work of politicians and perform simple mapping operations, like the production of locator maps. The tendering of more extensive cartographic products militated against the development and homogeneity of EU cartography. A fine example of such commissioned work was the STATLAS project, to prepare an integrated electronic statistical atlas of the European Union. The rudimentary state of the EU's cartographic service provided an incentive for producing a European geospatial information database (GISCO; Geographic Information System of the European Commission), a goal that was realized by the year 2000 by Eurostat and the EU Joint Research Centre (mainly its branch in Ispra, Italy).

From a different perspective, the Council of Europe Conference of Ministers Responsible for Regional Planning (Conférence du Conseil de l'Europe des Ministres responsables pour l'aménagement du territoire—CEMAT) began to be interested in cartography as a planning tool in the 1970s and convened workshops. The first CEMAT took place in 1970 in Bonn. One of its resolutions (43e) concerned the harmonization of terminology, statistics, and cartographic methods. The next conference, in 1973 in La Grande Motte, called for the organization of European seminars comprising short-, medium-, and long-term programs for the benefit of cartographers and national officers responsible for regional planning. The first seminar of that series, held in Enschede, the Netherlands, in 1975, was the first large international meeting of European cartographers and regional planners (CEMAT 1975). Apart from homogenizing procedures it did much to prepare the audience for digital data handling and the onset of remotely sensed imagery. The next conference, held in 1976 in Bari, Italy, dealt with problems of standardizing urbanization statistics and terminology. In the meantime technical reports were produced regarding available software packages and their applications (Bernath 1977; Rimbert 1979). Toward the end of the century their work was continued by the European Spatial Planning Observation Network (ESPON).

As a supranational organization distributing enormous sums as agricultural subsidies, the EU needed a system of checks and balances, and that called for an objective measurement method for European land use. In 1985 the CORINE (Coordination of Information on the Environment) program began to build a set of comparable land cover data for Europe, irrespective of national categorizations. It was based on satellite imagery at a scale of 1:100,000. The first version of the database (CLC1990), completed in the 1990s, included forty-four classes of land use categories. Its successor (CLC2000) also provided information on erosion, land use, and biotopes.

In 1979 CERCO (Comité Européen des Responsables de la Cartographie Officielle), an association of Europe's national mapping agencies (NMAs), was founded to coordinate national mapping operations for the EU's original six. By the year 2000 it had become EuroGeographics, based in Champs-sur-Marne near Paris. Its erstwhile operational arm, MEGRIN (Multipurpose European Ground-Related Information Network), had also been incorporated. Its mission was to contribute to the development of geographic information in Europe, primarily by making the databases of European NMAs interoperable and widely available. One of its first products was SABE, the Seamless Administrative Boundaries of Europe file (after 2000 known as EuroBoundaryMap) for georeferencing statistical data. EuroGeographics specialized in formulating technical standards to boost geospatial data interoperability. It supported the work of the International Association of Geodesy (IAG) subcommission, EUREF (European Reference Frame), which defined common datums for geodetic coordinates for Europe (ETRS89) and for vertical heights (EVRF2000). The European national mapping and cadastral organizations provided information on transformation parameters between the national reference systems and the European Terrestrial Reference System ETRS89. For the International Steering Committee for Global Mapping (ISCGM) it produced a seamless and unified pan-European data set at the scale of 1:1,000,000 on the basis of national databases (Global Map). By 2000 it was considering production of a 1:250,000 pan-European vector data set (EuroRegionalMap). The overarching structure of all EuroGeographics activities, called EuroSpec, was designed to implement full operability of geospatial reference information produced by national mapping agencies and to create a European Spatial Data Infrastructure (ESDI). By 1999 the EU was also planning to add a third global satellite navigation network, Galileo, to the two existing networks, Russia's GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) and the U.S.'s GPS (Global Positioning System).

During the second half of the twentieth century the member countries of the EU collaborated on various cartography-related projects, including publication of maps and atlases; coordination of regional planning; creation of land cover, boundary, and other databases; and planning a new global satellite navigation network. Those geospatial tools and data sets were generated to facilitate the governance of an increasingly unified Europe.

