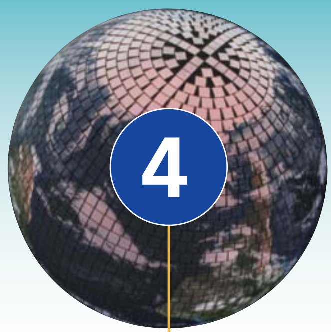


4 Georeferencing

LEARNING OBJECTIVES

Geographic location is the element that distinguishes geographic information (GI) from all other types of information, so methods for specifying location on the Earth's surface are essential to the creation of useful GI. Many such techniques have been developed over the centuries, but in recent years it has become possible to convert from one to another with ease using GI systems and Web-based services. This chapter provides a basic guide to georeferencing for GISS students—what you need to know about georeferencing to succeed. The first section lays out the principles of georeferencing, including the requirements that any effective system must satisfy. Subsequent sections discuss commonly used systems, starting with the ones closest to everyday human experience, including place-names and street addresses, and moving to the more accurate scientific methods that form the basis of geodesy and surveying, and the most recent methods developed for the Web. The final sections deal with issues that arise over conversions between georeferencing systems, with the Global Positioning System (GPS), with georeferencing of computers and cell phones, and with the concept of a gazetteer.

After studying this chapter you will:

- Know the requirements for an effective system of georeferencing.
- Be familiar with the problems associated with place-names, street addresses, and other systems used every day by humans to define locations that are important in their daily lives.
- Know how the Earth is measured and modeled for the purposes of positioning.
- Know the basic principles of map projections and the details of some commonly used projections.
- Know about conversion between different systems of georeferencing.
- Understand the principles behind GPS and learn some of its applications.

4.1 Introduction

Chapter 3 introduced the idea of an atomic element of GI: an atom made up of location, time (optionally), and attribute. To make a GI system work there must be techniques for assigning values to all three aspects in ways that are commonly understood by people who wish to communicate. Almost all the world agrees on a common calendar and time system, so there are only minor problems associated with communicating that element of the atom when it is needed (although different time zones, different names of the months in different languages, the annual switch to summer or Daylight Saving Time, and systems such as the classical Japanese convention of dating by the year of the emperor's reign or the Islamic tradition of dating from the prophet's arrival in Medina all sometimes manage to confuse us).

Specification of time is optional in GI systems, but location is not, so this chapter focuses on techniques for specifying location and the problems and issues that arise. Locations are the basis for many of the benefits of GI systems: the ability to map, to tie different kinds of information together because they refer to the same place, to measure distances and areas, or to make decisions.

Time is an optional element in geographic information, but location is essential.

Several terms are commonly used to describe the act of assigning locations to atoms of information. We use the verbs *georeference*, *geolocate*, and *geocode* and say that facts have been *georeferenced* or *geocoded*. We talk about *tagging* records with geographic locations, or about *locating* them. The term *georeference* will be used throughout this chapter.

The primary requirements of a georeference are (1) that it be *unique*, so that there is only one location associated with a given georeference, and therefore no confusion about the location that is referenced; and (2) that its meaning be *shared* among all of the people who wish to work with the information. For example, the georeference 3334 NE Blakeley St, Seattle, Washington, USA, points to a single house—there is no other house anywhere on Earth with that address—and its meaning is shared sufficiently widely to allow mail to be delivered to the address from virtually anywhere on the planet. The address may not be meaningful to everyone living in China, but it will be meaningful to a sufficient number of people within China's postal service, so that a letter mailed from China to that address will likely be delivered successfully, even if all of the address is written in the Roman alphabet and Arabic numerals. Uniqueness and shared meaning are sufficient also to allow people to link different kinds of information based on common location: for example, home address could be used to link information from databases that store that information as part of each record.

To be as useful as possible, a georeference must be *persistent through time* because it would be very confusing if georeferences changed frequently, and very expensive to update all the records that depend on them. This can be problematic when a georeferencing system serves more than one purpose or is used by more than one agency with different priorities. For example, a municipality may change its boundaries by incorporating more land, creating problems for mapping agencies and for researchers who wish to study the municipality through time. Street names sometimes change, and postal agencies sometimes revise postal codes. Changes even occur in the names of cities (Saigon to Ho Chi Minh City) or in their conventional transcriptions into the Roman alphabet (Peking to Beijing).

To be most useful, georeferences should stay constant through time.

Although some georeferences are based on simple names, others are based on various kinds of *measurements* and are called *metric* georeferences. They include latitude and longitude and various kinds of coordinate systems, many of which are discussed in more detail later in this chapter and are essential to the making of maps, the display of mapped information, and any kind of numerical analysis. One enormous advantage of such coordinate systems is that they provide the potential for unlimited accuracy. Provided we have sufficiently accurate measuring devices and use enough decimal places, such systems will allow us to locate information to any level of accuracy. Another advantage is that from measurements of two or more locations, it is possible to compute distances, a very important requirement of georeferencing in GI systems.

Metric georeferences are much more useful because they allow maps to be made and distances to be calculated.

Every georeference has an associated uncertainty. In some cases this is a form of spatial resolution, equal to the size of the area that is assigned to that georeference. For example, knowing that an address is somewhere in Alaska clearly has much greater uncertainty than knowing that an address is somewhere in Rhode Island. When georeferences are measured, for example, by using GPS to georeference a tweet, the uncertainty is the result of errors of measurement, which we might express as the area around the measured location in which the true location might exist. For example, a tweet georeferenced using GPS with a measurement error of 100 m might be said to have an uncertainty equal to the area of a circle of radius 100 m, that is, 3.14 hectares. A mailing address could be said to have an uncertainty equal to the size of the mailbox, or perhaps to the area of the parcel of land or structure assigned that address. Many other systems of georeferencing have similarly wide-ranging uncertainties.

In each of the examples in the previous paragraph, uncertainty was expressed in area measure. Often, however, we think of uncertainty of position in linear measure. But it is easy to connect the two by taking the square root of area. Thus the positional uncertainty inherent in the georeference "in Rhode Island" might be expressed either as the area of Rhode Island (3140 sq km) or as its square root (56 km).

Many systems of georeferencing are unique only within an area or *domain* of the Earth's surface. For example, many populated places in the United States have the name Springfield (62 according to the official online Geographic Names Information System geonames.usgs.gov; similarly, there are in the United Kingdom nine populated places called Whitchurch in the Geonames database geonames.org that integrates official and volunteered sources). However,

Figure 4.1 Place-names are not necessarily unique at the global level. This map shows the locations of 40 places named Santa Barbara in the Geonames database (geonames.org). Additional information would be needed (e.g., limiting the search to California) to locate a specific Santa Barbara.

Basemap courtesy: Google. Imagery copyright 2013 by NASA and TerraMetrics, map data copyright 2013 by MapLink and Tele Atlas

the advent of postal systems in many countries led to the renaming of many duplicates, so that in the UK city names are unique within counties. Today there is no danger that there are two Springfields in Massachusetts; a driver can therefore confidently ask for directions to "Springfield, Massachusetts" in the knowledge that there is no danger of being sent to the wrong Springfield. But people living in London, Ontario, Canada, are well aware of the dangers of talking about "London" without specifying the appropriate domain. Even in Toronto, Ontario, a reference to "London" may be misinterpreted as a reference to the older (UK) London on a different continent rather than to the one 200 km away in the same province (Figure 4.1). Street name is unique in the United States within municipal domains, but not within larger domains such as county or state. There are 120 places on the Earth's surface with the same Universal Transverse Mercator coordinates (see Section 4.8.2), and a zone number and hemisphere must be added to make a reference unique in the global domain.

This section has reviewed some of the general properties of georeferencing systems, and Table 4.1 shows some commonly used systems. The following sections discuss the specific properties of the systems that are most important in GI practice.

Table 4.1 Some commonly used systems of georeferencing.

System	Domain of uniqueness	Metric?	Example	Positional uncertainty
Place-name or POI	varies	no	London, Ontario, Canada	varies by type of feature
Postal address	global	no, but ordered along streets in some countries	3334 NE Blakeley St, Seattle, WA, USA	size of one mailbox
Postal code	country	no	98104 (U.S. ZIP code)	area occupied by a defined number of mailboxes
Telephone calling area	country	no	804	varies
Cadastral system	local authority	no	Parcel 01442944, City of Springfield, MA	area occupied by a single parcel of land
Public Land Survey System	Western Canada and United States only, unique to Principal Meridian	yes	Sec 4, Township 4N, Range 6E	defined by level of subdivision
Latitude/ longitude	global	yes	119 degrees 44 minutes West, 34 degrees 40 minutes North	infinitely fine (2.8 sq km in this example)
Universal Transverse Mercator	zones six degrees of longitude wide, and N or S hemisphere, but not polar latitudes	yes	463146E, 4346732N	infinitely fine (1 sq m in this example)
State Plane Coordinates	U.S. only, unique to state and to zone within state	yes	4408634E, 7421076N	infinitely fine (1 sq ft in this example)

