ELEMENTS OF CARTOGRAPHY

FIFTH EDITION

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Elements of Cartography

Fifth Edition

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Preface

Cartography is in transition. Where the changes will lead is uncertain, but change in the discipline is pervasive, and the rate of change seems to be accelerating. Many of the changes are the result of very rapid and substantial development in the technology available to cartography. But, equally important, a conceptual maturation of the discipline itself has evolved. Technological changes alone would be relatively easy to deal with, but the maturation of the discipline coupled with the rapid changes in technology demand that practitioners learn not only ways of doing new things, but additional ways of doing old things with new equipment. Many practitioners must also adopt a new awareness of why cartography exists and develop an appreciation for its growing usefulness.

The revision of a textbook during such a time of transition is a challenge. Until recently, many people outside the field have viewed cartography as essentially a technology, and any book purporting to serve satisfactorily as a text for a technology was supposed to be simply a recipe book. But as cartography has matured into an independent field, its basic principles have received increasing attention with the result that the field of cartography has developed to the stage where it is possible to talk with some confidence about basic theoretical principles that guide the mapping process. In fact, today the choice between the mapping alternatives that technological advances have made possible depends more on an understanding of mapping requirements than on technical training itself. Thus, more than a recipe book is needed because the discipline is at the point where a balanced treatment must be given both cartographic theory and cartographic practice. This fifth edition of *Elements of Cartography*, then, is an attempt to provide that balance. Not only has a new, fourth author joined the team, but many other changes have been made as well.

Because so many conceptual and technological changes have taken place since the publication of the fourth edition six years ago, much new material has been added. Many of the appendices of earlier editions have been dropped as being unnecessary in a world of computers and calculators. In response to many requests, a chapter on the representation of the land surface, missing from the fourth edition, has been added. A glossary has been compiled, consisting of terms from related sciences that a cartographer should know. Many of these terms are used in the text of the fifth edition. Cartographic terminology itself is well defined in the text and can be found by referring to the index. The manipulation of cartographic data that appears in image form has received greater attention in the fifth edition as has the systemization of the graphic elements used in creating a map image.

While the field of cartography has been experiencing change, cartographic curricula have remained rather conservative and have lagged somewhat behind the research frontiers. Many institutions still offer only one or two courses, and many students take such courses primarily in the hope of gaining a marketable skill. To accommodate the wide variety of situations in which *Elements* is used, the authors have divided the text into four parts. Part One is general and introductory, consisting of three chapters introducing the student to the nature, the history, and the technology of cartography. These three chapters may serve as an introduction to the field for any student. The remaining three parts may be used together for a one-year course or individually, each as the basis for a separate semester or quarter course. Part Two deals with fundamental operations and principles of cartography, such as map scale, coordinate systems and projections, data manipulation and generalization, and the basic aspects of map design from a more theoretical point of view. Part Three treats data manipulation, generalization, and map symbolization in a more practical manner. Part Four details map production and reproduction procedures as practiced today. The continuing move to the use of computer technology is incorporated throughout the text wherever appropriate.

The authors are deeply indebted to many people without whom the production of the fifth edition would have been made more difficult, if not impossible. Research findings published by many scholars and the expertise of colleagues were immensely useful as were the many comments and suggestions made directly to the authors. Onno Brouwer prepared many and coordinated all of the hundreds of illustrations that appear in the fifth edition. June Bennett helped immensely with typing and managing distribution of copies. The many students at the University of Wisconsin and elsewhere who were subjected to the organization and reorganization of the material in this book over the years deserve much credit for their feedback to its authors. Finally, as always in the production of such works, the families of the authors must sacrifice. Collectively to our wives and, for some of us, our children, the authors express their appreciation and thanks for their support and help.

A.H.R.
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P.C.M.

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PART ONE

Introduction to Cartography

1

The Nature of Cartography

An appropriate question at the beginning of this book is: What is cartography? To answer we will first look at where cartography fits in our endeavor to know and communicate. The beginnings of that struggle are lost in prehistory, but we can confidently assume that the earliest ways used utterances and drawings to create the mental images involved in understanding objects and their relationships. From these sounds developed the spoken and written natural languages of today and the sketches evolved into the variety of present-day graphics.