FERJAN ORMELING

SEE ALSO: Comité Européen des Responsables de la Cartographie Officielle (European Committee of Representatives for Official Mapping; International); Geographic Information System (GIS): Metadata; Intellectual Property; Standards for Cartographic Information

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Exclusive Econonomic Zone. See Law of the Sea

Experimental Cartography Unit, Royal College of Art (U.K.). The Experimental Cartography Unit (ECU) was a cartographic research unit funded through the Natural Environment Research Council (NERC) of the United Kingdom. From the late 1960s through the 1980s, the ECU was the primary European research organization involved in the development of computer-assisted cartography and was a pioneer in high-quality computer mapping and early geographic information systems (GIS) work. David P. Bickmore, a cartographer for the Clarendon Press, proposed the idea for a research unit in automated cartography to the NERC in 1965. Bickmore's experience in creating *The Atlas of Britain and Northern Ireland* had convinced him of the need for computerized cartographic methods to improve the efficiency of cartographic production (Bickmore 1968; Margerison 1976, 4). The council approved Bickmore's proposal, and by 1967–68 the ECU was fully operational, with Bickmore heading the new research unit and Sir Michael James Lighthill appointed as the chair of the steering committee.

London's Royal College of Art was the original home of the ECU, but it also maintained links to the Imperial College of Science and Technology of the University of London and the Clarendon Press. While the Royal College of Art may seem like an untraditional location for a cartographic research unit, it was chosen intentionally in an effort to break from cartographic traditions, and to embrace new theories and technological advances in graphic design. To support the development of the new theories and technologies necessary for the automation of cartographic design and production, the ECU was staffed by individuals with expertise in a wide range of areas such as computer science, software engineering, geography (including David Rhind), graphic design, and optical physics.

Research at the ECU was project based and primarily tied to Bickmore's interests in automating cartographic design and map production. Some of the ECU's early collaborators were the British Ordnance Survey, the Institute of Oceanographic Studies, the Institute of Geologic Sciences (later the British Geological Survey)—another component of the NERC—and several local government agencies. The cartographic needs of these agencies were influential in setting the research agenda for the ECU.

The primary research activities at the ECU can be divided into three categories: data capture, computer processing of data, and data output. In the early years, the work of the ECU was focused on developing the hardware technology and software necessary to digitize and create reusable computerized databases. Some of the earliest projects of the ECU were based on translating digitizer coordinates to global coordinates, projecting digitized coordinates, creating database structures for indexing digitized features, and developing the tools necessary to edit the digitized databases. This work resulted in the creation of a new database structure for geographic information involving only points and lines, with a complicated set of feature codes signifying the relationship of points and lines as well as relating lines to one another in order to form complex objects. The initial work on data structures and digitizing hardware resulted in the development of a large cartographic database of entries from *The Atlas of Britain and Northern Ireland*. This effort also resulted in the publication of "the first map proper to be produced by automation (crude lineprinter or tabulator-produced maps had been published earlier)" (Experimental Cartographic Unit 1971, 72). This was a bathymetric chart of the Gulf of Aden in the northwest Indian Ocean (figs. 264 and 265) published in October 1968. In addition to developing their cartographic database, the ECU actively worked on routines for processing digitized data and for simplifying the transfer of data. In particular, the ECU created a set of recommendations for standardizing data transfer and produced a significant literature on computerized contour creation and smoothing and on theories of scale-dependent generalization.

While much of the work of the ECU was focused strictly on the design and implementation of new cartographic technologies, it was all guided by the need to produce cartographic products for the agencies with which they collaborated. Bickmore felt that little was known about effective cartographic design and that the cartographic conventions in use may not have been optimal for cartographic communication. The use of automated cartographic methods allowed for greater flexibility in customizing maps, and it facilitated testing the effectiveness of different cartographic design elements. From the early 1970s through the 1980s, the ECU conducted empirical map design studies with human research subjects, including perceptual studies of symbols, typefaces and sizes, and color schemes (e.g., Hill 1974). While this research did not produce any particular general theory, it led to the design of "innovative and provocative maps" (Rhind 1988, 286) for the ECU's collaborating agencies.