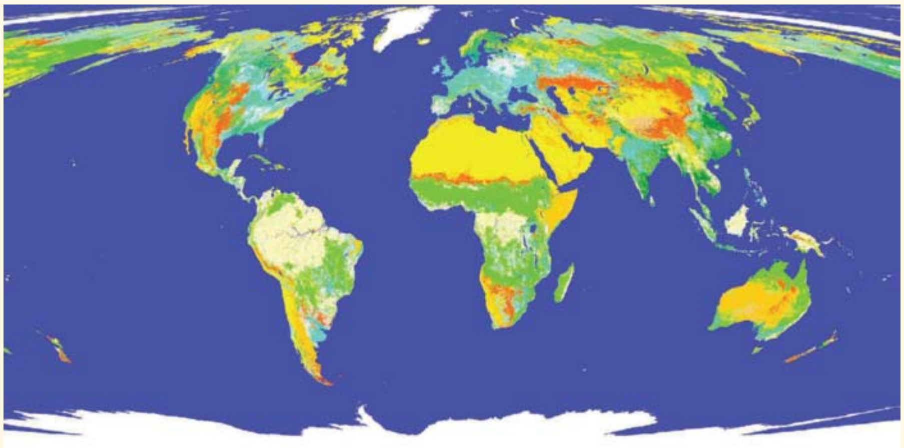
Biographical Box 4.1

Lynn Usery

E. Lynn Usery (Figure 4.2) is a Research Physical Scientist and Director of the Center of Excellence for Geospatial Information Science (CEGIS) with the U.S. Geological Survey (USGS). Lynn's work has spanned traditional field-surveying, photogrammetric, and cartographic processes for topographic mapping in the 1970s to modern all-digital processes of GI systems and Internet mapping today. He was involved in the automation of topographic mapping for the USGS and then explored feature-based GI concepts at the University of Wisconsin–Madison and the University of Georgia. Returning to the USGS and topographic mapping in 1999, Lynn began examining problems of map projections and coordinate transformations, particularly for large raster datasets. Treating the raster cells as areas rather than points, which was the approach used in commercial transformation software at that time, a USGS research team under Lynn's direction provided solutions to projection problems of raster data, including pixel loss and gain in categorical datasets and repeated areas, the so-called wrap-around problem (Figure 4.3). The large data volumes of fine resolution and global geospatial data, and the complex calculations of map-projection transformations, are well suited to parallel and grid computing approaches. With its grid cell structure, raster data are ideally partitioned by rows, columns, or blocks for multiple processors. Lynn and his USGS research team paired with the CyberGIS community to develop parallel solutions to map projection transformations. Results of that effort include a map projections package, pRasterBlaster, that operates in parallel and can be used with the XSEDE supercomputer network of the National Science Foundation. In an era of multiple petabytes of data for USGS mapping operations, CyberGIS provides a practical solution. In addition to the projections research, Lynn is also engaged in researching semantics for geographic information, particularly for terrain features, such as hills, mountains, and valleys.

Courtesy: E. Lynn Usery

Figure 4.2 E. Lynn Usery, cartographer and GI scientist for the U.S. Geological Survey.



Basemap courtesy: Google. Imagery copyright 2013 by NASA and TerraMetrics, map data copyright 2013 by MapLink and Tele Atlas.

Figure 4.3 The wrap-around problem of map projection transformations resulting from improper framing of the output transformation space. Note the repetition of Alaska and Siberia on both east and west edges of this Hammer projection.

4.2 Place-Names and Points of Interest

Giving names to places is the simplest form of georeferencing and was most likely the first one developed by early hunter–gatherer societies. Any distinctive feature on the landscape, for example, a particularly old tree or a restaurant, can serve as a point of reference for two people who wish to share information, such as the existence of good game in the tree's vicinity or a proposed rendezvous. Human landscapes rapidly became littered with names, as people sought distinguishing labels to use in describing aspects of their surroundings and as other people adopted them. Today, of course, we have a complex system of naming oceans, continents, cities, mountains, rivers, and other prominent features, plus a rich collection of named points of interest. Each country maintains a system of authorized naming, often through national or state committees assigned with the task of standardizing geographic names. Nevertheless, multiple names are often attached to the same feature, for example, when cultures try to preserve the names given to features by the original or local inhabitants (Mount Everest to many, but Chomolungma to many Tibetans), or when city names are different in different languages (Florence in English, Firenze in Italian). Even the question of what merits naming is culturally related and depends on how different cultures make use of the landscapes they occupy. Collections of official names are termed *gazetteers*, but in recent years much larger databases of points of interest have been assembled to support online services for mapping and navigation, and the term *point-of-interest* (POI) database is now more appropriate. In what follows the term *place-name* will be used to refer both to officially recognized features and also to points of interest.

Many commonly used place-names and named points of interest have meanings that vary between people and with the context in which they are used.

But place-names are sometimes of limited use as georeferences. First, they often imply very substantial uncertainty. "Asia" covers over 43 million sq km, so the information that something is located "in Asia" is not very helpful in pinning down its location. One approach to this issue is to use a point to represent the area. This can lead to unintended consequences, as, for example, when Google Maps is asked to find a route from "Colorado" to "Wyoming." The area of Colorado is represented by a central point west of Denver and Wyoming by a central point west of Casper—and a detailed route of 634 km is recommended by the service. But of course a single step is all that might be needed to move between these neighboring states if one were located at the border.

Second, only certain place-names are officially authorized by national or subnational agencies. Many more are recognized only locally, so their use is limited to communication between people in the local community. Place-names may even be lost through time: Although there are many contenders, we do not know with certainty where the "Camelot" described in the English legends of King Arthur was located, if indeed it ever existed.

The meaning of certain place-names can become lost through time.

The growing Web phenomenon of volunteered geographic information (VGI) is changing this situation, however, and creating an alternative to the traditional top-down system of naming. Individuals are now able to assign names to features quite independent of officialdom by using sites such as Wikimapia (www.wikimapia.org; see Figure 4.4). At time of writing, individuals worldwide had added descriptions of over 20,000,000 features, from the largest cities to the smallest buildings. Descriptions can be in any language and a wide range of scripts and can include photographs and links to other sources of information.

Wikimapia's mantra is "Let's describe the whole world," and it is one example of a growing phenomenon that draws individual citizens into the process of creating geographic knowledge. In essence, it echoes an earlier era before the establishment of national mapping agencies and authoritative committees, when place-names were created by explorers and local citizens. Many names fell by the wayside, but some were adopted and shown on maps. The process by which America was named, in 1507, was essentially of this nature: an act by an individual cartographer, Martin Waldseemüller, in St-Dié-des-Vosges in France. Waldseemüller and his colleague, Vautrin Lud, had recently read letters from the Florentine explorer Amerigo Vespucci claiming credit for recognizing that the lands discovered to the west of Europe formed a previously unknown continent. Accordingly, he invented a name by feminizing Vespucci's first name, believing that all continents should have feminine names (Figure 4.5). Copies of the map were distributed across Europe, and the name stuck.

Figure 4.4 Wikimapia coverage of the area of Lhasa, Tibet. Each of the hundreds of polygons in white represents one entry, where a volunteer has provided a description and possible images and links to other information, all of which can be exposed by clicking on the polygon. The identification of the highlighted feature as "underground missile site" is clearly open to question, given the voluntary nature of the Wikimapia project.

Basemap courtesy: Google. Imagery copyright 2013 by TerraMetrics.

Courtesy: Library of Congress Map Collection

Figure 4.5 Detail of the Waldseemüller map of 1507, which for the first time showed the name the cartographer selected for the new continent.

4.3 Postal Addresses and Postal Codes

Postal addresses were introduced after the development of mail delivery in the Nineteenth Century. They rely on several assumptions:

- Every dwelling and office is a potential destination for mail.
- Dwellings and offices are arrayed along paths, roads, or streets and are numbered sequentially.
- Paths, roads, and streets have names that are unique within local areas.
- Local areas have names that are unique within larger regions.
- Regions have names that are unique within countries.

If the assumptions are true, then mail address provides a unique identification for every dwelling and office on Earth.

Today, postal addresses are an almost universal means of locating many kinds of human activity: delivery of mail, place of residence, or place of business. They fail, of course, in locating anything that is not a potential destination for mail, including almost all kinds of natural features (Mount Everest does not have a postal address and neither does Manzana Creek in Los Padres National Forest in California). They are not as useful when dwellings are not numbered consecutively along streets, as happens in some cultures (notably in Japan, where street numbering can reflect date of construction, not sequence along the street; it is temporal, rather than spatial) and in large building complexes like condominiums. Many applications of GI systems rely on the ability to locate activities by postal address and to convert addresses to some more universal system of georeferencing, such as latitude and longitude, for mapping and analysis.

Postal addresses work well to georeference dwellings and offices, but not natural features.