A significant part of peoples' interest focuses on their surroundings, and the desire for imagery of the spatial organization of things, particularly things in the environment, seems to be as normal as breathing. It can be simple and elementary, as when one is concerned with basic relations, such as inside or outside, near or far, in front or behind, or it can be quite sophisticated as when it involves abstract concepts like the distribution of air pollution. Other animals, primitive people, and young children probably construct unique and situational kinds of spatial images, while experienced adults obviously are capable of highly rational spatial constructions. These images formed in our brains are concerned with the spatial relationships among things or ideas and with the spatial forms of entire distributions. If one person were to attempt to communicate with someone else by describing verbally such relationships or forms, we can only hope that the description would evoke a more or less similar image if all conditions were favorable. That would, however, be much more likely to happen were we to provide a visual representation of the image. This graphic representation of spatial relationships and spatial forms is what we call a *map,* and, very simply, cartography is the making and study of maps in all their aspects.

Written and verbal languages allow us to develop ideas and concepts and express them in a variety of ways, ranging from tightly structured scholarly dissertations to literary creations and dramatics which evoke emotional responses. The use of the written and spoken language, sometimes called "literacy" and "articulacy," is a way of developing, manipulating, analyzing, expressing, communicating various sorts of ideas and beliefs. Mathematics, which has been referred to as "numeracy," is a way of symbolizing and dealing with the relationships among abstractions, sets, numbers, and magnitudes. Just as literacy can range from dealing with highly emotive novels to staid scientific matters, and mathematics from abstract relationships to very precise and accurate calculations, in similar fashion graphics, a fourth way of communicating concepts and relationships, deals with a variety of image presentational methods. These methods range from drawing and painting to the construction of plans and diagrams. The term "graphicacy" denotes this form of communication. Cartography is an important branch of graphics, since it is an extremely efficient way of manipulating, analyzing, and displaying, and thus expressing, ideas, forms, and relationships that occur in two- and three-dimensional space.

In the broad sense, cartography includes any activity in which the presentation and use of maps is a matter of basic concern. This includes teaching the skills of map use; studying the history of cartography; maintaining map collections with the associated cataloging and bibliographic activities; and the collection, collation, and manipulation of data and the design and preparation of maps, charts, plans, and atlases. Although each activity may involve highly specialized procedures and require particular training, they all deal with maps, and it is the unique character of the map as the central intellectual object that unites those cartographers who work with them.

Maps Are a Necessity

People must have assistance in observing and studying the great variety of phenomena that concern them. Some things are very tiny, and we must use complex electronic and optical means (such as the microscope) to enlarge them in order to understand their configuration and structural relationships. In contrast, some geographical phenomena are so extensive that we must somehow reduce them to bring them into view. Cartography consists of a group of techniques fundamentally concerned with reducing the spatial characteristics of a large area—a portion or all of the earth, or another celestial body—and putting it in map form to make it observable. The same techniques can be used to enlarge microscopic things to make them easily visualized. Although it is uncommon to refer to these activities as cartography, the resulting images are sometimes called maps. Just as spoken and written language allows people to express themselves beyond the restriction of having to point to everything, a map allows us to extend the normal range of vision, so to speak, and makes it possible for us to see the broader spatial relations that exist over large areas or the details of microscopic particles.

Even an ordinary map is much more than a mere reduction. It is a carefully designed instrument for recording, calculating, displaying, analyzing, and in general understanding the interrelation of things in their spatial relationship. Nevertheless, its most fundamental function is to bring things into view.

Maps range in size from the tiny portrayals that appear on some postage stamps to the enormous mural-like wall maps used by civilian and military security groups to keep track of events and forces. They all have one thing in common: to add to the geographical understanding of the viewer. All beings live in a temporal and spatial environment in which everything is related to everything else in one way or another. Since classical Greek times, curiosity about the geographical environment or milieu has steadily grown in one civilization or another, and ways to represent it in a meaningful way have become more and more specialized. Today there are many different kinds of mapmaking, and the objectives and methods involved seem very different. It is important to realize, however, that all maps have the same basic objective of serving as a means of communicating spatial relationships and forms; therefore, however dissimilar the maps may seem, the cartographic methods involved are fundamentally alike.

The rapidly growing population of the earth and the increasing complexity of modern life, with its attendant pressures and contentions for available resources, has made necessary detailed studies of the physical and social environment, ranging from population to pollution, from food production to energy resources. The geographer, the planner, historian, economist, agriculturalist, geologist, and others working in the basic sciences and engineering long ago found the map to be an indispensable aid.