In 1978, the ECU moved from London to Swindon, U.K. During the period of the move, the ECU was renamed the Thematic Information Service (TIS) of the NERC. Around this time, Bickmore retired as the head of the ECU, and Dr. Michael Jackson was appointed director. In 1985, the research component of the TIS moved to the Geography Department at the University of Reading and became the Natural Environment Research Council Unit for Thematic Information Systems (NUTIS). This was eventually renamed the Environmental Systems Science Centre, which was still active in the early twenty-first century.

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SEE ALSO: Electronic Cartography; Software: Geographic Information System (GIS) Software

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Rhind, David. 1988. "Personality as a Factor in the Development of a Discipline: The Example of Computer-Assisted Cartography." *American Cartographer* 15:277–89.

Exploratory Data Analysis. John W. Tukey was the father of exploratory data analysis (EDA). The publication of his book *Exploratory Data Analysis* in 1977 marked the recognition of EDA as a field of study with an emerging methodology. Tukey continued to shape this new field by coauthoring and coediting several books and by writing papers that further fleshed out the associated concepts and methods.

Tukey (1977, v) said EDA is about "looking at data to see what it seems to say." EDA methods include use of resistant statistics, such as the median, that change little if the data contain a few anomalous values, and data transformations (reexpressions) that simplify appearance, increase symmetry, and facilitate comparisons of data subsets. EDA methods also include decomposing data into fit plus residuals. Either may reveal patterns when shown in the context of additional variables. For time series, local smoothing provides fitted values and residuals. For analysis of variance there is an exploratory analog. EDA fitting often uses resistant statistics and iterative procedures to progressively separate structure from noise.

Tukey (1977, v) noted that "a basic problem about any body of data is to make it more easily and effectively handleable by minds." He laid out two key tasks: simplifying descriptions and making descriptions more effective by looking below previously described surfaces. Tukey's box plots provided a simple univariate description that spread around the world. His automated cartography suggestions for looking below surfaces included adjusting mortality rates for known sources of variation beyond sex and age before mapping. EDA made available focusing methods and linked views that