Postal codes were introduced in many countries in the late Twentieth Century in order to simplify the sorting of mail. In the UK system, for example, the first characters of the code identify an Outward Code, and mail is initially sorted so that all mail directed to a single Local Delivery Office (LDO) is together. Incoming mail is accumulated in a local sorting station and sorted a second time by the last characters of the code so that it can be delivered by an LDO. Figure 4.6 shows a map of the Outward Codes for Southend-on-Sea (SS). The full six or seven characters of the postal code (e.g., SS5 4PJ) are unique to roughly 13 houses, a single large business, or a single building. Different countries are more or less insistent on completeness of postal codes; in the UK, for

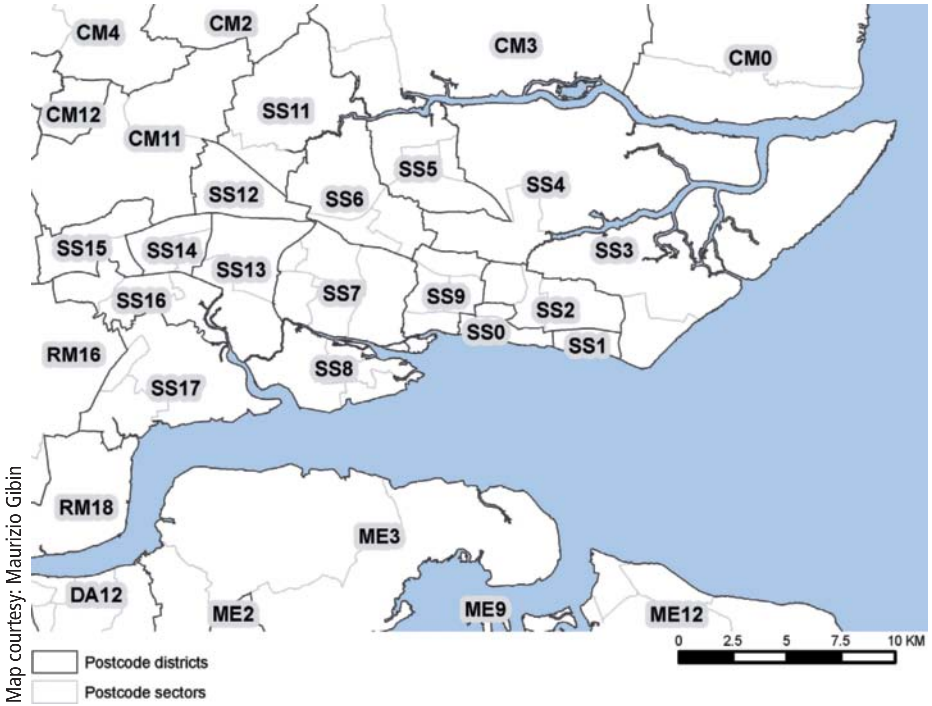


Figure 4.6 Outward Codes for the Southend-on-Sea, UK, Local Delivery Offices (LDOs). Outward codes form the first two, three, or four characters of the UK postal code and are separated from the three characters that identify the Inward Codes.

example, sorters will deliver mail with only an Outward Code because LDOs are required to know their local communities.

Postal codes have proven very useful for many purposes besides the sorting and delivery of mail. Although the area covered by a Canadian FSA (Forward Sortation Area), a U.S. ZIP code, or a UK postcode varies and can be changed whenever the postal authorities want, it is sufficiently constant to be useful for mapping purposes, and many businesses routinely make maps of their customers by counting the numbers present in each postal code area, as well as by dividing by total population to get a picture of market penetration. Figure 4.7 shows an example of summarizing data by postal code. In Figure 4.7A it has been necessary to suppress the locations of postcodes where there are fewer than five resident patients; it is not necessary to hide any data in the choropleth map shown in Figure 4.7B because privacy is not violated at this coarser level of granularity. Most people know the postal code of

Figure 4.7 The use of Outward Code boundaries as a convenient basis for summarizing data. In this instance (A) points identifying the residential unit (Inward) postcode have been used to plot the locations of a doctor's patients, and (B) the Outward Code areas have been shaded according to the density of patients per square kilometer.

their home, whereas almost no one knows his or her latitude and longitude, and in some instances postal codes have developed popular images (the ZIP code for Beverly Hills, California, 90210, became the title of a successful television series).

4.4 IP Addresses

Every device (computer, printer, etc.) connected to the Internet has a unique IP (Internet Protocol) address, such as 128.111.106.183, the address used by the computer of one of the authors when in his office. IP addresses are allocated to organizations, and the street address included in the registration record can provide an approximate location. The IP address of the user's computer is provided whenever the computer is used to access a Web site, allowing the operators of major sites to determine the user's location. Positional uncertainty will vary, however, because all the IP addresses allocated to a university campus may be georeferenced to a single point on the campus, and all the addresses allocated to an Internet Service Provider that operates a broadband service may be georeferenced to a point that is many kilometers from some customers.

The ability to determine even approximate locations for computers has led to some powerful applications. It allows search engines to order the results of search by proximity to the user's location, and it also permits sites such as Wikimapia to open centered on the user's location. Many Web services offer conversion between IP address and geographic coordinates. For example, www.networldmap.com resolves the address 128.111.106.183 to 34.4119 north, 119.7280 west, approximately 10 km from the location of the office at the University of California, Santa Barbara, where the IP address is used. Wikimapia does rather better, opening centered on a location only 1 km away.

4.5 Linear Referencing Systems

A linear referencing system identifies location on a network by measuring distance from a defined point of reference along a defined path in the network. Figure 4.8 shows an example, an accident whose location is reported as being a measured distance from a street intersection, along a named street. Linear referencing is closely related to street address, but uses an explicit measurement of distance rather than the much less reliable surrogate of street address number. Linear referencing is widely used in applications that depend on a linear network. This includes highways (e.g., Mile 1240 of the Alaska Highway), railroads

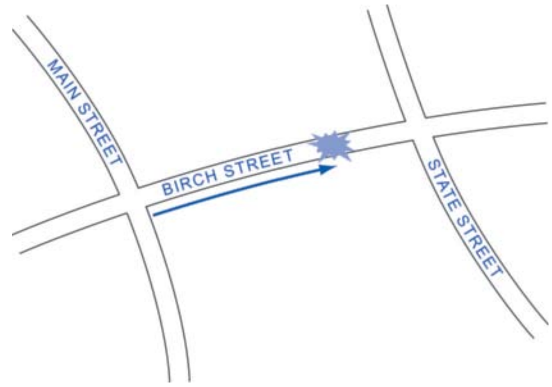


Figure 4.8 Linear referencing—an incident's position is determined by measuring its distance (87 m) along one road (Birch Street) from a well-defined point (its intersection with Main Street).

(e.g., 25.9 miles from Paddington Station in London on the main line to Bristol, England), electrical transmission lines, pipelines, and canals. Highway agencies use linear references to define the locations of bridges, signs, potholes, and accidents and to record pavement condition.

Linear referencing systems are widely used in managing transportation infrastructure and in dealing with emergencies.

Linear referencing provides a sufficient basis for georeferencing for some applications. GI systems have many applications in transportation that are known collectively as GIS-T, and in the developing field of intelligent transportation systems, or ITS. But for other applications it is important to be able to convert between linear references and other forms, such as latitude and longitude. For example, the OnStar system that is installed in many Cadillacs sold in the United States is designed to radio the position of a vehicle automatically as soon as it is involved in an accident. When the airbags deploy, a GPS receiver determines position, which is then relayed to a central dispatch office. Emergency response centers often use street addresses and linear referencing to define the locations of accidents, so the latitude and longitude received from the vehicle must be converted before an emergency team can be sent to the accident.

Linear referencing systems are often difficult to implement in practice in ways that are robust in all situations. In an urban area with frequent intersections, it is relatively easy to measure distance from the nearest one (e.g., on Birch St 87 m east of the intersection with Main Street). But in rural areas an incident may be a long way from the nearest intersection. Even in urban areas it is not uncommon for two streets to intersect more than once (e.g., Birch may have two intersections with Columbia Crescent), or for a street to intersect with itself (Figure 4.9)

Figure 4.9 The intersection of a street with itself (Calgary, Alberta, Canada), causing problems for linear referencing.

4.6 Cadasters and the U.S. Public Land Survey System

The *cadaster* is defined as the map of land ownership in an area, maintained for the purposes of taxing land or of creating a public record of ownership. The process of *subdivision* creates new parcels by legally subdividing existing ones.

Parcels of land in a cadaster are often uniquely identified, by number or by code and are also reasonably persistent through time, thereby satisfying the requirements of a georeferencing system. Indeed, it has often been argued that the cadaster could form the universal basis of mapping (a *multipurpose cadaster*), with all other geographic information tied to it. But very few people know the identification code of their home parcel; thus use of the cadaster as a georeferencing system is limited largely to local officials, with one major exception.

The U.S. Public Land Survey System (PLSS) evolved out of the need to survey and distribute the vast land resources of the Western United States, starting in the early Nineteenth Century, and expanded to become the dominant system of cadaster for all the United States west of Ohio, and all of Western Canada. Its essential simplicity and regularity make it useful for many purposes and understandable by the general public. Its geometric regularity also allows it to satisfy the requirement of a metric system of georeferencing because each georeference is defined by measured distances.

The Public Land Survey System defines land ownership over much of western North America and is a useful system of georeferencing.

Figure 4.10 Google Earth simulation of the view looking east along Baseline Road in Ontario, California—the road that follows the original survey baseline for Southern California laid out by Colonel Henry Washington in 1842. The monument marking the intersection between the baseline and the principal meridian is atop Mount San Bernardino, which appears on the horizon.

