1

BASELINES

What is a map? is a question that invites diverse answers. In *The Nature of* *Maps*, a gospel in long-forgotten graduate seminars, Arthur Robinson and Barbara Petchenik sidestepped a needlessly narrow focus on Planet Earth or its physical environment by resurrecting an obscure French term for their definition, "graphic representation of the milieu."[1] No less basic is the triad "scale, projection, and symbolization," which framed more than a half century of map design courses.[2] But neither definition captures the flexibility and promise of late twentieth-century electronic maps designed for machines faster, if not more reliable, than the human eye/brain system.

A more encompassing definition must accommodate both the maps our eyes see and the maps a digital computer reads as data, as when software finds the shortest route between two points or crafts a politically advantageous yet legally acceptable configuration of voting districts. For the visual map's basic role in describing regions and connecting places, map symbols depict networks of nodes and links. For the electronic map's role in informing algorithms, these networks exist in computer memory as systematically organized data. Making a clear distinction between visual maps that depict networks and electronic maps that are networks of memory locations and digital addresses is more important than any compromise definition of map I could cobble together. Whatever its wording, that definition could not ignore the notion of networks.

That said, *network* has a much broader connotation in cartography because other kinds of networks provide an indispensable geometric framework for detailed topographic mapping or an integrated system for the efficient and timely flow of geographic information from dispersed observation points to a widespread community of internet or wireless users. A classic example is the complementary radar and telecommunications networks that collect and distribute data for the weather map, which could not otherwise exist in any of its varied formats.

These diverse applications beg the question: What is a network? Although dictionaries suggest numerous answers, I like Supreme Court Justice Potter Stewart's famous retort when asked to define pornography: "I know it when I see it." Figure 1.1 illustrates three basic types of network, as represented cartographically.[3] The simplest is the *branching network*, exemplified by rivers and streams, which merge into generally wider channels as their waters flow from higher to lower elevations and from smaller to larger catchment areas. In network terminology, the points of confluence are *nodes* or *vertices*, and the intervening paths are *links*, *edges*, *chains*, *arcs*, or [stream] *segments*. By contrast, *circuit networks* have loops, like those that allow a motorist to circle the block or choose among several routes. There are also *barrier networks*, principally political or administrative boundaries, the segments of which block or constrain flows of goods, travelers, or migrants. Topographic maps, which integrate drainage, transportation, and political jurisdictions, have all three types, as do many web maps.

Some networks incorporate directional bias. Because water does not flow uphill, a stream network is a *directed* network, in contrast to a telecommunications or highway network, which is *nondirected* because two-way flow is the norm. But because of one-way streets, road networks can have both directed and nondirected links. And as pilots are aware, networks can be three-dimensional and include links that represent airline connections, which crisscross on a two-dimensional map without intersecting at nodes.

In contrast to stream and road networks, in which links can be highly sinuous, some networks connect their nodes with straight lines, as shown on the right side of figure 1.1, under "Circuit Network." On an abstract network map, sometimes called a *schematic diagram or planar graph*, the lengths of these straight-line links are not strictly proportional to the measurements on which the network is based; examples include road distance, travel time, and per-ton transport cost. Road maps and tour books often include small maps showing average driving time between principal cities. These cartographic caricatures help motorists compare different routes between widely separated travel points.

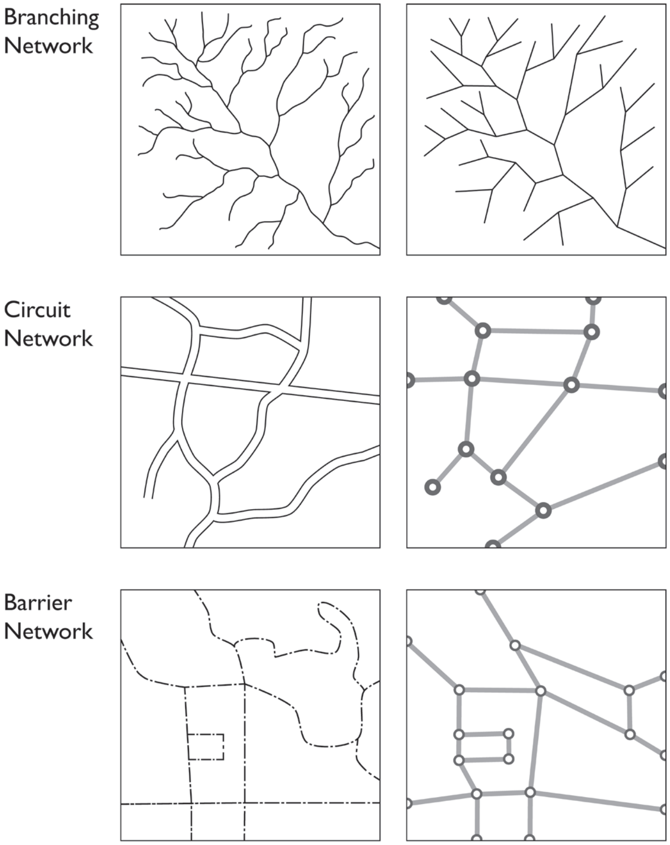

Figure 1.1. The three principal types of network, as portrayed on a map by geographically realistic links (*left*) or treated more abstractly as a planar graph (*right*).

Mapmakers go one step further by making some links directly proportional in length to the horizontal distance between nodes. As illustrated by the terrain profile in figure 1.2, the overland distance between nodes can be much greater than the corresponding horizontal distance, particularly in rough terrain. Cartographers call it *planimetric distance* because length is measured in a plane. Planimetric distance is the only distance reliably portrayed on topographic maps with a bar scale. The remainder of this chapter focuses on networks that frame planimetric maps.[4]

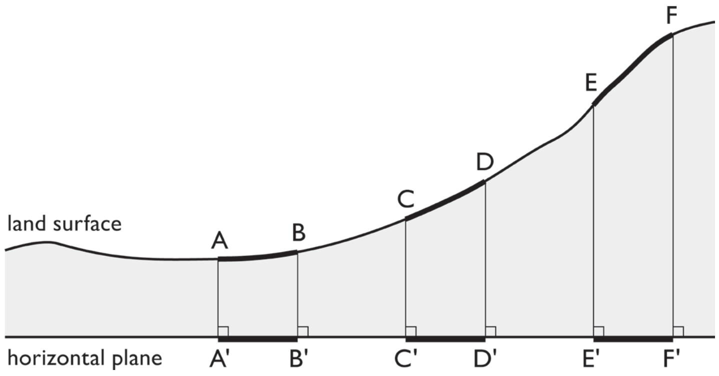

Figure 1.2. Points *A* through *F* on this hypothetical terrain profile project vertically onto a horizontal plane at points *A'* through *F'*. Overland distances *A–B*, *C–D*, and *E–F* are equal in planimetric distance despite longer overland distances resulting from progressively steeper slopes.

One strategy for making topographic maps employs an adjustable drawing board known as a *plane table*, shown in an 1865 engraving (figure 1.3) to which I added labels identifying key components, such as *clamps* for firmly anchoring a sheet of waterproof drawing paper. Mounted on a tripod, the drawing board can be rotated around a vertical line through the center of the tripod and made perfectly horizontal with a circular bull's-eye spirit level; when the bubble aligns with the circle on a small glass dome, the board is sufficiently level to represent the horizontal plane in figure 1.2. Some plane tables use a T-shaped spirit level, with a pair of linear bubbles fixed at right angles. Though no longer used, except perhaps in field method courses that lack newer technology, the plane table affords a straightforward visual explanation of key concepts important to an appreciation of cartography's historic roots in field observation of real-world landscapes treated as networks of surveying points connected by lines of sight.