A large map of a small region, depicting its land forms, drainage, vegetation, settlement patterns, roads, geology, or a host of other detailed distributions, makes available the knowledge of the relationships necessary to plan and carry on many works intelligently. The ecological complexities of the environment require maps for their study. The building of a road, a house, a flood-control system, or almost any other constructive endeavor requires prior mapping. Smaller maps of larger areas showing things such as flood plain hazards, soil erosion, land use, population character, climates, income, and so on, are indispensable to understanding the problems and potentialities of an area. Maps of the whole earth indicate generalizations and relationships of broad earth patterns with which we may intelligently consider the course of past, present, and future events.

Basic Characteristics of Maps

The radar map on the television weather report showing precipitation and storms seems very unlike the map in the travel brochure proclaiming the "glories of ancient Greece"; yet, they have much in common.

All maps are concerned with two fundamental elements of reality: locations and attributes at locations. Locations (L) are simply positions in a two-dimensional space, such as places with the coordinates x,y. Attributes (A) at locations are some qualities or magnitudes, such as languages or temperatures. From these two basic elements many relationships can be formed. Some examples are:

$L_1 - L_2$ relationships among locations when no attributes are involved, such as the distances or bearings between origins and destinations needed for navigation;

$L_1(A_1,A_2,A_3)$ relationships among various attributes at one location, such as temperature, precipitation, and soil type;

$(L_1)A_1 - (L_2)A_1$ relationships among the locations of the attributes of a given distribution, such as the variation of precipitation amounts from place to place;

$(L_1)A_1A_2 - (L_2)A_1A_2$ relationships among the locations of derived or combined attributes of given distributions, such as the relation of per capita income to educational attainment, as they vary from place to place.

All sorts of topological and metrical properties of relationships can be identified and derived, such as distances, directions, adjacency, insidedness, patterns, networks, interactions. A map is therefore a very powerful tool.

Most maps are reductions, and thus the map is usually smaller than the region it portrays. Each map has a defined dimensional relationship between reality and the map; this relationship is called *scale* and is of primary importance. Because of the relative "poverty" of map space the scale sets a limit on the information that can be included and on the manner in which it can be delineated.

All maps involve transformations of various kinds. A common geometric one is to transform a spherical surface (essentially the shape of the earth) to an easier surface to work with, such as the screen of a monitor or a flat map sheet, by a systematic transformation called a *map projection*. The choice of a map projection affects how a map should be used. It is often convenient to employ on maps referencing systems called *plane coordinate grids*. These coordinate systems assist the map user in calculating distances and directions from the map, two metric properties of common interest. Coordinate systems depend on map projections for their accuracy.

All maps are abstractions of reality. The real world is so intricate and wonderfully complex that merely reducing it or putting a small part of it in image form would make it even more confusing. Consequently, maps ordinarily portray data that have been chosen to fit the use of the map, and these data are subjected to a variety of operations, such as classification and simplification, to enhance their comprehension.

All maps employ signs to designate the elements of reality. Even the responses of the various systems of remote sensing, which produce or yield kinds of maps, are signs in that the display of their spectral sensitivities is different from that which would result from our direct observation if that were possible. The designated meanings of the signs constitute the symbolism of cartography. Relatively few of the symbols used on maps have universal meanings, just as relatively few words have universal meanings in all written and spoken languages. Some maps use unique symbolization schemes, while some map series use many conventional signs, which make the map readable by persons who do not speak the same natural language and thus find it difficult to communicate verbally.

All maps portray data by using various kinds of marks, such as lines, dots, colors, tones, patterns, and so on, which require the user constantly to compare the symbols with those in a legend. Unlike the words we read in the natural language or languages we know, which usually convey information to us without our paying much attention to their appearance, the marks of a graphic display are often very noticeable. Whether the marks are on a luminous cathode ray tube or on a piece of paper, their selection and the way they are assembled (how the map is designed graphically) greatly affects the communicability of the map, that is, the way a viewer will organize the data it presents.

CLASSES OF MAPS

The number of possible combinations of scales, subject matter, and objectives is astronomical; consequently, there is an almost unlimited variety of maps. Nevertheless, there are recognizable groupings of objectives and uses for maps, which permit us to catalog them to some degree. One of the problems in doing so is distinguishing between the objectives of the mapmaker and the responses of the viewer. As observed by R. A. Skelton, "Maps have many functions and many faces, and each of us sees them with different eyes."* The chart that serves the utilitarian purpose of providing bearings, depths, and coastal positions for a ship's navigator will, for another, conjure up visions of coconut palms and an idyllic beach life. We cannot, therefore, reasonably predict responses; we can be quite sure only of the cartographer's objectives. In order to provide a basis for the appreciation of the similarities and differences among maps and cartographers, we will look at maps from three points of view: (1) their scale, (2) their function, and (3) their subject matter.