To implement the PLSS in an area, a surveyor first laid out an accurate north–south line or *principal meridian*. An east–west *baseline* was then laid out perpendicular to this (Figure 4.10). Rows were laid out 6 miles apart and parallel to the baseline, to become the *townships* of the system. Then blocks or *ranges* were laid out in 6 mile by 6 mile squares on either side of the principal meridian (see Figure 4.11). Each square is referenced by township number, range number, whether it is to the east or to the west, and the name of the principal meridian. Thirty-six *sections* 1 mile by 1 mile were laid out inside each township and numbered using a standard system (note how the numbers reverse in every other row). Each section was divided into four quarter-sections of 1/4 square mile, or 160 acres, the size of the nominal family farm or homestead in the original conception of the PLSS. The process can be continued by subdividing into four to obtain any level of spatial resolution.

The PLSS would be a wonderful system if the Earth were flat and if survey measurements were always exact; but unfortunately neither of these assumptions is true. To account for the Earth's curvature, the squares are not perfectly 6 miles by 6 miles, and the rows must be offset frequently; errors in the original surveying complicate matters still further, particularly in rugged landscapes. Figure 4.11 shows the offsetting exaggerated for a small area. Nevertheless, the PLSS remains an efficient system and one with which many people

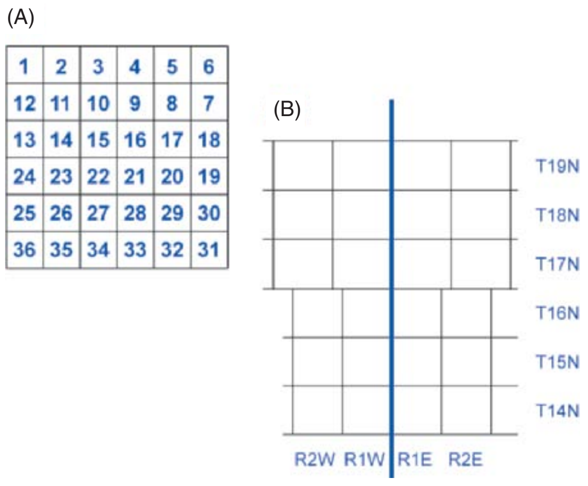


Figure 4.11 Portion of the Township and Range system (Public Lands Survey System) widely used in the Western United States as the basis of land ownership (B). Townships are laid out in 6-mile squares on either side of an accurately surveyed Principal Meridian. The offset shown between T16 N and T17 N is needed to accommodate the Earth's curvature (shown much exaggerated). The square mile sections within each township are numbered as shown in (A).

in the Western United States and Western Canada are familiar. It is often used to specify location, particularly in managing natural resources in the oil and gas industry and in mining, and in agriculture. Services have been built to convert PLSS locations automatically to and from latitude and longitude (Section 4.7).

4.7 Measuring the Earth: Latitude and Longitude

The most powerful systems of georeferencing are those that provide the potential for very accurate measurement of position, that allow distance to be computed between pairs of locations, and that support other forms of spatial analysis (see Chapters 13 and 14). The system of latitude and longitude is in many ways the most comprehensive and is often called the *geographic* system of coordinates. It is based on the Earth's rotation about its center of mass.

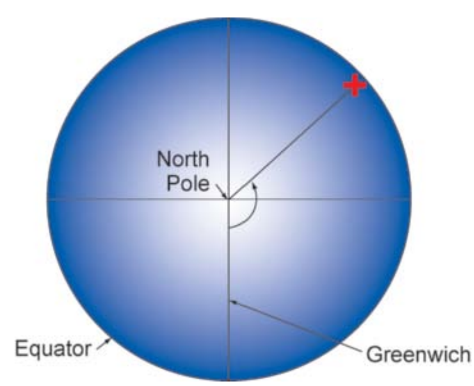
To define latitude and longitude, we first identify the *axis* of the Earth's rotation. The Earth's center of mass lies on the axis, and the plane through the center of mass perpendicular to the axis defines the *equator*. Slices through the Earth parallel to the axis, and perpendicular to the plane of the equator, define lines of constant longitude (Figure 4.12), rather like the segments of an orange. In 1884 a conference attended by delegates from 25 nations agreed that zero longitude, the *prime meridian*, should be defined by a line marked on the ground at the Royal Observatory in Greenwich, England; the angle between this slice and any other slice defines the latter's measure of longitude. Each of the 360 degrees of longitude is divided into 60 minutes and each minute into 60 seconds. But it is more conventional to refer to longitude by degrees East or West, so longitude ranges from 180 degrees West to 180 degrees East of the prime meridian. Finally, because computers are designed to handle numbers ranging from very large and negative to very large and positive, we normally store longitude in computers as if West was negative and East was positive, and we store parts of degrees using decimals rather than minutes and seconds. A line of constant longitude is termed a *meridian*.

Longitude can be defined in this way for any rotating solid, no matter what its shape, because the axis of rotation and the center of mass are always defined. But the definition of latitude requires that we know something about the Earth's shape. The *geoid* is defined as a surface of equal gravity formed by the oceans at rest, and by an imaginary extension of this surface under the continents; it has a complex shape that is only approximately spherical (a radius of 6378 km is a reasonable approximation if the Earth is assumed to be spherical). A much better mathematical approximation or *figure of the Earth* is the *ellipsoid of rotation*, the figure formed by taking a mathematical ellipse and rotating it about its shorter axis (Figure 4.13). The term *spheroid* is also commonly used.

The difference between the ellipsoid and the sphere is measured by its *flattening*, or the reduction in the minor axis relative to the major axis. Flattening is defined as:

$$f = (a - b)/a$$

Figure 4.12 Definition of longitude. The Earth is seen here from above the North Pole, looking along the axis, with the equator forming the outer circle. The location of Greenwich defines the Prime Meridian. The longitude of the point at the center of the red cross is determined by drawing a plane through it and the axis and measuring the angle between this plane and the Prime Meridian.



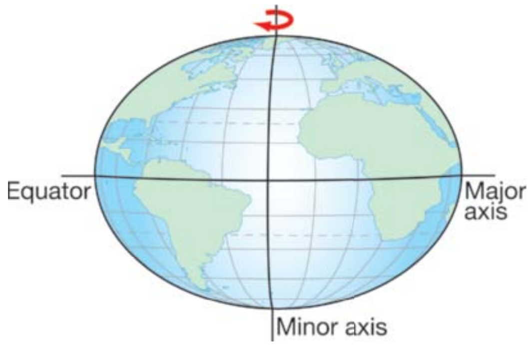


Figure 4.13 Definition of the ellipsoid, formed by rotating an ellipse about its minor axis (corresponding to the axis of the Earth's rotation).

where *a* and *b* are the lengths of the major and minor axes, respectively (we usually refer to the *semi*-axes, or half the length of the axes, because these are comparable to radii). The actual flattening is about 1 part in 300.

The Earth is slightly flattened, such that the distance between the poles is about 1 part in 300 less than the diameter at the equator.

Much effort was expended over the past 200 years in finding ellipsoids that best approximated the shape of the Earth in particular countries, so that national mapping agencies could measure position and produce accurate maps. Early ellipsoids varied significantly in their basic parameters and were generally not centered on the Earth's center of mass. But the development of intercontinental ballistic missiles in the 1950s and the need to target them accurately, as well as new data available from satellites, drove the push to a single international standard. Without a single standard, the maps produced by different countries using different ellipsoids could never be made to fit together along their edges, and artificial steps and offsets were often necessary in moving from one country to another (navigation systems in aircraft would have to be corrected, for example).

The ellipsoid known as WGS84 (the World Geodetic System of 1984) is now widely accepted (though minor adjustments continue to be made, they are largely insignificant in magnitude for GIS applications), and North American mapping has been brought into conformity with it through the adoption of the virtually identical North American Datum of 1983 (NAD83). It specifies a semimajor axis (distance from the center to the equator) of 6378137 m and a flattening of 1 part in 298.257, and its line of zero longitude passes about 100 m to the east of the Greenwich Observatory. But many other ellipsoids remain in use in certain parts of the world, and much older data still adhere to earlier standards, such as the North American Datum of 1927 (NAD27). For locations in the continental United States the difference between two points with identical latitude and longitude, but determined according to the NAD27 and NAD83 datums, can be as much as 100 m. Thus GIS users sometimes need to convert between datums, and functions to do that are commonly available.

Applications Box 4.2

Newton, Descartes, and the Shape of the Earth

Isaac Newton's understanding of centrifugal forces led him to conclude that a planet such as the Earth rotating about its axis should bulge at the equator, where the diameter should therefore be greater than the distance between the poles. The French mathematician René Descartes, on the other hand, argued that the reverse should be true—a greater distance between the poles than the diameter at the equator. Given the definition illustrated in Figure 4.14, lines of latitude should grow further apart as one moves away from the equator if Newton is right, and closer together if Descartes is right. In 1734 the French Academy of Sciences dispatched expeditions to Finland and Peru to make accurate determinations of the distance between lines of latitude. The results proved conclusively that Newton was right.

One of the members of the expedition to Peru, Jean Godin, married a Peruvian and promised to take her home to France via a difficult route over the Andes and down the Amazon, at a time when the Spanish authorities in Peru were at odds with the Portuguese authorities in Brazil. He left first, and the 20-year story of Isabel's epic and ultimately successful adventure to rejoin him is admirably told in Robert Whitaker's *The Mapmaker's Wife*.