The surveyor begins by drawing a line marking the direction from point *A*, the plane table's initial location, to a distant point *B* at which an assistant holds a vertical pole. Figure 1.4 describes the sequence of steps that follow. The surveyor sights through a device called an *alidade*, essentially a telescope joined to a straightedge aligned in the same direction. Once the pole is centered in the telescope's crosshairs, a line is drawn along the straightedge to mark the direction to point *B*. Point *A* is marked on the drawing, and the plane table is carried to point

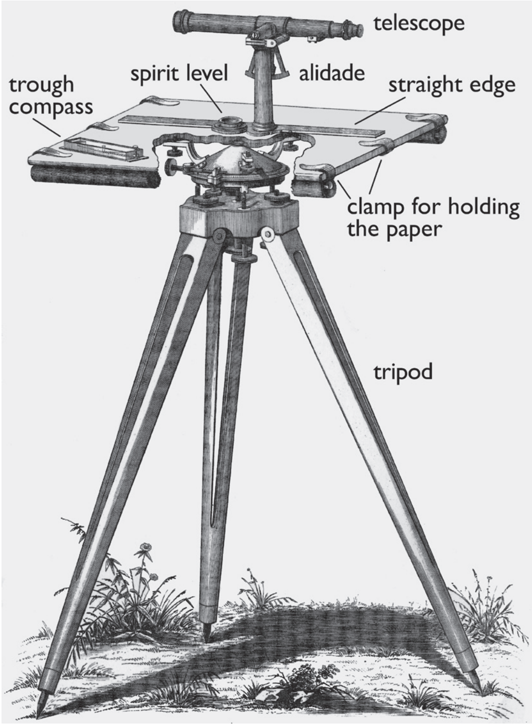

Figure 1.3. Plane table with a movable spirit level (on the drawing board, *toward the left*) and an alidade, with a straightedge for drawing a line aligned with its telescope.
NOAA Photo Library.

B and leveled. The surveyor then aligns the alidade with the original line drawn at *A* and rotates the drawing board until a pole set up at *A* is visible in the telescope. Marking point *B* along that line fixes the scale of the map.

Although the exact scale might not yet be known, all planimetric distances will be proportional to the length of line *A*–*B*. Determine that distance, or the distance between any pair of nodes, and you can calculate the map's scale as the ratio of map distance to ground distance, and then add a bar scale representing one or more typical distances in miles, feet, or kilometers. A carefully measured line used to establish the scale of the map is known as the *baseline*, highlighted as the title of this chapter. If the area mapped is not large, say only five miles east to west and a similar distance north to south, a conventional bar scale might show a mile divided into quarters, eighths, or tenths.

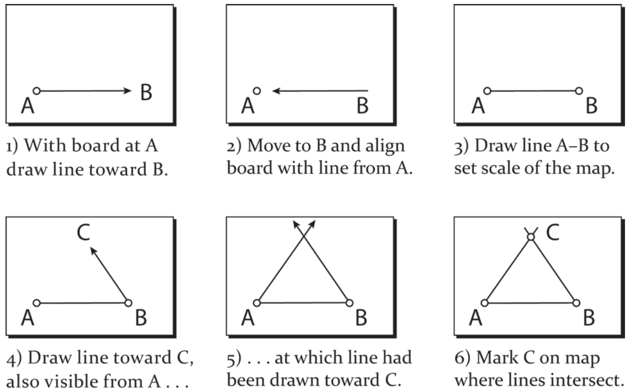

Figure 1.4. Steps in discerning the location of point *C* by drawing lines of sight on a plane table from points *A* and *B*.

The lower row in figure 1.4 shows how the surveyor adds other points to the map. At point *B*, he draws the line of sight to point *C*, toward which he had earlier drawn a line of sight from point *A*. Where the two lines intersect, he marks point *C* on the map. The plane table is a sixteenth-century innovation, rarely used in recent decades.[5] Nowadays, a surveyor uses a more complex but versatile instrument known as a *total station*. More about total stations later in this chapter.

William Gillespie (1816–68), a civil engineering professor at Union College, in Schenectady, New York, wrote a widely used nineteenth-century textbook on land surveying, in which he labeled this strategy, known as *intersection*, as "the most usual and most rapid method of using the Plane-table."[6] Gillespie used a simple line drawing (figure 1.5, *upper*) to show how intersecting lines of sight drawn on the plane table at two locations, *X* and *Y*, could fix the positions of additional points. On the lower right, a depiction of the drawing board at the second location, *Y*, shows a network with six nodes and twelve links. As Gillespie noted, another sheet could be placed on the drawing board and used to add points on the far side of this first line, *x–y*, to form a larger network.

Another diagram in his book (figure 1.5, *bottom*) describes how a second plane table method, called *progression*, could extend the network farther afield. If the length and direction of just one link, the baseline, was known with reasonable certainty, the enlarged network provided the skeletal framework for a multisheet map, which the surveyor could enrich by using lines of sight to sketch intervening

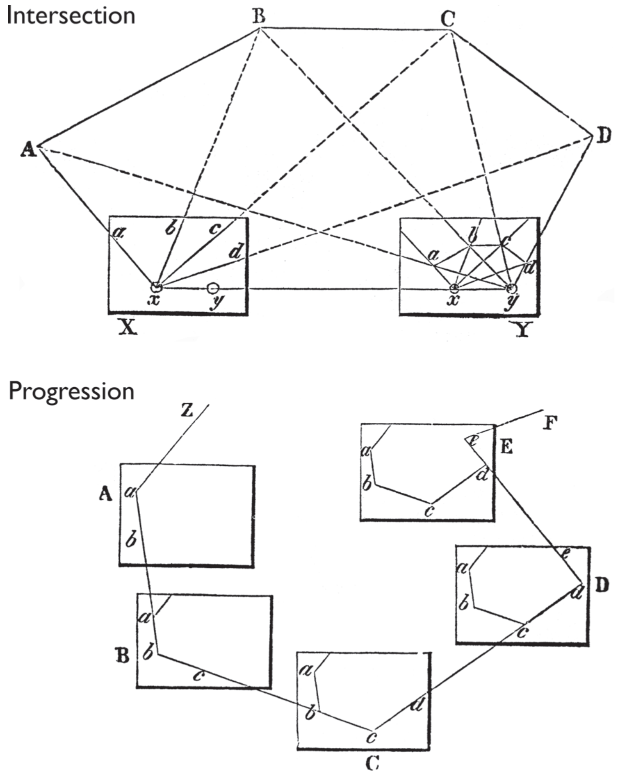

Figure 1.5. The plane table methods of intersection (*top*) and progression (*bottom*) as described in William Gillespie's 1855 textbook on land surveying. The *top* drawing illustrates how setting up the plane table in two locations can incorporate points beyond the initial line *x*–*y*. The *bottom* illustration shows how moving the plane table along a traverse can incorporate additional points along that traverse.

features. Indeed, a key advantage of the plane table is the ease with which a property surveyor or topographer can compose a map in the field, where it is easy to determine what's worth including. After completing his fieldwork, the mapmaker could carefully transfer all features onto a single sheet, typically drawn at a smaller scale. Reduction was straightforward if the original plane table drawings were on graph paper with four or five squares to the inch and the reduced drawing had a grid with twenty squares to the inch.