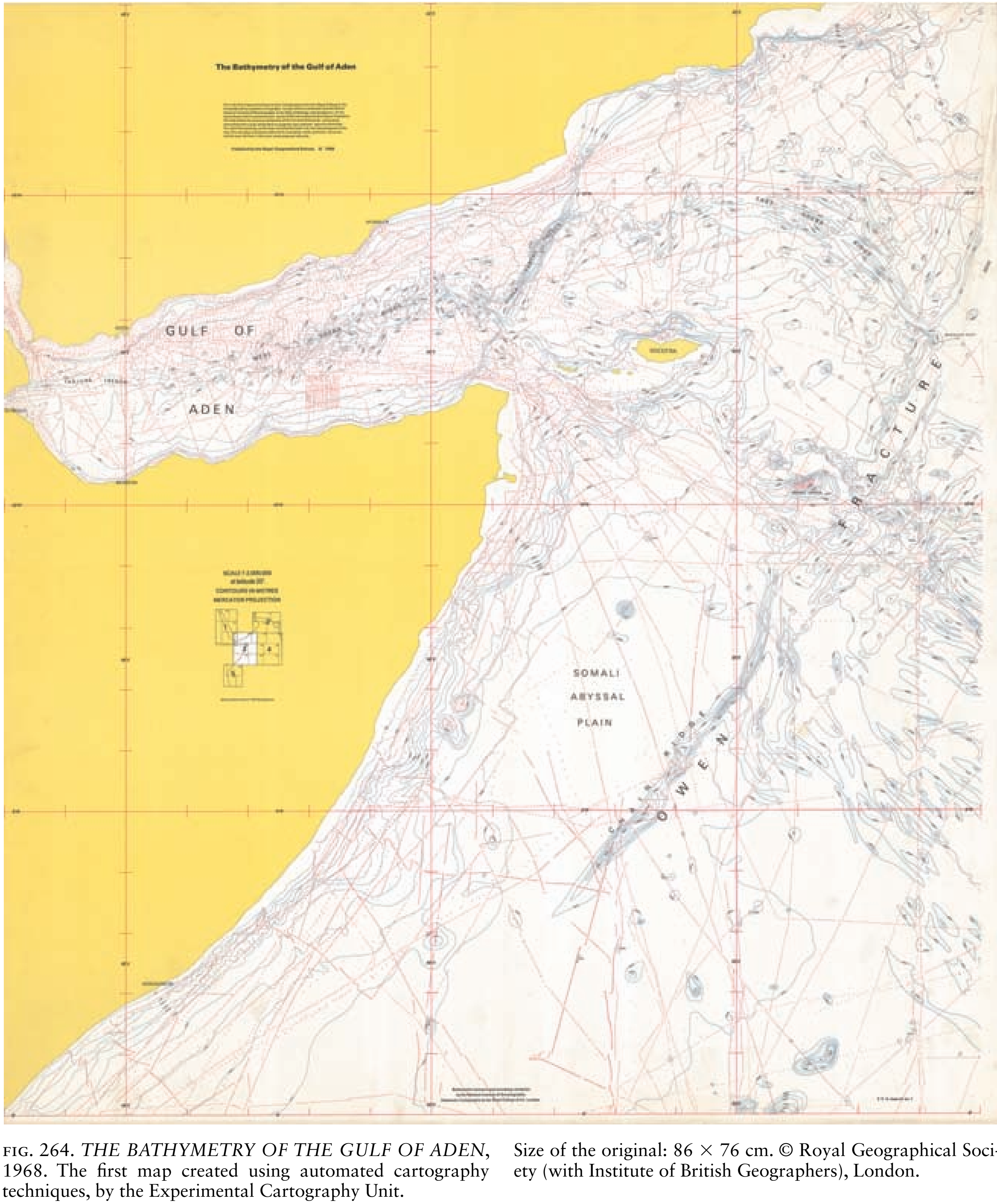

FIG. 264. *THE BATHYMETRY OF THE GULF OF ADEN*, 1968. The first map created using automated cartography techniques, by the Experimental Cartography Unit. Size of the original: 86 × 76 cm. © Royal Geographical Society (with Institute of British Geographers), London.

FIG. 265. DETAIL FROM *THE BATHYMETRY OF THE GULF OF ADEN*, 1968.
Size of the detail: 18.7 × 17.3 cm. © Royal Geographical Society (with Institute of British Geographers), London.

provide a way to look below surfaces by considering additional variables and including contexts of place and time. The methodology emerged from interactive statistical graphics and spread into many fields.

In the late 1970s and the 1980s access to inexpensive microprocessors and raster graphics plus advances in software tools opened the door to development and experimentation with a wide range of EDA tools. There was a whole world of multivariate graphics to explore using interactive and dynamic methods. System building strategies included graphics pipelines, data analysis environments, and data analysis management. The variety of computers included Lisp machines, Silicon Graphics workstations, and specially constructed systems.

EDA graphics for multivariate data included a scatterplot matrix that showed scatterplots for all pairs of variables, rotating and/or stereo 3-D scatterplots, animated sequences of 2-D scatterplots, and glyph plots. Graphical interaction methods for scatterplots soon supported case identification and case subset selection.

Case subset selection and highlighting in a scatterplot matrix helps the analyst to focus attention and make conditioned comparisons. Selection conditions in a scatterplot define two sets of cases, selected and not selected, whose distributions can be compared in other scatterplots. Researchers implemented graphical subset selection in different ways such as point-in-polygon selection and selection based on distance from a cursor. Richard A. Becker and William S. Cleveland (1987) developed a more widely used selection approach called brushing. This allowed the analyst to select a subset of cases by moving a rectangle (the brush) over points in a scatterplot. Brushing with cumulative case selection enabled selection of cases appearing in nonrectangular regions. Scatterplot matrix brushing caused immediate highlighting of the subset's points in all the scatterplot matrix views. Such linked brushing was a focusing tool that enabled multivariate distribution comparisons of data subsets.