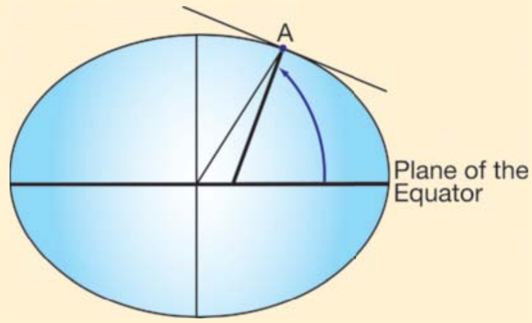


Figure 4.14 Definition of the latitude of Point A, as the angle between the equator and a line drawn perpendicular to the ellipsoid.

We can now define latitude. Figure 4.14 shows a line drawn through a point of interest perpendicular to the ellipsoid at that location. The angle made by this line with the plane of the equator is defined as the point's latitude and varies from 90 South to 90 North. Again, south latitudes are usually stored as negative numbers and north latitudes as positive. Latitude is often symbolized by the Greek letter phi (ϕ) and longitude by the Greek letter lambda (λ), so the respective ranges can be expressed in mathematical shorthand as: $-180 \leq \lambda \leq 180$; $-90 \leq \phi \leq 90$. A line of constant latitude is termed a *parallel.*

It is important to have a sense of what latitude and longitude mean in terms of distances on the surface. Ignoring the flattening, two points on the same north–south line of longitude and separated by one degree of latitude are 1/360 of the circumference of the Earth apart, or about 111 km apart. One minute of latitude corresponds to 1.86 km and also defines one nautical mile, a unit of distance that is still commonly used in navigation. One second of latitude corresponds to about 30 m. But things are more complicated in the east–west direction, and these figures only apply to east–west distances along the equator, where lines of longitude are furthest apart. Away from the equator the length of a line of latitude gets shorter and shorter, until it vanishes altogether at the poles. The degree of shortening is approximately equal to the cosine of latitude, or $\cos \phi$, which is 0.866 at 30 degrees North or South, 0.707 at 45 degrees, and 0.500 at 60 degrees. So degrees of longitude are only 55 km apart along the northern boundary of the Canadian province of Alberta (exactly 60 degrees North).

In GI systems, latitude and longitude are often expressed as decimals of degrees, rather than degrees, minutes, and seconds. It is helpful to know that the 5th decimal place of degrees of latitude is about 1 m on the Earth's surface. In GIS it is very uncommon to know positions to greater accuracy, so any additional decimal places that may be displayed or recorded are probably beyond the limits of accuracy and therefore meaningless. Unfortunately it is all too common for online services to display latitudes and longitudes with precisions that are so far beyond the accuracy of measurement systems as to be almost laughable.

Lines of latitude and longitude are equally far apart only at the equator; toward the poles lines of longitude converge.

Given latitude and longitude, it is possible to determine distance between any pair of points, not just pairs along lines of longitude or latitude. It is easiest to pretend for a moment that the Earth is spherical because the flattening of the ellipsoid makes the equations more complex. On a spherical Earth the shortest path between two points is a *great circle*, or the arc formed if the Earth is sliced through the two points and through its center (Figure 4.15; an off-center slice creates a *small circle*). The length of this arc on a spherical Earth of radius R is given by:

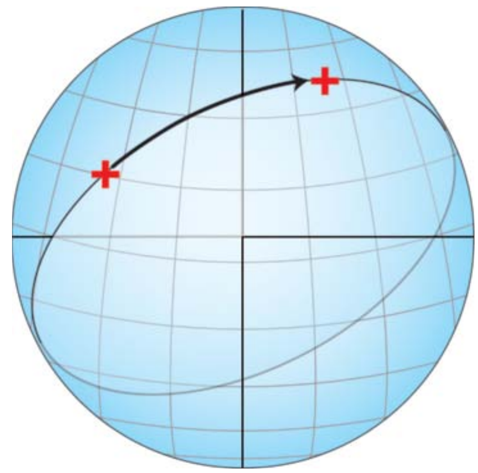


Figure 4.15 The shortest distance between two points on the sphere is an arc of a *great circle*, defined by slicing the sphere through the two points and the center (all lines of longitude, and the equator, are great circles on a spherical Earth). The circle formed by a slice that does not pass through the center is a *small circle* (all lines of latitude except the equator are small circles).

$$R \arccos [\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos(\lambda_1 - \lambda_2)]$$

where the subscripts denote the two points. For example, the distance from a point on the equator at longitude 90 East (in the Indian Ocean between Sri Lanka and the Indonesian island of Sumatra) and the North Pole is found by evaluating the equation for $\phi_1 = 0$, $\lambda_1 = 90$, $\phi_2 = 90$, $\lambda_2 = 90$. It is best to work in radians (1 radian is 57.30 degrees, and 90 degrees is $\pi/2$ radians). The equation evaluates to $R \arccos 0$, or $\pi R/2$, or one-quarter of the circumference of the Earth. Using a radius of 6378 km, this comes to 10,018 km, or close to 10,000 km (not surprising because the French originally defined the meter in the late Eighteenth Century as one ten-millionth of the distance from the equator to the pole).

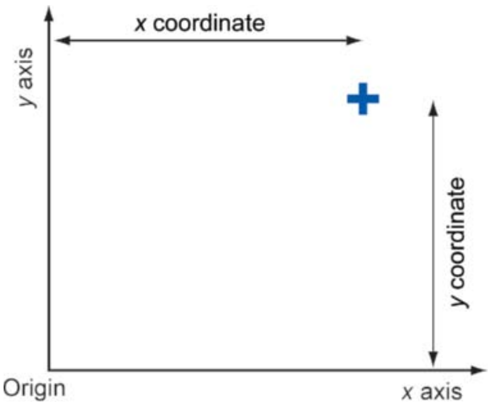
4.8 Projections and Coordinates

Latitude and longitude define location on the Earth's surface in terms of angles with respect to well-defined references: the prime meridian, the center of mass, and the axis of rotation. As such, they constitute the most comprehensive system of georeferencing and support a range of forms of analysis, including the calculation of distance between points, on the curved surface of the Earth. But many technologies for working with geographic data are inherently flat, including paper and printing, which evolved over many centuries long before the advent of digital geographic data and GI systems. For various reasons, therefore, much work in GI science deals with a flattened or *projected* Earth, despite the price we pay in the distortions that are an inevitable consequence of flattening. Specifically, the Earth is often flattened because:

- Paper is flat, and paper is still used as a medium for inputting data to GI systems by scanning or digitizing (see Section 9.3) and for outputting data in map or image form.
- Rasters (Section 7.2.2) are inherently flat because it is impossible to cover a curved surface with equal squares without gaps or overlaps.
- Photographic film is flat, and film cameras are still used widely to take images of the Earth from aircraft to use as GI.
- When the Earth is seen from space, the part in the center of the image has the most detail, and detail drops off rapidly, the back of the Earth being invisible. In order to see the whole Earth at once with approximately equal detail, it must be distorted in some way, and it is most convenient to make it flat.

The Cartesian coordinate system (Figure 4.16) assigns two coordinates to every point on a flat surface by measuring distances from an origin parallel to two axes drawn at right angles. We often talk of the two axes as *x* and *y*, and of the associated coordinates as the *x*- and *y*-coordinate, respectively. Because it is common to align the *y*-axis with North in geographic applications, the coordinates of a projection on a flat sheet are often termed *easting* and *northing*.

Figure 4.16 A Cartesian coordinate system, defining the location of the blue cross in terms of two measured distances from the origin, parallel to the two axes.



Although projections are not absolutely required, there are several good reasons for using them to flatten the Earth.

One way to think of a map projection, therefore, is that it transforms a position on the Earth's surface identified by latitude and longitude (ϕ, λ) into a position in Cartesian coordinates (x, y). Every recognized map projection, of which there are many, can be represented as a pair of mathematical functions:

$$x = f(\phi, \lambda)$$
$$y = g(\phi, \lambda)$$

For example, the famous Mercator projection uses the functions:

$$x = \lambda$$
$$y = \ln \tan[\phi/2 + \pi/4]$$

where ln is the natural log function. The inverse transformations that map Cartesian coordinates back to latitude and longitude are also expressible as mathematical functions: in the Mercator case they are

$$\lambda = x$$
$$\phi = 2 \arctan e^{y} - \pi/2$$

where *e* denotes the constant 2.71828. Many of these functions have been implemented in GI systems, allowing users to work with virtually any recognized projection and datum and to convert easily between them.

Two datasets can differ in both the projection and the datum, so it is important to know both for every dataset.

Projections necessarily distort the Earth, so it is impossible in principle for the scale (distance on the map compared to distance on the Earth; for a discussion of scale see Box 2.3) of any flat map to be perfectly uniform or for the pixel size of any raster to be perfectly constant. Although this point is unimportant for maps of small areas, for maps at global scale the result can be very misleading. In Figure 4.1, for example, which was generated from a Web service that uses Google Maps, there is a scale bar shown in the bottom left corner, indicating the distances on the map that correspond to 2000 km and 1000 mi. But the projection used in the map is Web Mercator (see Section 4.8.3), with a scale that varies continuously. At high latitudes the Mercator projection is acknowledged to produce a very distorted impression of area, Greenland and Russia appearing much larger in relation to countries in lower latitudes than they really are. The 2000-km bar should be positioned at the equator and should be roughly twice as long at the top and bottom of the map (approximately 60 North and 60 South respectively; at latitude ϕ the scale factor is $1/\cos\phi$) as it is in the middle.