Plotting a composite drawing at a smaller scale diminished inaccuracies that arose in making the plane table plots, which were purely graphical solutions,

limited not only by the precision with which an alidade and sharp pencil can reproduce reliable lines of sight but also by the accuracy with which even a present-day surveyor can measure the length of a suitably long horizontal baseline. Although it is relatively easy to measure a short, essentially horizontal baseline, the resulting measurement is useful for a survey covering only a limited area—for example, a precise survey for reconstructing a crime scene or traffic accident. In mapping the site of a future strip mall, the surveyor might place a 25-foot measuring tape on level ground—if level ground can be found or made level by carefully joining and supporting a few long lengths of lumber. Even so, a 25-foot base is not useful for finding an intersection point (such as *C* in figure 1.4) much more than a few hundred feet away.

If you're uncomfortable with numbers, brace yourself: the story of cartographic networks cannot be told without getting into at least a few numbers. Field surveys involve observations that are also numerical measurements, which are an unavoidable source of error. Surveyors deal with error by averaging multiple readings and by measuring different parts of a network and checking for consistency, a process evident in everyday language whenever we assert the need to *triangulate* by looking at a problem from different viewpoints. Journalists call this process *fact checking*.

A surveyor's lengths and angles become useful only when leveraged by invoking basic trigonometry and simple statistics: concepts that might remind some readers of their first encounter with math anxiety. Recall trigonometry, that high school subject that ventured beyond plane geometry and basic algebra by obsessing over right triangles and introducing arcane terms such as *sine*, *cosine*, and *tangent*. Despite an undergraduate degree in mathematics, I am leery of confusing *sine* (opposite over hypotenuse) and *cosine* (adjacent over hypotenuse) because angular relationships are not part of a routine day. If you're from my generation, you might recall looking up these ratios in "trig tables." If you're my daughter's age and attended middle school in the mid-1990s, you might recall using a clunky multifunction calculator; nowadays, there's an app for it on your mobile device. Although trigonometric calculation was comparatively laborious for the nineteenth-century surveyors who established a national framework for detailed topographic mapping, their efforts depended on the fundamental mathematic concept of basic ratios shared by similar right triangles that vary in size.

No less basic is the notion that any non–right triangle can be partitioned into two right triangles with a common side. I'll spare you the formulas, but a bright ninth or tenth grader can prove that if you know two of the angles and one of the sides of a non–right triangle, you can calculate the lengths of the other two sides. Nowadays, a perhaps not-so-bright but nonetheless resourceful student will merely Google "irregular triangle calculator" to find a relevant app.[7] This notion is important because triangles in an actual survey network almost never include a right angle.

Trigonometry was useful in exploring my hypothetical 25-foot baseline's effect on the accuracy of locations estimated using intersecting lines of sight on a plane table. For this example, I imagined an intersection point 500 feet away from the endpoints of the 25-foot baseline. The resulting isosceles triangle has an acute angle measuring a mere 2.9°—I am rounding here to one decimal place—and angles of 88.6° at the ends of the baseline.[8] If the lines of sight are perfect, the intersection would lie 4,999 feet from the center of the baseline. But if the two lines of sight drawn on the plane table underestimate their angles by only a tenth of a degree (88.5°, instead of 88.6°), the distance from the intersection to the baseline shrinks to 467.2 ft.: an error of 32.6 ft.! Increasing the baseline to 100 ft. lowers the tenth-of-a-degree error to 8.6 ft., and increasing it to 500 ft., thereby forming an equilateral triangle, would further reduce the error to only 1.7 ft.

Surveyors are understandably concerned about what Gillespie called "ill-conditioned" triangles, in which an angle less than 30° or more than 120° makes graphical or numerical estimates highly sensitive to minor inaccuracies.[9] In an ideal, well-conditioned network, almost all triangles are nearly equilateral.

Surveyors further minimize error by measuring angles with a *theodolite* or *transit* and using numerical measurements and trigonometry to calculate the lengths of links and locations of nodes in a triangulation network.[10] Despite little agreement on the difference between a theodolite and a transit, the former term generally refers to a more accurate instrument. Nowadays, theodolites and transits are electronic devices designed to display and record digital measurements, but older devices measured horizontal and vertical angles by relating a telescope's line of sight to horizontal and vertical circles divided into degrees by evenly separated marks inscribed on glass or metal. In general, the greater the diameters of these horizontal and vertical circles, the more accurate the readings. But before any

readings were taken, the instrument had to be carefully leveled, typically using three or four leveling screws at the top of the tripod and perpendicular spirit levels, as shown in figure 1.6, a comparatively Spartan mid-nineteenth-century theodolite used principally for measuring horizontal angles. More versatile instruments included magnifying lenses for reading the horizontal and vertical circles, which could be read to "single minutes or even less," according to Gillespie.[11]

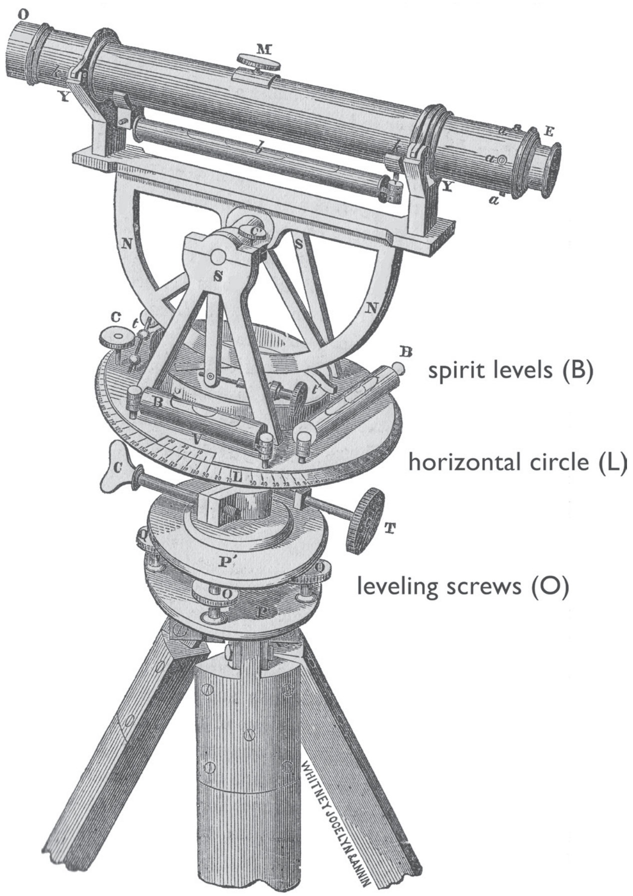

Figure 1.6. Engraving of an "English form" theodolite in William Gillespie's 1855 surveying text. Labels (*added on the right*) highlight the otherwise obscure locations of the leveling screws (*O*), spirit levels (*B*), and horizontal circle (*L*). Present-day theodolites typically use only three leveling screws.

Because an arc minute is a mere one-sixtieth of a degree, theodolites provide reliable observations for networks with much larger triangles than appropriate for a plane table. Consider the example, a baseline 5 mi. (26,400 ft.) long serving as one side of an equilateral triangle. If the angles at opposite ends are measured flawlessly, trigonometry calculates a distance of 22,863.1 ft. from the center of the baseline to the observed vertex. Underestimating the angles at the ends by one-sixtieth of a degree (59.983° instead of 60°) shortens the distance by only 15.4 ft. Increasing the side of the equilateral triangle to 10 mi. (52,800 ft.) merely doubles the discrepancy. For many purposes, the resulting error of 30.7 ft. would be insignificant. For example, if the map was to have a scale of 1:50,000 (1 in. on the map representing 50,000 in. on the ground), the center of a point symbol would be off by a miniscule 0.007 in.: less than a fifth of a millimeter and far, far smaller than the symbol plotted. Although an error of 31 ft. is potentially relevant to a surveyor who intends to install a boundary marker, the monument's exact location would need to be verified by observations from other points in a denser triangulation network.