Scale

The dimensions of reality must necessarily be changed to the proportion that will accomplish the objectives and serve the function of the map. The proportion or ratio between the map dimensions and those of reality is called the *map scale;* the various ways map scale can be stated and portrayed are treated in Chapter 4. Here it is necessary only to point out that the ratio between the size of a map and the size of the area it represents can range from very small to very large. When a small sheet is used to show a large area (such as a map of the United States, or even the world on a sheet the size of this page), that map is described as being a *small-scale* map. If a map the size of this page showed only a small part of reality (for example, less than 1 km^2), it would be described as a *large-scale* map.

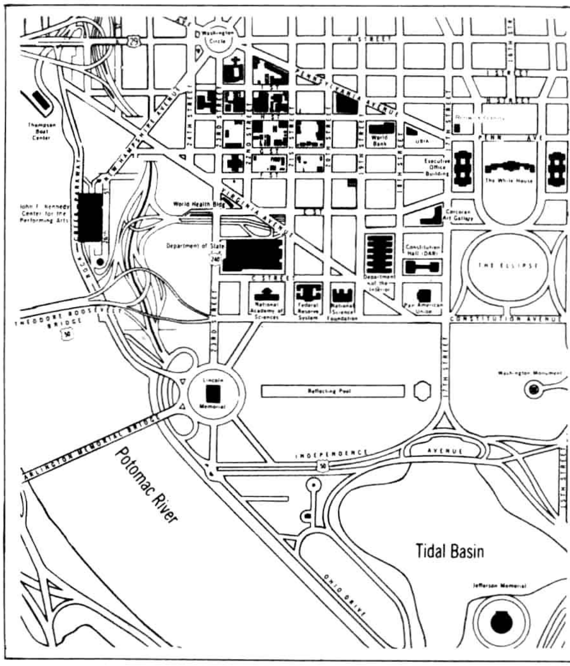


FIGURE 1.1 An example of a large-scale map. (From *George Washington University Bulletin*, courtesy, George Washington University.)

The terms *large* and *small* when combined with scale refer to the relative sizes at which objects are represented, not to the amount of reduction involved. Accordingly, when comparatively little reduction is involved and things such as roads and other features are shown with considerable magnitude, the map is termed a large-scale map (Fig. 1.1). When great reduction has been employed, as for a small-scale map, most of the smaller features on the earth cannot be shown at a size proportional to the amount of reduction, but must be greatly magnified and symbolized to be seen at all. Consequently, reality must be portrayed selectively and with considerable simplification on small-scale maps (Fig. 1.2). On the other hand, although selection is also characteristic of large-scale maps, such maps can portray many aspects of reality in the actual proportion of the amount of reduction employed.

There is no general consensus on the quanti-

*R. A. Skelton, *Maps: A Historical Survey of Their Study and Collecting*. Chicago: University of Chicago Press, 1972, p. 3.

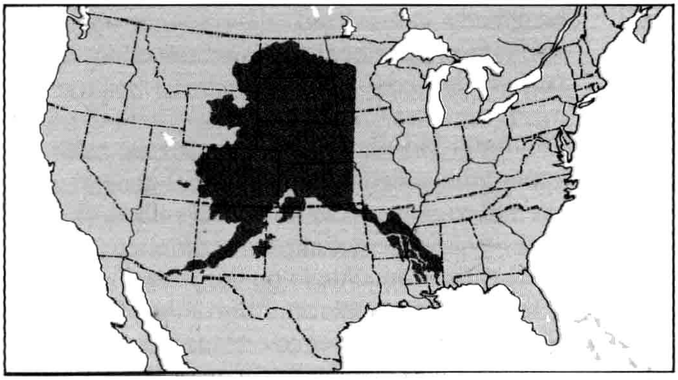


FIGURE 1.2 An example of a small-scale map. (After F. Van Zandt, "Boundaries of the United States and the Several States," U.S. Geological Survey Professional Paper 909, Washington, D.C.: U.S. Government Printing Office, 1976.)

tative limits of the terms small, medium, and large scale, and there is no reason why there should be, since the terms are hardly more than relative. Most cartographers would agree, however, that a map with a reduction ratio of 1 to 50,000 or less (for example, 1 to 25,000) would be a large-scale map, and maps involving ratios of reductions of 1 to 500,000 or more (for example, 1 to 1,000,000) would probably be considered small-scale maps.