Biographical Box 4.3

Gerard Mercator

Gerard Mercator was born Gerard Kremer on March 4, 1412, in Gangelt, close to the Dutch border in what is now Germany. (Kremer is German and Dutch for merchant, mercator in Latin; Gerard changed his name at age eighteen). Like many others before and since, he was intrigued by the problem of portraying the curved surface of the Earth on a flat sheet of paper. His solution, known today as the Mercator Projection, was originally designed to aid navigation; a course set on a constant compass bearing will be straight on the projection. It also displays the conformal property, meaning that scale is locally constant in all directions and making it ideally suited to many Web applications. It achieves these properties at some cost, however, and the Mercator Projection is today often derided. The poles are at infinity, and scales at high latitudes are badly distorted, making countries such as Greenland and Iceland appear much larger in relation to low-latitude countries.

Mercator was imprisoned by the Inquisition and survived plague, war, and famine, living to the remarkable age (for his time) of 82,

But although projections must distort the Earth, they can preserve certain properties. Two such properties are particularly important, although any projection can achieve at most one of them, not both:

- The *conformal* property, which ensures that the shapes of small features on the Earth's surface are preserved on the projection: in other words, that the scales of the projection in the *x*- and *y*-directions are always equal
- The *equal area* property, which ensures that areas measured on the map are always in the same proportion to areas measured on the Earth's surface

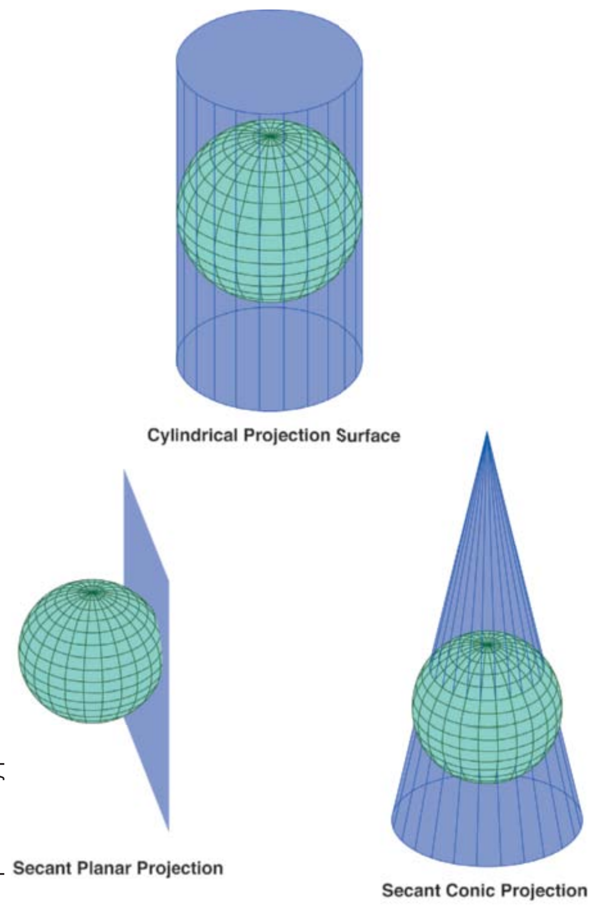
The conformal property of the Mercator projection is useful for navigation because a straight line drawn on the map has a constant bearing (the technical term for such a line is a *rhumb line* or *loxodrome*). The equal area property is useful for various kinds of analysis involving areas, such as the computation of the area of someone's property.

Besides their distortion properties, another common way to classify map projections is by analogy to a physical model of how positions on the map's flat surface are related to positions on the curved Earth. There are three major classes (Figure 4.17), but note that they do not cover all known projections:

- *Cylindrical* projections, which are analogous to wrapping a cylinder of paper around the Earth, projecting the Earth's features onto it, and then unwrapping the cylinder
- *Azimuthal* or *planar* projections, which are analogous to touching the Earth with a sheet of flat paper
- *Conic* projections, which are analogous to wrapping a sheet of paper around the Earth in a cone

In each case, the projection's *aspect* defines the specific relationship, for example, whether the paper

Figure 4.17 The basis for three types of map projections—cylindrical, planar, and conic. In each case a sheet of paper is wrapped around the Earth, and positions of objects on the Earth's surface are projected onto the paper. The cylindrical projection is shown in the tangent case, with the paper touching the surface, but the planar and conic projections are shown in the secant case, where the paper cuts into the surface.



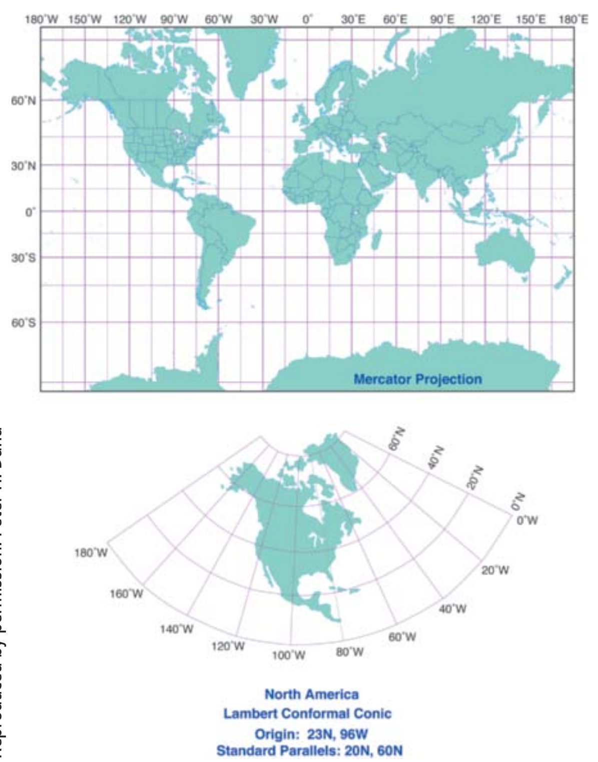
Reproduced by permission: Peter H. Dana

is wrapped around the equator or touches at a pole. Where the paper coincides with the surface the scale of the projection is 1, and where the paper is some distance outside the surface the projected feature will be larger than it is on the Earth. *Secant* projections attempt to minimize distortion by imagining the paper cutting through the surface, so that scale can be both greater and less than 1 (Figure 4.17; projections for which the paper touches the Earth and in which scale is always 1 or greater are called *tangent*).

All three types can have either conformal or equal area properties, but of course not both. Figure 4.18 presents examples of several common projections and shows how the lines of latitude and longitude map onto the projection, in a (distorted) grid known as a *graticule*.

The next sections describe several particularly important projections in detail, together with the coordinate systems that they produce. Each is important to GI systems, and users are likely to come across them frequently. The map projection (and datum) used to make a dataset is sometimes not known to the user of the dataset, so it is helpful to know enough about map projections and coordinate systems to make intelligent guesses when trying to combine such a dataset with other data. Several excellent books on map projections are listed in Further Reading.

Figure 4.18 Examples of some common map projections. The Mercator projection is a tangent cylindrical type, shown here in its familiar equatorial aspect (cylinder wrapped around the equator). The Lambert Conformal Conic projection is a secant conic type. In this instance, the cone onto which the surface was projected intersected the Earth along two lines of latitude: 20 North and 60 North.

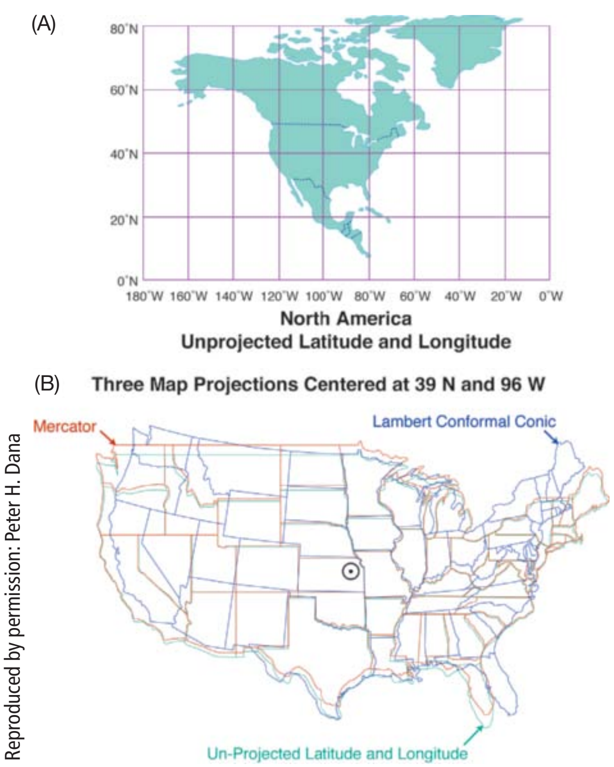


Reproduced by permission: Peter H. Dana

4.8.1 The Plate Carrée or Cylindrical Equidistant Projection

The simplest of all projections maps longitude as *x* and latitude as *y*; for that reason this map is also known informally as the *unprojected* projection. The result is a heavily distorted image of the Earth, with the poles smeared along the entire top and bottom edges of the map and a very strangely shaped Antarctica. Nevertheless, it is the view that we most often see when images are created of the entire Earth from satellite data (for example, in illustrations of sea-surface temperature that show the El Niño or La Niña effects). The projection is not conformal (small shapes are distorted) and not equal area, though it does maintain the correct distance between every point and the equator. It is normally used only for the whole Earth, and maps of parts of the Earth, such as the United States or Canada, look distinctly odd in this projection. Figure 4.19

Figure 4.19 (A) The so-called unprojected or Plate Carrée projection, a tangent cylindrical projection formed by using longitude as *x* and latitude as *y*. (B) A comparison of three familiar projections of the United States. The Lambert Conformal Conic is the one most often encountered when the United States is projected alone and is the only one of the three to curve the parallels of latitude, including the northern border on the 49th Parallel.