To illustrate how trigonometric triangulation works, Gillespie included an excerpt from a US Coast Survey map describing the primary triangulation network for New England (figure 1.7). To place this configuration of surveying points and lines of sight in a geographic context, note the label "Atlantic Ocean," which places east toward the bottom, and the progression Rhode Island–Massachusetts–New Hampshire, which puts north toward the right. Gillespie's diagram describes the middle part of a massive project organized as a hierarchy of networks, with the more precise, primary triangulation connecting three baselines: one on Fire Island, off the south coast of Long Island, New York; another, along a relatively level 10¾-mile stretch of the Boston and Providence Railroad in Massachusetts; and a third, over unavoidably more rugged terrain at Epping Plain, Maine, near the Canadian border. Links connected local high points visible from each other over distances as long as fifty miles—visible at night, that is, from a portable tower that elevated the theodolite above trees and other obstacles. In a triangulation network, each node must be visible from at least two other nodes. Gillespie's diagram is important because it describes a primary, or first-order, survey that framed secondary and tertiary surveys, which in turn anchored more detailed mapping with a plane table.

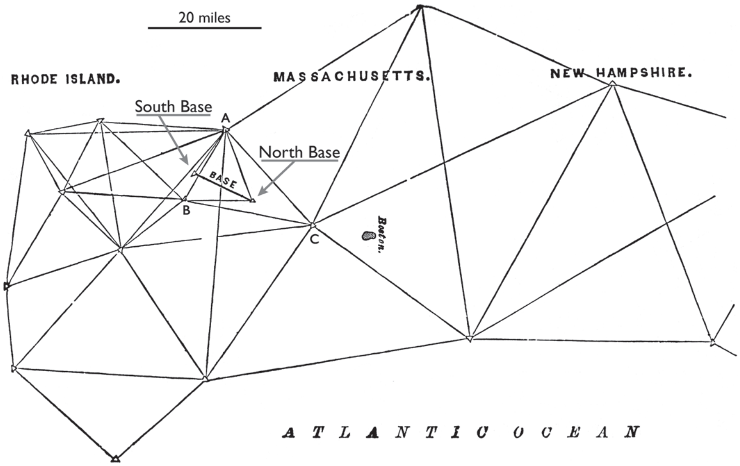

Figure 1.7. Southern portion of the US Coast Survey's primary triangulation for Section 1, extending from eastern Maine to Rhode Island, as shown in in William Gillespie's 1855 textbook on land surveying. North lies roughly *to the right*. The bar scale, labels identifying North Base and South Base, and markings for stations *A*, *B*, and *C*, mentioned in the discussion, were added by the author.

For each observation, the theodolite's telescope was focused on a signal mast positioned at a stationary location, or *station*, at which a triangulation tower was erected. Locations were selected after a reconnaissance survey verified that no intervening hill or structure would block the line of sight along a link. Each node's exact location was marked by a permanent monument not likely to disintegrate in bad weather or be easily carried off. The Coast Survey's annual report for 1854 described a typical monument as consisting of "an underground brick structure, enclosing a freestone block, in which a copper bolt is sunk [with] the extremity of the base .... marked by crosslines on the bolt head, over which a stone cap is laid."[12] Other designs were similarly immovable. If intended for daytime observation, the signal mast had to be sufficiently tall to be visible in the telescope and stand out against its background. Gillespie described a signal intended for nighttime observation that directed oxygen gas onto an alcohol flame amplified by a parabolic mirror and visible 66 miles away.[13]

In organizing its triangulation survey of the East and Gulf Coasts, the Coast Survey established nine project areas called *sections*, with Section 1 covering the coasts of Maine, New Hampshire, Massachusetts, and Rhode Island. Gillespie's drawing was based on the southern portion of the primary network for Section 1 as it existed in 1854.[14] (Other stations and links were added over the following decade.) Most of the stations had names such as Indian Hill (on Martha's Vineyard) and Quaker Hill (near Newport, Rhode Island), abbreviated Indian H. and Quaker H., with the abridgement *H* confirming that hills were natural places to erect triangulation towers. By contrast, the baseline's endpoints, chosen because they bracketed a long, straight, and generally level railway grade, were named North Base and South Base. In figure 1.7, North Base is on the right of South Base and closer to the bottom of the page, which seems counterintuitive because north is more commonly at the top of the map. In clipping a representative segment out of the larger Section 1 network, Gillespie rotated the map so that north lies to the right and south to the left. Because adjoining portions of the larger network had to fit together, the Fire Island baseline was in Section 2, which extended from Connecticut to Delaware.

Baselines are necessarily shorter than most other links in a triangulation network. Figure 1.7 shows how smaller triangles and trigonometric calculation helped integrate the Massachusetts baseline into New England's primary network. Careful examination of the upper-left portion of the figure shows how the triangle that includes the baseline was used (along with its measured angles) to calculate the length (13.13 mi.) of the side opposite the angle at South Base. Try it yourself.[15]

Although the side opposite North Base is not part of any other triangle, the length opposite South Base could be used to calculate distance *A*–*B* (14.43 mi.), which was then used in calculating distances *C*–*A* (22.85 mi.) and *C*–*B* (23.58 mi.), used in turn to calculate lengths for adjoining triangles and so on. Reliability at each step depends not only on accurately observed angles for the new triangle but also on the distance calculated in the last step. Whatever error occurs in measuring the baseline will be magnified as this basic length is propagated outward, step by step, through successive calculations. A small amount of uncertainty is inevitable, but mapmakers understand the importance of a highly reliable original length.

A note on the map that Gillespie had copied explained that many of the triangles were also parts of *quadrilaterals* (four-sided polygons), "both diagonals of which are determined," that is, treated as links in the triangulation network.[16]

This strategy "strengthened" the network by affording additional checks on measured angles and calculated distances. For example, in much the same way that the angles of a plane triangle must sum to exactly 180°, the interior angles of a quadrilateral should add up to 360°. The additional links also helped Coast Survey scientists check calculations carried outward from baselines in different parts of the network using trigonometry and measured angles. Multiple baselines were a further source of strength, insofar as baselines at opposite ends of the Section 1 network, as well as near the center, minimized the step-wise propagation of length errors from one triangle to the next. The Coast Survey's annual report for 1865, in announcing the completion of primary triangulation for Section 1, applauded its three baselines as "peculiarly independent of each other" and valuable because "the estimates of the accuracy of the results .... may be received with confidence."[17]

Measuring the Massachusetts baseline took three months in the fall of 1844.[18] The project was directed by Edmund Blunt (1799–1866), a civilian "assistant" in what was then called the Survey of the Coast. (Although his job title might suggest a low-level lackey, the typical assistant was skilled in mathematics and measurement, and survey parties included more junior staff called '*aids*' or *subassistants*.) Blunt visited the Seekonk Plain, an area west of Boston near the border with Rhode Island, which an earlier, uncompleted survey for the state of Massachusetts had deemed suitable for a straight baseline of approximately five miles. Although a reconnaissance of the proposed baseline revealed irregular ground and woodland that would complicate the work, Blunt serendipitously discovered a straight stretch of double-track railroad still under construction. The timing was perfect because only one track had been laid along the recently graded right-of-way, and the railway's president and its superintendent willingly cooperated. In addition to expediting the work, the railroad afforded an opportunity to measure a baseline almost eleven miles long, a distance not surpassed for several decades.[19] Blunt selected endpoints, North Base and South Base, that could be connected by lines of sight to the larger triangulation network.