Linking across views provides a broader context for understanding the apparent patterns in the scatterplot. Graham Wills and collaborators (1989) included a map as part of linked views. Patterns in either a scatterplot or map can motivate a graphical query, and linked views can suggest explanations. Andreas Buja and collaborators (1991) stressed the importance of focusing and linking, and their companion video includes 1980s examples of linking scatterplot matrixes with point maps, satellite images, and brain images (the web-viewable video is in the video library of the Statistical Graphics Section of the American Statistical Association).

Many fields began referring to EDA applications involving maps as exploratory spatial data analysis, ESDA. Spatial analysis extensions of EDA brought new linked graphics addressing spatial and temporal autocorrelation. Jürgen Symanzik and colleagues (2000) cite related 1990s research and describe the new challenges posed when implementing linked brushing across packages to address the spatial analysis extensions.

EDA focusing and linking methods are not restricted to graphical subset selection. Stratified comparison provides a systematic way to control for known or suspected sources of variation, while looking for relationships across multiple views. Stratification may be based on variables, model residuals, or regions on a map.

Mark Monmonier (1993, 233–38) provided an example of both one-way and two-way stratification (conditioning) based on a scatterplot of two U.S. state variables. The scatterplot includes a linear regression line and two parallel lines that partition the regression residuals into four ordered classes that link by gray levels to a four-class map. The appearance of spatial patterns under such circumstances can provide clues about potential regression model inadequacies. Exploratory methods are useful for model criticism. The scatterplot also shows vertical and horizontal lines located at x and y variable means respectively. For each variable, states are classified into two categories indicating values above or below the mean. The corresponding map, called a cross map, uses gray level to encode each state's pair