Reproduced by permission: Peter H. Dana

shows the projection applied to the world and also presents a comparison of three familiar projections of the United States: the Plate Carrée, Mercator, and Lambert Conformal Conic.

When longitude is assigned to *x* and latitude to *y*, a very odd-looking Earth results.

Serious problems can occur when doing analysis using this projection. Moreover, because most methods of analysis in GI systems are designed to work with Cartesian coordinates rather than latitude and longitude, the same problems can arise in analysis when a dataset uses latitude and longitude, or so-called geographic coordinates. For example, a command to generate a circle of radius one unit in this projection will create a figure that is two degrees of latitude across in the north–south direction and two degrees of longitude across in the east–west direction. On the Earth's surface this figure is not a circle at all, and at high latitudes it is a very squashed ellipse.

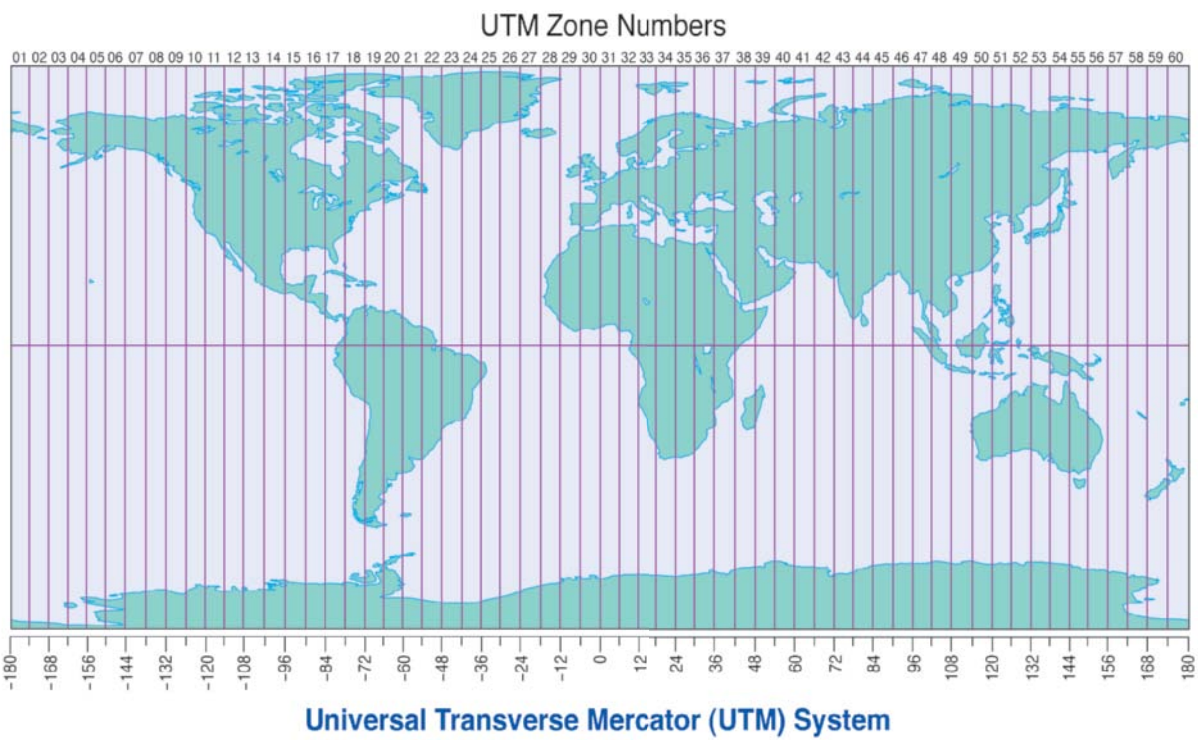
It is wise to be careful when using a GI system to analyze data in latitude and longitude rather than in projected coordinates because serious distortions of distance, area, and other properties may result.

4.8.2 The Universal Transverse Mercator (UTM) Projection

The UTM system is often found in military applications and in datasets with global or national coverage. It is based on the Mercator projection, but in the *transverse* rather than equatorial aspect, meaning that the projection is analogous to wrapping a cylinder around the poles rather than around the equator. There are 60 zones in the system, and each zone corresponds to a half cylinder wrapped along a particular line of longitude, each zone being 6 degrees wide. Thus Zone 1 applies to longitudes from 180 W to 174 W, with the half cylinder wrapped along 177 W; Zone 10 applies to longitudes from 126 W to 120 W centered on 123 W, and so on (Figure 4.20).

The UTM system is secant, with lines of scale 1 located some distance out on both sides of the Central Meridian. Because the projection is conformal, small features appear with the correct shape, and scale at each point is the same in all directions. Scale is 0.9996 at the Central Meridian and at most 1.0004 at the edges of the zone, so the maximum distortion of distances using this projection is about 4/100 of 1%. Both parallels and meridians are curved on the projection, with the exception of the zone's Central Meridian and the equator. Figure 4.21 shows the major features of one zone.

Figure 4.20 The system of zones of the Universal Transverse Mercator system. The zones are identified at the top. Each zone is six degrees of longitude in width.



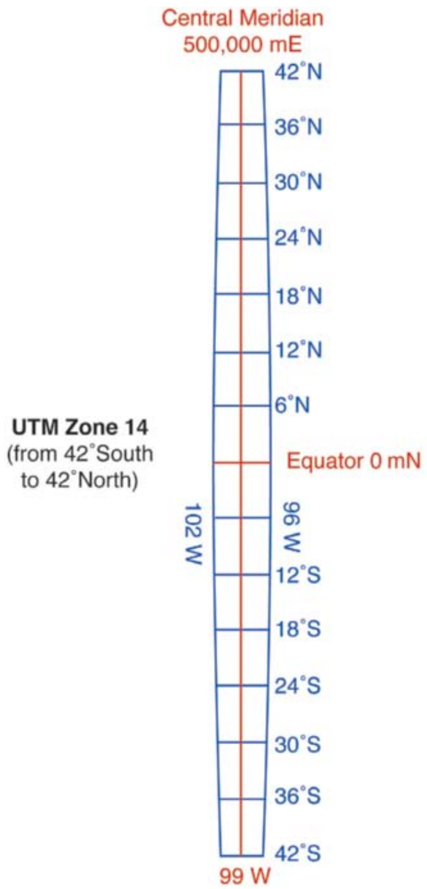


Figure 4.21 Major features of UTM Zone 14 (from 102 W to 96 W). The Central Meridian is at 99 W. Scale factors vary from 0.9996 at the Central Meridian to 1.0004 at the zone boundaries. See text for details of the coordinate system. (Reproduced by permission: Peter H. Dana)

The coordinates of a UTM zone are defined in meters and are set up such that the Central Meridian's easting is always 500,000 m (a *false* easting), so easting varies from near zero to near 1 million m. In the Northern Hemisphere the equator is the origin of northing, so a point at northing 5 million m is approximately 5000 km from the equator. In the Southern Hemisphere the equator is given a false northing of 10 million m, and all other northings are less than this.

UTM coordinates are in meters, making it easy to make accurate calculations of short distances between points.

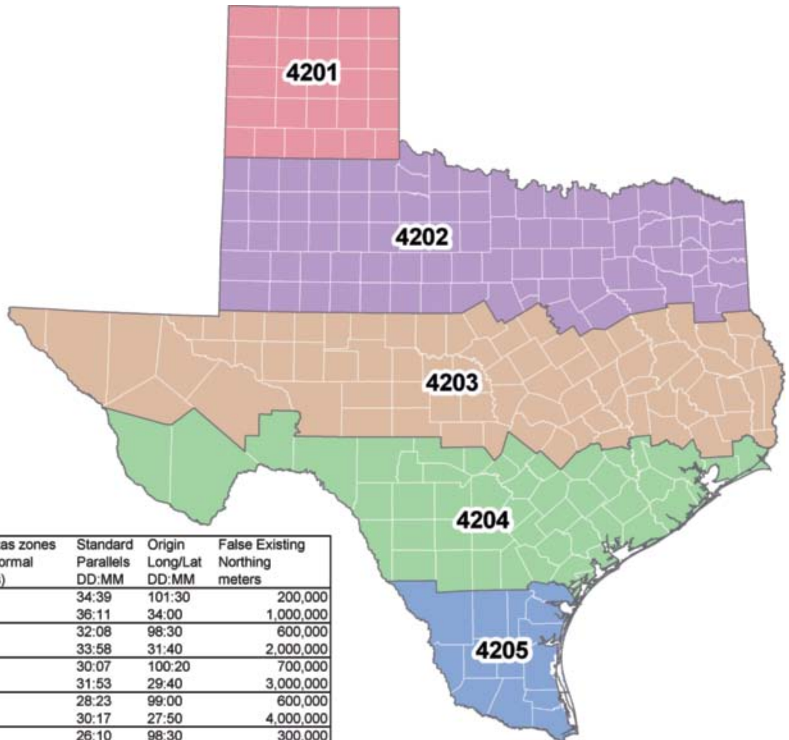
Because there are effectively 60 different projections in the UTM system, maps will not fit together across a zone boundary. Zones become so much of a problem at high latitudes that the UTM system is normally replaced with azimuthal projections centered on each pole (known as the UPS or Universal Polar Stereographic system) above 80 degrees latitude. The problem is especially critical for cities that cross zone boundaries, such as Calgary, Alberta, Canada (which crosses the boundary at 114 W between Zone 11 and Zone 12). In such situations one zone can be extended to cover the entire city, but this results in distortions that are larger than normal. Another option is to define a special zone, with its own Central Meridian selected to pass directly through the city's center. Italy is split between Zones 32 and 33, and many Italian maps carry both sets of eastings and northings.