Measuring a baseline was a painstaking process of advancing a cumulative measurement forward in increments using precision metal bars that were carefully positioned end to end and held perfectly level and in a perfectly straight line using movable tripods called *trestles*. Figure 1.8, an etching from the historic imagery collection of the National Oceanic and Atmospheric Administration (NOAA), describes the process for the Epping baseline, surveyed in 1856 and 1857 at the eastern end of the New England network, at Epping Plain, Maine. Note the two measuring tubes, each containing a metal bar six meters long, and the six trestles, designed to sit on metal plates. The two trestles supporting a tube could be adjusted upward or downward as needed to keep the line level. Instruments in a box at the end of the tube assured the precise making and breaking of contact as the tubes leapfrogged along a carefully cleared path. Note the two trestles positioned ahead of the forward tube, ready to receive the aft tube, which was carried forward after breaking contact. *Leapfrogging* is an apt metaphor.

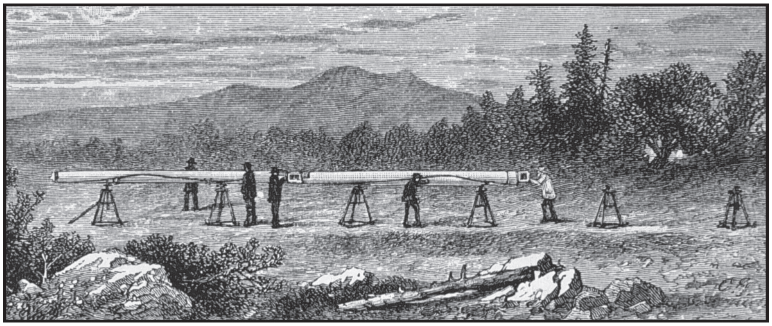

Figure 1.8. Coast Survey party measuring the northeastern baseline at Epping Plain, Maine. Leveling tripods called *trestles* supported canvas-covered tubes containing measuring bars. NOAA Photo Library.

An 1868 Coast Survey report described a carefully choreographed process involving ten men, a horse, and various pieces of equipment.[20]

> One assistant, to make the contact, give the signals, etc.
>
> One aid (sic), to align the bars, using a transit.
>
> One aid (sic), to record the inclination, temperature, and number of the bar, and, when measurement stops or halts for the day, to transfer the end of the rod to copper tack in stub, employing, for this purpose, the other transit.
>
> Two men, to carry the bar.
>
> Two men, to pick up the trestles, carry them forward, adjust them in line, and level them.

> One man, to attend the aid in charge of alignment, bring up [the] instrument, etc.
>
> One man, to keep up the transfer transit, and to be provided with stub, axe, and copper tack for an emergency, and to assist generally.
>
> Cart, horse, and driver, for the transportation of [the] heavy wooden box, in which the bars are kept when not in use; of water, stubs, spades, and tools, and of tent, in case of sudden storm.

The report's author, Coast Survey scientist Richard D. Cutts (1817–83), had been a brevet brigadier general during the Civil War and, no doubt, appreciated precision teamwork.

For the Massachusetts baseline, Blunt was the last to use an older measuring apparatus based on four bars two meters long and designed by Ferdinand Rudolph Hassler (1770–1843), who had founded the Survey of the Coast and directed it until his death in 1843. A Swiss surveyor and mathematics teacher who immigrated to the United States in 1805, Hassler insisted on measurements in meters, not feet. The Coast Survey's report for 1865 mentioned a combined length of 7.99987165 m at 32° F, calibrated against an 84-in. brass scale manufactured in London for the Survey of the Coast and brought to Washington in 1815.[21] Temperature readings from eight thermometers, two attached to each bar, were used to collect data so that the surveyors could adjust for thermal expansion, which made the bars a bit longer. The bars were placed end to end in a box 8 m long, and an elaborate set of tripods and levels was used to count the number of bars added incrementally as the apparatus advanced forward.[22]

Distilling multiple observations into a single measurement was an elaborate process. An initial estimate of 17,320 m, calculated by multiplying 8 m by 2,165 (the number of carefully counted incremental advances), required several corrections and adjustments.[23] Subtracting the "defect" of 0.00012835 (the amount by which the combined bar fell just short of 8 m) reduced the total by 0.2779 m, but because of an average temperature of 58.85° while the line was advancing, 3.2383 m was added to reflect thermal expansion. Because the railway grade was not precisely level, 0.5629 m was subtracted to yield the actual planimetric distance. And because the baseline was a bit longer than 2,165 increments, 3.9999 m (the length of two 2 m bars) was added between the end of the last increment and the North Base marker, and 0.0003 m was deducted to correct for "10° of temperature below 32°." Finally, an "additional scale measure" of 0.1012 m was added because the length was slightly longer than two 2 m bars, and 0.1220 m was subtracted to reduce the distance from an average elevation of 44.83 m to the "half-tide level of the ocean." Because of Earth curvature, a distance measured above sea level was a wee bit longer than the distance at sea level on a spherical planet. Coast Survey scientists tried to account for all possible errors.

Like true scientists, they then appended an error term based on the "probable error" of the four 2 m bars, for rising and falling temperatures while advancing the bars, and the probable error of the microscopes used to confirm a precise contact between leapfrogging bars. The result was an official measurement of 17,326.3763 ± 0.0358 m.

Nineteenth-century mapmakers responsible for the reliable depiction of the nation's coast also understood that efficient use of limited personnel and equipment required a hierarchy of networks, with a more carefully surveyed primary network anchoring a denser but less rigorously measured secondary triangulation that supported an even denser, not quite so intensively observed, tertiary network. The third network, in turn, framed the topographic mapping of land above the shoreline as well as the hydrographic charting of channel depth and submerged hazards. This hierarchy of systematically designed networks, each with a specific standard for reliability, differentiates geodetic surveying from comparatively ad hoc land surveys focused on property lines, roads, railways, canals, and bridges.

Cutts, who had described the teamwork required to advance the bars, also disclosed marked differences in triangle size among the primary, secondary, and tertiary networks.[24] In the primary network, the sides of triangles were between 20 and 146 mi. in length, in contrast to a range of 5 to 40 mi. for the secondary network and lengths generally shorter than 6 mi. for the tertiary network.

Cutts emphasized that triangulation was not the only responsibility of the geodetic survey. Highly reliable astronomical measurements of latitude and longitude, carried out at selected primary stations, were propagated mathematically to other parts of the network so that quadrangle maps could be properly bounded by specific parallels and meridians. Moreover, "from this special class of the geodetic work, subject to the least probable error, the dimensions and figure of the earth are deduced, as in the measurements, made and in progress, of the arcs of the meridian in the eastern, middle, and southern states, and of the Arc of the 39th Parallel across the continent." (In geodetic surveying, an arc is a chain of triangles

that follows a meridian, parallel, or other curved line that it is intended to measure.)[25] With responsibilities no longer confined to coastal states, the agency was renamed the US Coast and Geodetic Survey in 1878.

Cutts also described the cleverly designed portable towers that expedited the accurate measurement of angles at the network's nodes.[26] A tripod that supported the theodolite was surrounded by scaffolding that supported the observer, and accuracy required that tripod and scaffolding not touch. Towers as tall as 60 ft. not only elevated the line of sight above nearby terrain and trees but also compensated for the disappearance of distant objects beneath the horizon, as occurs at sea. Though a properly assembled tower was appropriately sturdy, I doubt that I could overcome my fear of heights sufficiently to climb one without considerable coaxing and shaming.