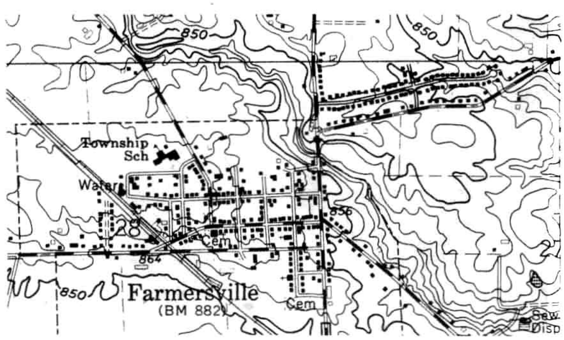
Function

As we have just seen, the range from large scale to small scale is a continuum with no clear divisions separating the classes of map scale. Similarly, if we try to divide maps into classes based on their function, we find a great difference between extremes, but the transition along the range from one class to another is a gradual instead of an abrupt change. We can recognize three main classes of maps: *general* maps, *thematic* maps, and *charts*.

General Maps. General, or reference, maps are those in which the objective is to portray the *spatial association* of a selection of diverse geographical phenomena. Things such as roads, settlements, boundaries, water courses, elevations, coastlines, and bodies of water are typically chosen for portrayal on general maps.

Large-scale general maps of land areas are usually called *topographic* maps (Fig. 1.3). They are issued in series of individual sheets and are very carefully made, usually by photogrammetric methods, by national or other public agencies. Maps of much larger scale are required for site location and other engineering purposes, and they employ only ground survey methods. Great attention is paid to their accuracy in terms of positional relationships among the items mapped. In many cases they have the validity of legal documents and are the basis for boundary deter-

FIGURE 1.3 A section of a modern topographic map. (From USGS 1:24,000 Farmersville, Ohio, quadrangle, 1974.)