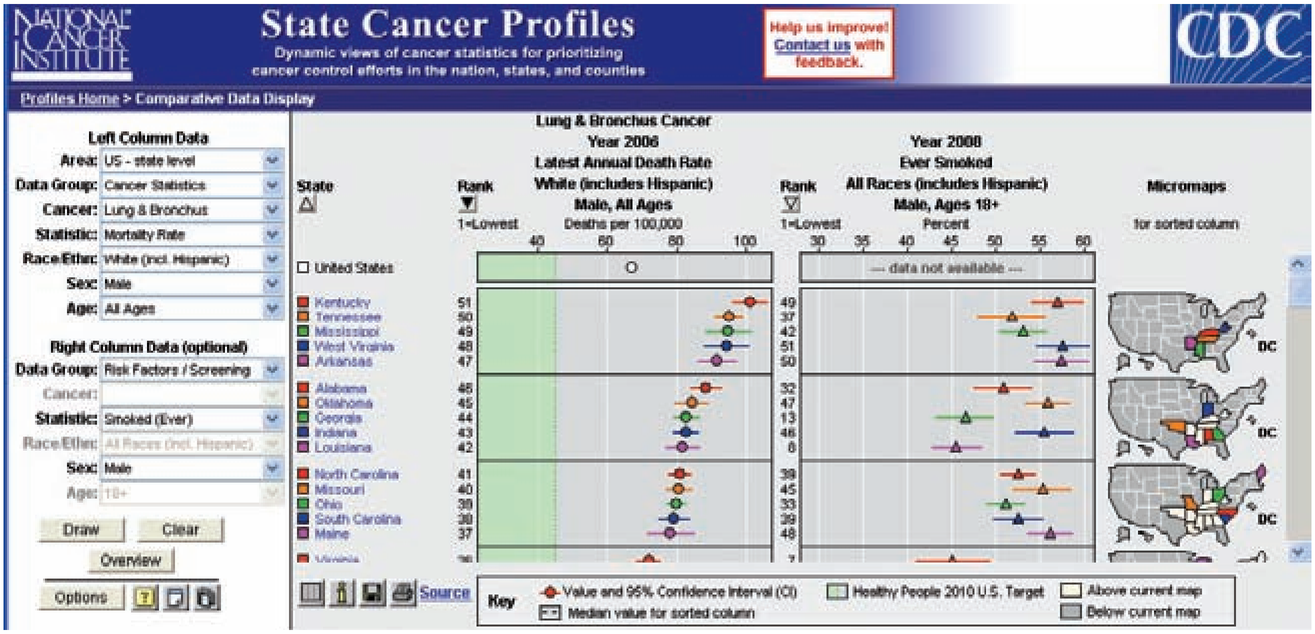

FIG. 266. LINKED MICROMAPS FROM THE STATE CANCER PROFILES WEBSITE. Data selection pick lists are on the left. Scrolling on the right occurs with the page to retain the context of top labeling and bottom key. Micromap panels show highlighted states and accumulation patterns with previously highlighted states appearing in light yellow. State name selection shows county linked micromaps. See Carr and Pickle 2010 or the National Cancer Institution website for more information.
Figure courtesy of Daniel B. Carr.

of classifications. The legend shows the gray levels in a 2×2 matrix with labels indicating the two class stratification for two variables.

Daniel B. Carr and Linda Williams Pickle (2010, 79–108) described the continuing development of two stratified linked view variations called conditioned choropleth maps (CCmaps) and linked micromap plots (fig. 266). CCmaps use two conditioning variables with three-class sliders to highlight and partition map regions in a 3×3 grid of micromaps. The study variable with a three-class slider determines the choropleth classes. This design shows associations among three variables while emphasizing maps. Algorithms provide interactive guidance, suggesting good candidate slider settings and displaying dynamic feedback about manual adjustments.

An early noninteractive exploratory/data mining study of Omernik ecoregions for the coterminous United States used linked micromaps to provide region specific distribution summaries of large data sets such as land cover categories for eight million pixels on 1 kilometer $\times$ 1 kilometer grid. Later, a U.S. National Cancer Institute website included a linked micromap Java applet with variable selection and other interactive options.

With growing masses of data, the fields of data mining and knowledge discovery in databases grew rapidly in the 1990s. The data mining emphasis included rapid database access and algorithms for many tasks such as finding clusters and producing predictive models. Clustering/unsupervised classification methods can serve as automated focusing tools that support EDA. Predictive models often are viewed as sufficiently accurate, even those too complex for human understanding. While many data mining algorithms can support EDA and exploratory applications abound, by the late 1990s the label "EDA" was in decline in this emergent field and other research fields that focused on algorithms.

Alan M. MacEachren and collaborators (1999) promoted integration of geographical visualization and knowledge discovery in databases at the conceptual, operational, and implementation levels. The associated prototype implementation included three views: geoviews (maps), 3-D scatterplots, and parallel coordinate plots—while including interactive EDA tools such as variable assignment, brushing, focusing, colormap manipulation, perspective manipulation, and sequencing (fig. 267). Newer implementations have expanded these tools to include time series plots.

While the label "EDA" is used less and less, EDA-compatible focusing and linking tools continue to evolve in the twenty-first century, particularly in the fields of statistical graphics, geographical visualization, data mining and knowledge discovery, and information visualization. Advances have come from modifying previous tools and from new ideas combined with improvements in computing/graphics technology, data availability, and new algorithms for view prioritization and focusing.