Because of Earth curvature, the relatively large triangles of the primary and secondary networks must be treated as spherical triangles, for which the sum of their angles is greater than 180°. This effect, known as *spherical excess*, is greater for larger triangles and can be predicted from their area as well as their latitude, which is relevant because the planet is flattened slightly toward the poles—think of a mandarin orange. For spherical triangles identical in area, the spherical excess will be measurably smaller at higher latitudes, and a precise geodetic survey must adjust for latitude.

To diminish instrumentation and human errors, the surveyor took multiple readings, half as "direct" readings, with the theodolite's telescope in the normal position, aimed toward the distant station, and half as "reverse" readings, with the telescope rotated 180° around the vertical circle and then 180° around the horizontal circle so that it was still sighted on the same distant station. This trick forces some instrumentation errors to work against each other and, in large measure, cancel each other out, but the geometry involved in designing, setting up, and reading a theodolite is complex, and I have necessarily simplified it.[27] Taking multiple readings, half in direct mode and half in reverse mode, is important because subsequent readings of the same angle are likely to be ever so slightly different—a single reading is just an observation, but multiple observations, when averaged, become a measurement. What's more, the variation of these readings about their average, or mean, is a useful estimate of the error incurred in making the measurement.

Geodesists make two kinds of adjustments. More straightforward is the *station adjustment*, which satisfies the basic rules of geometry by making certain that all angles surrounding a node sum to 360° and that the three angles in a plane triangle sum to 180°. More complex is the *figure adjustment*, which must accommodate not only the individual node and its adjoining triangles but also their neighboring nodes and triangles, all subject to errors of measurement. According to University of Pennsylvania professor Edward Lovering Ingram (1862–1938), the necessary adjustment "could be made in an infinite number of ways, but the adjustment that is sought is the one that assigns the most probable values to the various angles in view of their actually measured values."[28]

Ingram outlined the strategy in his 1911 textbook, *Geodetic Surveying and the Adjustment of Observations (Method of Least Squares)*. The process begins by removing (or apportioning) the spherical excess, so that subsequent calculations can be based on plane triangles. It then corrects for likely errors of measurement, based on each angle's weight, or "relative worth," calculated from the number of observations—the more observations the better. Ingram's computational procedure, known as *least squares*, recognizes that a perfect fit is unlikely: for any hypothetical trial adjustment of the network, each angle in the adjusted network will differ (ever so slightly, in most cases) from its observed value (after spherical excess is removed). For a satisfactory adjustment, most of these differences, known as *residuals*, will be small, but a few might be relatively large and potentially troubling. The method of least squares addresses this problem by finding a solution that minimizes the sum of the squares of the residuals.[29]

Anyone who has taken a course in elementary statistics is familiar with least squares, widely used to fit a straight line to points in an x,y graph. In a typical example, the horizontal coordinate might represent a person's years of formal education while the vertical coordinate reflects annual income, and the points describe a random sample of adults between 50 and 60 years old. Because the relationship between education and income is not perfect, a straight line representing the overall trend might not pass directly through any of the points. Although we could try using a straightedge to fit a line ourselves, least squares yields a "best fit" line that satisfies most researchers, who appreciate a standardized, presumably unbiased solution. Geodesists are similarly satisfied with the least-squares adjustment of triangulation networks.

How good was the Massachusetts Base and the New England network? Longtime Coast and Geodetic Survey mathematician Charles Anthony Schott (1826–1901) addressed this question in a report on the Eastern Oblique Arc of the United States. An endeavor that took two-thirds of a century to complete, this massive network stretched from the Gulf of Mexico near New Orleans to the Canadian border in eastern Maine (figure 1.9).[30] In a table summarizing the reliability of the arc's 483 triangles, Schott listed each section's average error of closure, a concept familiar to land surveyors. In a property survey, the series of line segments that enclose a parcel can be plotted sequentially, one after the other, starting at and returning to the traverse's point of beginning. Because measurement error makes precise closure highly unlikely, the distance from the ending point of the last boundary segment to the starting point of the first segment is called the "closing error," and is usually distributed throughout the traverse.[31] In a network of triangles, the closing error of any one triangle is the net sum of the corrections (some positive, some negative) made during figure adjustment, which can be averaged for all triangles in a regional network.[32] Schott went a step further by calculating the "probable error of an observed direction," which he considered "a more precise measure of accuracy."[33] His table showed the New England section, encompassing 53 triangles linking the Epping, Fire Island, and Massachusetts baselines, with a probable error of only ±0.26", matched only by the Dauphin Island base net, a small section in coastal Alabama with only five triangles—although the double-prime (") symbol is commonly associated with inches, in geodesy it refers to arc seconds. For comparison, the weighted mean for the entire arc is ±0.51", no less impressive insofar as one arc second is a mere 1/3,600 of a degree.

A folded map in Schott's 1902 report portrayed the arc as a long, thin polygon bounded by the sides of triangles along its outer edge (figure 1.9). The cartographer focused on the network's extent and coverage by omitting interior nodes and links and by filling the polygon with a blue tint, except for areas near the network's six baselines, which are tinted orange. Because the original map is over 18 in. from left to right—making it impossible to preserve a moderately detailed coastline and the names of state capitals in a significantly scaled-down rendering—I redrew its essential features, in black and white, to fit this book. These include the 1,623-mi. "geodetic line" along a great circle (shortest-path route)

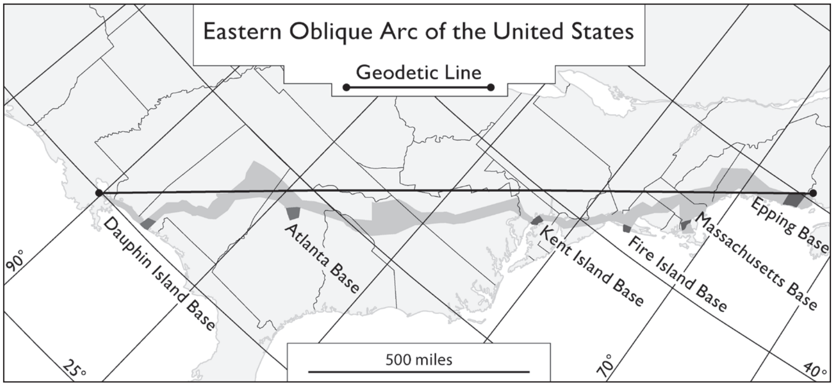

Figure 1.9. The Eastern Oblique Arc, redrawn at a much reduced size from a 1:7,000,000 map in Charles Schott's 1902 report. The darker shaded area encompasses the arc's 483 triangles.

from Calais, Maine, to New Orleans, at opposite ends of the arc, and meridians and parallels 5° apart, which show that north is toward the upper right and west is toward the upper left. In places, the arc is no wider than about 30 mi., and the longest stretch between baselines runs along the eastern edge of the Appalachians into northern Georgia. Note the westward bulges to incorporate Mount Washington (in New Hampshire), Mount Mitchell (in North Carolina), and several high-elevation stations in northern Alabama. Particularly prominent is the southeastward bulge to include the Massachusetts Base, initiated before the Coast Survey decided to integrate numerous regional networks into a national network that was also useful in calculating a more precise description of the earth's shape, known to resemble a sphere flattened slightly at the poles. Although triangulation arcs typically run hundreds of miles along a parallel or meridian, an oblique arc is especially useful in calculating the size of a three-dimensional figure formed by rotating an ellipse about its shorter axis.[34]

Aside from labeling the arc's six baselines, Schott did not explain the orange areas on his map (dark gray on mine). In figure 1.10, an enlarged facsimile excerpt focused on eastern Massachusetts, I used the grid of parallels and meridians to add the approximate location of the Massachusetts baseline, situated in the western part of its orange area.[35] A small map in Schott's report, titled *Massachusetts Base, and [Its] Connection with the Primary Triangulation of Massachusetts*, suggests that this patch of orange contains the triangles in the primary network immediately adjacent to the baseline.[36] Although similar maps for the other baselines confirm this interpretation, Schott apparently wanted to highlight the locations of baselines too short to show up without enhancement on his 1:7,000,000 map.[37] This interpretation is consistent with the continuation of the blue (lighter gray in figure 1.10) part of the arc on the eastern side of the orange area, where the primary triangulation ran seaward to connect secondary triangulations with the main network.