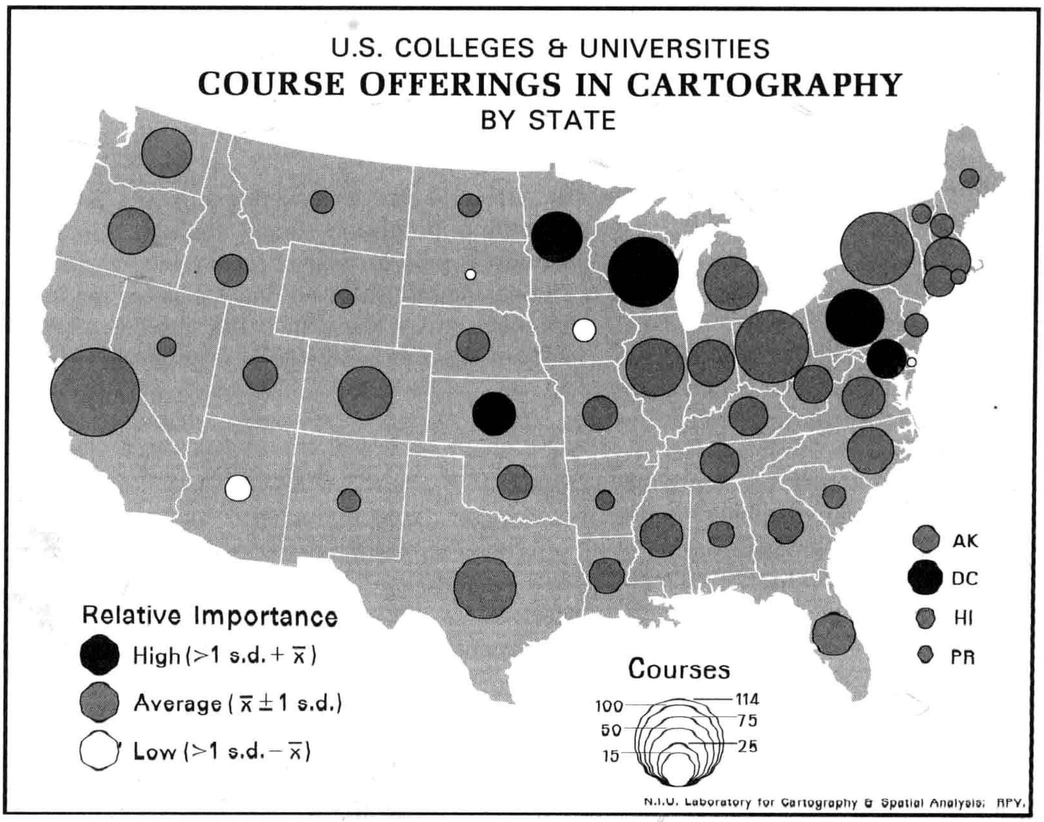


mination, tax assessments, transfers of ownership, and other such functions that require great precision. In the United States and other countries, official map accuracy standards have been established for such general, large-scale maps. The map accuracy standards apply only to the metrical horizontal and vertical qualities of the maps, not to nonmetrical aspects such as labeling blunders, incompleteness, or being out of date.

Small-scale general maps are typified by the maps of states, countries, and continents in atlases. These maps portray the array of phenomena similar to those shown on the large-scale general maps but, because they are small scale and the symbolization and representation must be greatly generalized, they cannot attain the standard of positional precision striven for on the large-scale maps.

Thematic Maps. Thematic maps are quite different from general maps. Whereas general maps attempt to portray the positional relationships of a variety of different attributes on one map, thematic maps concentrate on the spatial variations of the form of a single attribute or the relationship among several. In thematic maps the objective is to portray the form or structure of a distribution, that is, the character of the whole as consisting of the interrelation of the parts. There is no limit to the subject matter of thematic maps, and they

FIGURE 1.4 Distribution of course offerings in cartography by state. Data from the Mapping Sciences Education Data Base. AK = Alaska, DC = District of Columbia, HI = Hawaii, PR = Puerto Rico. "Relative importance" is the number of cartography courses as a percentage of all mapping sciences courses in that state. (From Dahlberg, 1981, courtesy Richard E. Dahlberg.)



range in appearance from the satellite cloud cover image to the shaded map of election results. They are typified by maps of average annual precipitation or temperatures, populations, atmospheric pressure, and average annual income (Fig. 1.4).

Just because a map deals largely with a single class of phenomenon does not necessarily mean that it is a thematic map. Maps showing the diversity of soils, bedrock geology, or population density can be properly classified as general maps if the primary objectives are simply to show the locations of types of soils, rock, or population density at particular places. On the other hand, maps made from the same data may employ methods of symbolization that focus attention on the structure of the distribution, and they would then be properly called thematic maps.

Thematic maps are commonly small-scale maps largely because many geographical distributions occur over considerable areas, and to portray their essential structure requires great reduction. Nevertheless, this tends to be relative; when the area of interest is a city, for example, maps intended to show the structure of individual phenomena may be of relatively large scale (Fig. 1.5). At small scales accuracy in thematic mapping is less a matter of concern for the precision of individual map positions than it is for the truthfulness of the portrayal of the basic structural character of the distribution.

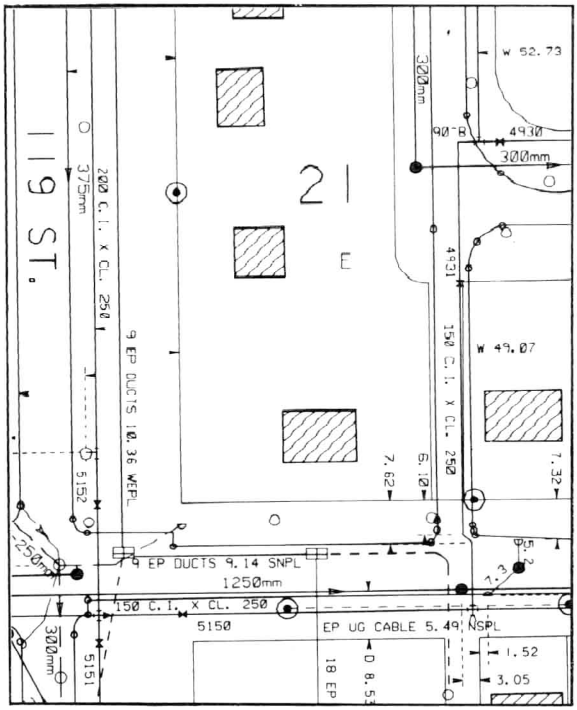


FIGURE 1.5 A portion of a 1:1,000 (large-scale) utility cadastre. (Reproduced by permission from E. A. Kennedy and R. G. Ritchie, "Mapping the Urban Infrastructure," *Proceedings of Auto-Carto V*, copyright 1983 by the American Congress on Surveying and Mapping and the American Society of Photogrammetry.)