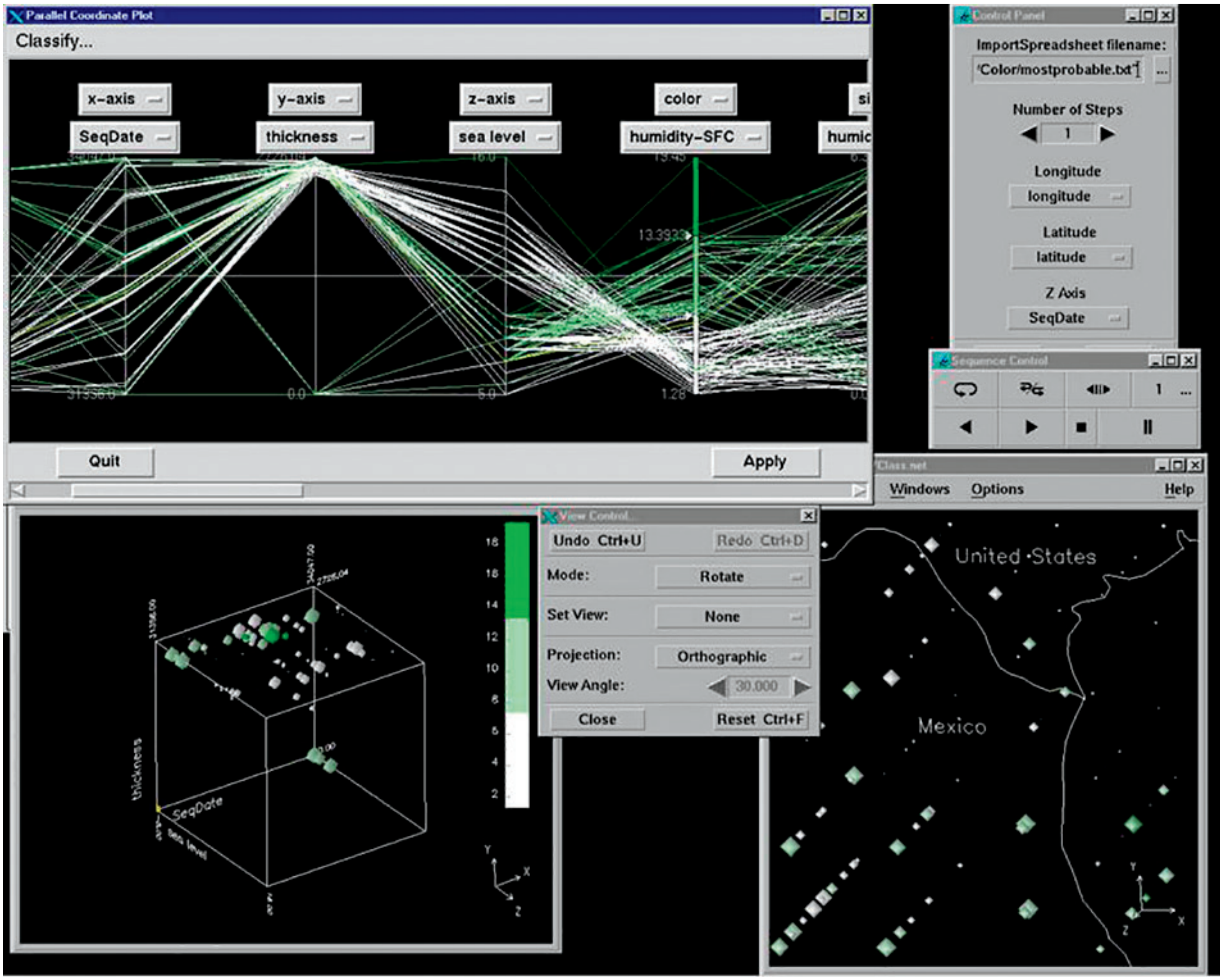

FIG. 267. DYNAMIC THREE-CLASS STRATIFICATION WITH COLOR LINKING A PARALLEL COORDINATE PLOT, A 3-D SCATTERPLOT (3-D OCTAHEDRONS SUPPORT COLOR AND SIZE ENCODINGS), AND A GEOMAP. The parallel coordinate plot has a scroll bar below and additional panels provide access to options. For system explanation, see MacEachren et al. 1999.
Figure courtesy of Alan M. MacEachren.

Cognitive scientists and usability researchers have influenced these developments by better understanding how people mentally process graphical images. Researchers still draw upon Tukey's questions and suggestions from decades ago to prioritize and simplify graphics for more efficient and enlightening data exploration.

DANIEL B. CARR

SEE ALSO: Interactive Map; Statistical Map; Statistics and Cartography; Visualization and Maps

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