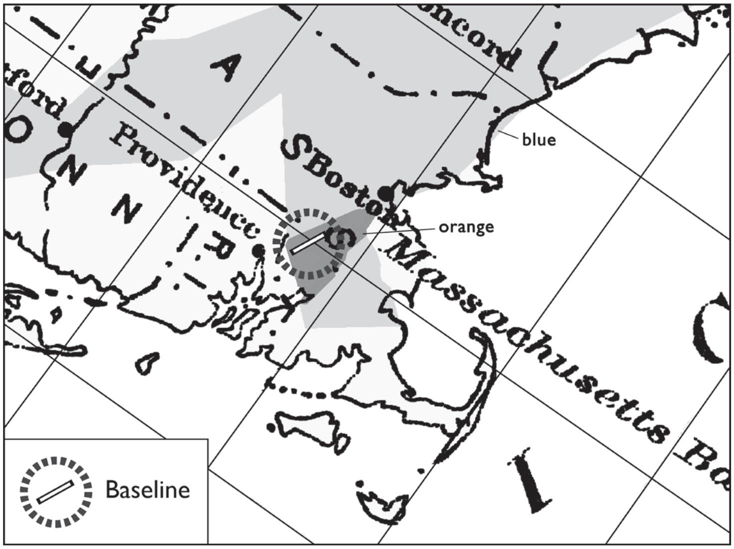

Figure 1.10. Enlarged excerpt from Schott's 1902 map in the vicinity of the Massachusetts baseline. Parallels and meridians were reconstructed and the baseline symbol was added by the author. The dark-gray area, colored orange on Schott's map, apparently encompasses the triangles immediately surrounding the baseline.

Maps in a 1922 report by Coast and Geodetic Survey mathematician Orlando Platt Sutherland (1889–1967) revealed impressive enhancements to the Massachusetts triangulation, which had grown significantly denser since the mid-nineteenth century.[38] One map described a "precise network" with thirty-nine links connecting nineteen nodes, including two in New Hampshire and one each in New York, Rhode Island, and Vermont. Sixteen additional maps covering smaller parts of the state showed hundreds of primary and secondary triangles linked to the more accurate network. Figure 1.11, a much reduced facsimile of the map that includes the Massachusetts baseline, reflects significant regional variation in network density, partly explained by spatial variation in prominent targets, such as church spires, tall chimneys, water towers, and other high points that can be triangulated from multiple stations and need not be occupied with a theodolite. Once the location of one of these secondary points was calculated and published, it could be used to triangulate other locations relevant to topographic mapping and construction surveys.

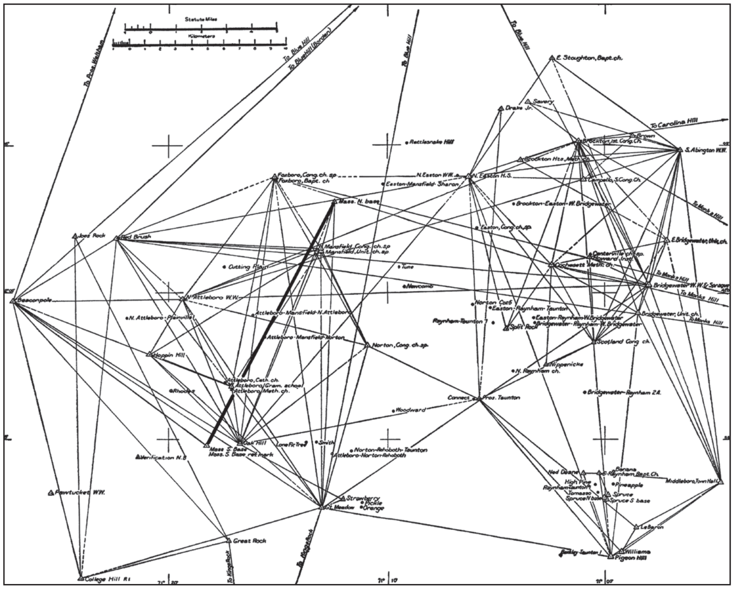

Figure 1.11. Reduced facsimile of figure 19, "Triangulation, Interior, Eastern Section," from Sutherland, *Triangulation in Massachusetts* (1922). Area shown is thirty-nine miles (*left to right*). The Massachusetts baseline (*left of center*), with a south-southwest to north-northeast trend, has been thickened slightly for emphasis.

According to Sutherland, federal mapmakers had recently adopted a new hierarchy of accuracy levels. Instead of the primary, secondary, and tertiary networks described by Richard Cutts in 1868, there were now four levels: precise, primary, secondary, and tertiary, with the first three characterized by average triangle closing errors of "about" 1, 3, and 5 seconds, respectively.[39] Under this new schema, *precise* was the highest level, "equal in accuracy [to] *primary* .... as previously designated," and what was now the primary network was "used principally as a means of connection between the precise and secondary work." Although Sutherland dismissively noted that "no tertiary triangulation is contained in this report," the new hierarchy recognized the need to tie additional points and smaller triangles to the secondary triangulation to accommodate public works surveys and other engineering projects.

By the end of the twentieth century, electronic distance measurement (EDM) was supplementing triangulation with trilateration for geodetic and engineering surveys. *Trilateration* uses distances rather than angles to solve the intersection problem in figure 1.4. Post–World War II advances in electronics took advantage of a simple principle: launch a pulse of light at a distant reflector, measure the difference in time between the pulse's emission and return, and use the speed of light to calculate the distance. Advanced EDM instruments with errors less than one part in 200,000 exceeded the requirements for first-order surveys by a factor of 10.[40] By century's end, third-order surveys were typically based on the less expensive total station, which combined a short-range EDM unit with a theodolite. Trilateration is also a fundamental principle of the global positioning system (GPS), widely used for vehicle navigation and scientific data collection as well as an indispensable element of the mobile phone and smartphone.

But wait, there's more. Able to calculate geographic positions to within millimeters—extreme accuracy requires multiple readings—GPS afforded independent verification of nineteenth-century baselines. Although the National Geodetic Survey (NGS), which inherited geodetic responsibilities after the Coast and Geodetic Survey was folded into NOAA in the 1970s, has moved well beyond the legacy networks of Hassler, Cutts, and Schott, the Eastern Oblique Arc caught the fancy of a cadre of geocaching enthusiasts, who hide or recover buried objects identified by their GPS coordinates. In spring 2008, for instance, a GPS hobbyist known as Papa-Bear-NYC sought out forgotten monuments of the New England geodetic network and posted his findings online.[41] Equipped with a handheld GPS receiver, a metal detector, a camera, and a list of published coordinates, he located several monuments of the original Massachusetts primary network, including the North Base station, hidden under the fall leaves in a backyard in

Foxboro, Massachusetts, where the home's owners allowed him to search. Papa Bear's finds included the original station monument (figure 1.12), a "3/4" copper bolt set in a 6" square granite block," and its two reference markers, placed nearby to help surveyors find, or "recover," the station marker. After finding one of the reference markers with his GPS and metal detector, he "guessed" accurately the location of the second, and then located the primary mark over which a tower had been erected long ago.