Charts. Maps especially designed to serve the needs of navigators, nautical and aeronautical, are called charts. Although it is an oversimplification, one distinction is that maps are to be looked at while charts are to be worked on; courses are plotted, positions determined, bearings are marked, and so on, on the chart. It should be noted that navigators also use general maps. The marine equivalent of the topographic map is the bathymetric map.

There are many varieties of charts. *Nautical* charts include sailing charts for navigation in open waters, general charts for visual and radar navigation offshore using landmarks, coastal charts for near-shore navigation, harbor charts for use in harbors and for anchorage, as well as small-craft charts. All show, precisely located, such things as soundings, coasts, shoal waters, lights, buoys, and radio aids (Fig. 1.6). Their scales vary depending upon the detail necessary; unlike topographic maps, chart series are not made at a uniform scale. Chart design is focused on producing something accurate and easy to read and to mark on.

There are two types of aeronautical charts, those for visual flying and those for instrument navigation. *Aeronautical* charts for visual flying are similar to general maps that show a selection of recognizable features, such as cities, roads, railroads, and so on, as well as other significant elements, such as airports and beacons (Fig. 1.7). Charts for instrument navigation include radio fa-

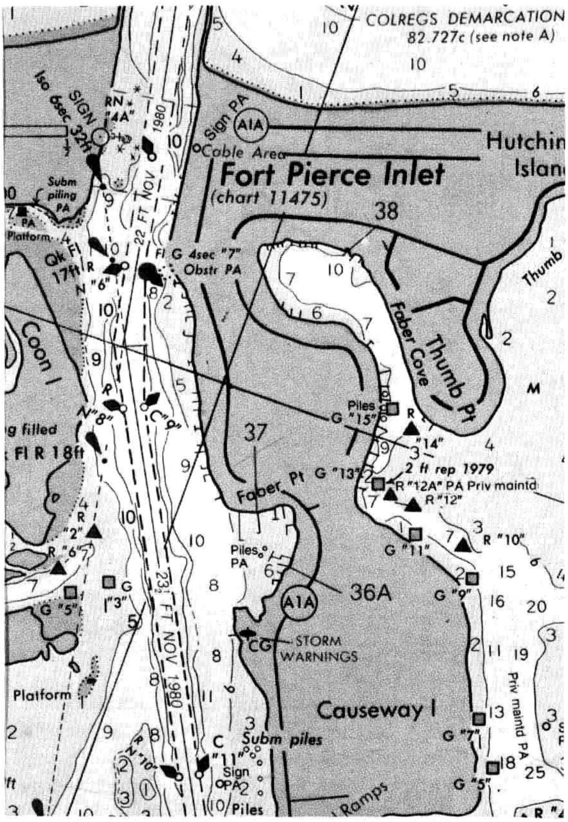


FIGURE 1.6 A section of the Fort Pierce–Fort Pierce Inlet areas on Nautical Chart 11472, Inset 1, Side A, by the National Ocean Survey. Soundings in feet at mean low water.

cility en route charts, high altitude en route charts, terminal arrival charts, taxi charts, and others.

Although it is not called a chart, the familiar road map is really a chart for land navigation. It supplies information about such things as routes, distances, road qualities, stopping places, and hazards, as well as incidental information such as regional names and places of interest.

It should be strongly emphasized that, while there are "pure" general maps, thematic maps, and charts, a majority tend to combine functions to some extent. For example, the green printing often seen on topographic maps shows the distribution of the forested areas, and the representation of terrain shows the structure of the land-surface form. Thus topographic maps, basically general maps, may have thematic components. Similarly, most thematic maps include a selection of boundaries, cities, rivers, and other features, so that the user can more easily fix the location of the subject distribution. Many charts are more "functionally specific," so that they tend to be less duplicative of functions.

Subject Matter

The variety of geographical phenomena and the myriad uses to which maps may be put combine to cause an enormous variety. Although they may all be classed as large-scale or small-scale and

FIGURE 1.7 A portion of a VFR (Visual Flying Rules) Terminal Area Chart—Kansas City, by the National Ocean Survey.