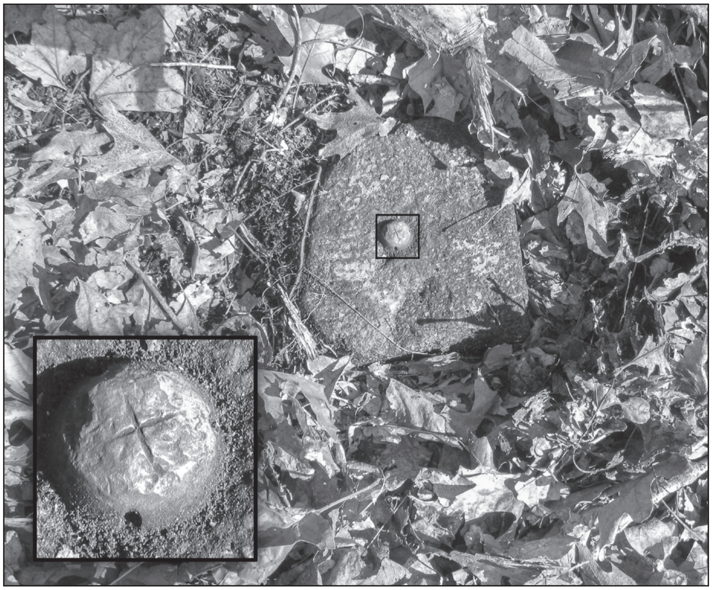

Figure 1.12. North Base station monument as recovered in 2008. Detail inset (*lower left*) shows a 3/4 in. copper bolt in a 6 sq. in. granite post. Courtesy of Richard Garland.

Papa Bear, whose real name is Richard Garland, reported his find to the NGS, which added "Recovery Note by Geocaching 2008 (RG)" to the station's official data sheet.[42] In addition to reporting that the three markers "were recovered in good condition," Garland included the address (42 Summer Street) where he found the station in the backyard "about 6 feet behind (north) [of] an ornamental wood fence which separates the lawn from the wooded area." He didn't bother looking for the Massachusetts South Base station because its data sheet reported that the Massachusetts Survey had failed in 1934 to find any of the markers placed ninety years earlier. "Inhabitants in the vicinity .... mentioned that the station had been looked for several times by surveyors in recent times but without success."[43] Apparently, the markers had been destroyed decades earlier, when the New York, New Haven, and Harford Railroad added a third track. The level grade that had made the eleven-mile baseline possible eventually undermined its recovery.

Geodetic survey monuments had a better survival rate in rural Maine than in suburban Massachusetts. Garland was pleasantly surprised that fall when he headed east to the Epping baseline and bagged all five stations on his list.[44] He found largely intact the 12-foot-wide Base Line Road constructed across the Epping Blueberry Barrens by Coast Survey superintendent Alexander Dallas Bache (1806–67) to provide a straight path for the 5.4-mile baseline, measured in seven days in July 1857 (see figure 1.8).[45] At opposite ends of the road, he recovered station monuments with copper bolts in granite, both "in good condition."[46] In his geocaching post, Garland paid homage to Bache's original work, noted that the corrected measurement of 8,715.9422 ± 0.0158 m "was calculated to be on the order of 1 part in 500,000," and gloated in boldface that "recent GPS measurements actually confirm this impressive accuracy."[47]

When I asked for clarification, Garland pointed me to Harry Nelson, the senior geodesist at the Maine Department of Transportation, who provided a *Bangor Daily News* account of how he helped recruit 43 other surveyors, who assembled in eastern Maine on the third Saturday in October 1991 with nine civilian GPS units—the only ones in the state—to estimate coordinates for thirteen points, four of them along the Epping baseline.[48] Multiple units were needed because a US Department of Defense policy known as "selective availability" blurred readings by nonmilitary receivers.[49] But multiple receivers, at least one at a station with precisely known coordinates, could filter out the noise.[50] The resulting unblurred coordinates, apparently never published, were used to calculate a length "within a centimeter" of Bache's original measurement.[51] Impressive.

When I asked my contacts at the NGS for comment, they offered nothing more definitive than the official data sheets for the endpoint stations, Epping East Base and Epping West Base, which report that "horizontal coordinates were established by GPS observations and adjusted by the National Geodetic Survey in June 2012."[52] Although GPS cannot measure distances directly, it provides coordinates that can be used to compute distances. The NGS also provides online software, with which I calculated the distance between endpoints as 8,715.9055 m—and although Bache's measurement of 8,715.9422 m is more than twice the estimated probable error (± 0.0158 m) above my GPS-based calculation, it's strikingly close nonetheless.[53]

Geodesy has numerous stories, most framed by networks such as those I explore in chapter 2, "Geometry." There's the electronic telegraph network, which helped the Eastern Oblique Arc propagate reliable estimates of longitude throughout the region. There's also the Great Arc of the 39th Parallel, which spanned the country from the Atlantic to the Pacific and joined triangulation arcs reaching from Mexico to Canada to inform a mathematical description of the planet as a sphere flattened at the poles and wider at the equator. Though the earth is not a perfect sphere, a simplified geometric representation, known as a *spheroid* or *ellipsoid*, provides a unified frame of reference for latitude, longitude, and elevation. And the intercontinental triangulation network that vaulted the Atlantic to link North America to Europe and Asia was an endeavor facilitated by dynamic networks of geodetic satellites, including giant reflective balloons that served as moving trilateration targets.[54] And finally, there's the role of the military, which recognized the importance of geodesy and global referencing systems in an era of intercontinental ballistic missiles (IBMs) and cruise missiles. This pursuit of precision also informed studies of crustal dynamics, continental drift, and sea level rise.

In chapter 3, "Symbols," the focus shifts from measurements to graphics, in particular the representation on paper and electronic screens of transportation systems and other surface networks. After mapping evolved to encompass canals, roads, and railways, topographic and thematic maps became more diverse and pervasive, as exemplified by pictorial and abstract symbols for subways and airlines. Chapter 4, "Infrastructure," examines the role of maps in planning, building, and managing networks that move goods, people, and energy and highlights the use of maps in keeping track of and protecting buried utility lines.

Chapter 5, "Telecommunications," focuses on nineteenth-century telegraphy, which not only facilitated efficient longitude measurements at triangulation stations but also fostered the efficient accumulation of atmospheric measurements used in making the synchronous weather map. Getting the data together at a

single location where nationwide measurements could be plotted, and plotting them several times a day, was essential to useful forecasts of severe storms. As the twentieth century progressed, national and global telecommunication networks not only distributed timely news maps but also gave the world's weather services a framework for making and distributing Doppler radar maps, now a staple on the internet along with cartographic predictions that look days, and even months, into the future. These stories remind us that disseminating geographic information is as much a part of cartography as collecting and mapping data.

Chapter 6, "Topology," turns to computer-readable networks known as *geographic base files* and *data models*, which use binary digits to describe relationships among households, businesses, and geographic features such as city blocks and street addresses. Among the earliest was the address coding guide (ACG), with which the US Census Bureau tabulated data scanned from mailed questionnaires for the 1970 Census. Later developments fostered a digital, data-driven geography that included interactive maps of census data, minimum-distance maps for dispatching ambulances and fire engines, GPS-based navigation systems, and efficient configurations of stores and distribution warehouses for large retail businesses eager to minimize transportation cost. Chapter 7, "Control," summarizes the diverse relationship between maps and networks as well as the role of electronic maps in guiding driverless cars and promoting partisan gerrymandering. Like many versatile tools, maps can serve nefarious aims.