UTM coordinates are easy to recognize because they commonly consist of a six-digit integer followed by a seven-digit integer (and decimal places if precision is better than a meter) and sometimes include zone numbers and hemisphere codes. They are an excellent basis for analysis because distances can be calculated from them for points within the same zone with no more than 0.04% error. But they are complicated enough that their use is effectively limited to professionals except in applications where they can be hidden from the user. UTM grids are marked on many topographic maps, and many countries project their topographic maps using UTM. It is therefore easy to obtain UTM coordinates from maps for input to digital datasets, either by hand or automatically using scanning or digitizing (Section 8.3).

4.8.3 Web Mercator

The advent of Web mapping services has created a need for a special projection that satisfies several specific requirements. First, it should be accurate enough to support simple kinds of analysis, such as calculation of distances when routing vehicles. Second, it should be fast to compute because users of Web services have little tolerance for response delays (latencies) of more than a fraction of a second. Third, it should be conformal so that local scale is the same in all directions. Finally, Web mapping services are most often used in areas of high population density, so high latitudes can be safely ignored.

Over the past decade the solution to this problem has emerged as what is sometimes called the Web Mercator projection and at other times the Google projection. The projection is also identified with the European Petroleum Study Group (EPSG), a standards organization, and has been assigned a number of EPSG identifiers over the years. Like any version of the Mercator projection it shows high latitudes greatly expanded, but preserves local shapes. It uses the equations for the ellipsoid, rather than the simpler equations for a spherical Earth, but its algorithms allow it to operate at speeds that satisfy user requirements. Figure 4.1 uses the Web Mercator projection, as do many other illustrations in this book derived from Web mapping services, and the misleading nature of its scale bar has already been discussed.



Zone Codes (Texas zones are Lambert conformal Conic Projections)	Standard Parallels DD:MM	Origin Long/Lat DD:MM	False Existing Northing meters
North TX N 4201	34:39 36:11	101:30 34:00	200,000 1,000,000
North Central TX NC 4202	32:08 33:58	98:30 31:40	600,000 2,000,000
Central TX C 4203	30:07 31:53	100:20 29:40	700,000 3,000,000
South Central TX SC 4204	28:23 30:17	99:00 27:50	600,000 4,000,000
South TX S 4205	26:10 27:50	98:30 25:40	300,000 5,000,000

Figure 4.22 The five State Plane Coordinate zones of Texas. Note that the zone boundaries are defined by counties, rather than parallels, for administrative simplicity.

4.8.4 State Plane Coordinates and Other Local Systems

Although the distortions of the UTM system are small, they are nevertheless too great for some purposes, particularly in accurate surveying. Zone boundaries also are a problem in many applications because they follow arbitrary lines of longitude rather than boundaries between jurisdictions. In the 1930s each U.S. state agreed to adopt its own projection and coordinate system, generally known as State Plane Coordinates (SPC), in order to support these high-accuracy applications. Projections were chosen to minimize distortion over the area of the state, so choices were often based on the state's shape. Some large states decided that distortions were still too great, and so they designed their SPCs with internal zones (for example, Texas has five zones based on the Lambert Conformal Conic projection [Figure 4.22], whereas Hawaii has five zones based on the Transverse Mercator projection). Many GI systems have details of SPCs already stored, so it is easy to transform between them and UTM, or latitude and longitude. The system was revised in 1983 to accommodate the shift to the new North American Datum (NAD83).

All U.S. states have adopted their own specialized coordinate systems for applications such as surveying that require very high accuracy.

Many other countries have adopted coordinate systems of their own. For example, the UK uses a single projection and coordinate system known as the National Grid that is based on the Oblique Mercator projection and is marked on all topographic maps. Canada uses a uniform coordinate system based on the Lambert Conformal Conic projection, which has properties that are useful at mid- to high latitudes, for applications where the multiple zones of the UTM system would be problematic.

4.9 Measuring Latitude, Longitude, and Elevation: GPS

The Global Positioning System and its analogs (GLONASS in Russia, the Galileo system in Europe, and Beidou in China) have revolutionized the measurement of position, for the first time making it possible for people to know almost exactly where they are anywhere on the surface of the Earth. The GPS consists of a system of 24 satellites (plus some spares), each orbiting the Earth every 12 hours on distinct orbits at a height of 20,200 km and transmitting radio pulses at precisely timed intervals. To determine position, a receiver must make exact calculations from the signals, the known positions of the satellites, and the velocity of light. Positioning in three dimensions (latitude, longitude, and elevation) requires that at least four satellites are above the horizon, and accuracy depends on the number of such satellites and their positions (if elevation is not required, then only three satellites need be above the horizon). Several different versions of GPS exist, with distinct accuracies.

A simple GPS receiver, such as one might buy in an electronics store for $100, acquire in an iPhone or Android, or install as an optional addition to a laptop or vehicle, has an accuracy within 10 m. This accuracy will degrade in cities with tall buildings, or under trees, and GPS signals will be lost entirely under bridges or indoors. Differential GPS (DGPS) combines GPS signals from satellites with correction signals received via radio or telephone from base stations. Networks of such stations now exist, at precisely known locations, constantly broadcasting corrections; corrections are computed by comparing each known location to its apparent location determined from GPS. With DGPS correction, accuracies improve to 1 m or better. Even better accuracies are possible by using various sophisticated techniques or by remaining fixed and averaging measured locations over several hours.

GPS is very useful for recording ground control points when building GI databases; for locating objects that move (for example, combine harvesters, tanks, cars, and shipping containers); and for direct capture of the locations of many types of fixed objects, such as utility assets, buildings, geological deposits, and sample points. Other applications of GPS are discussed in Chapter 10.

Some care is needed in using GPS to measure elevation. First, accuracies are typically poorer, and a position determined to 10 m in the horizontal may be no better than plus or minus 50 m in the vertical. Second, a variety of reference elevations or vertical datums are in common use in different parts of the world and by different agencies; for example, in the United States the topographic and hydrographic definitions of the vertical datum are significantly different.

4.10 Converting Georeferences

GI systems are particularly powerful tools for converting between projections and coordinate systems because these transformations can be expressed as numerical operations. In fact, this ability was one of the most attractive features of early systems for handling digital geographic data and drove many early applications. But other conversions, for example, between place-names and geographic coordinates, are much more problematic. Yet they are essential operations. Almost everyone knows their mailing address and can identify travel destinations by name, but few are able to specify these locations in coordinates or to interact with GI systems on that basis. GPS technology is attractive precisely because it allows its user to determine his or her latitude and longitude, or UTM coordinates, directly at the touch of a button.

Methods of converting between georeferences are important for:

- Converting lists of customer addresses to coordinates for mapping or analysis (the task known as *geocoding*; see Box 4.3)
- Combining datasets that use different systems of georeferencing

Technical Box 4.4

Geocoding: Conversion of Street Addresses to Coordinates

Geocoding is the name commonly given to the process of converting street addresses to latitude and longitude, or some similarly universal coordinate system. It is widely used, as it allows any database containing addresses, such as a company mailing list or a set of medical records, to be input to a GI system and mapped. Geocoding requires a database containing records representing the geometry of street segments between consecutive intersections, and the address ranges on each side of each segment (a street centerline database; see Section 7.2.3.3). Addresses are geocoded by finding the appropriate street segment record and estimating a location based on linear interpolation within the address range. For example, 950 West Broadway in Columbia, Missouri, lies on the side of the segment whose address range runs from 900 to 998, or 50/98 = 51.02% of the distance from the start of the segment to the end. The segment starts at 92.3503 West longitude, 38.9519 North latitude and ends at 92.3527 West, 38.9522 North. Simple arithmetic gives the address location as 92.3515 West, 38.9521 North. Four decimal places suggests an accuracy of about 10 m, but the estimate also depends on the accuracy of the assumption that addresses are uniformly spaced, as well as on the accuracy of the street centerline database.

- Converting to projections that have desirable properties for analysis, for example, no distortion of area
- Searching the Internet or other distributed data resources for data about specific locations
- Positioning map displays by recentering them on places of interest that are known by name (these last two are sometimes called *locator* services)

Place-name databases (including gazetteers and POI databases) make it easy to convert named features to coordinates, though in many cases, and as already illustrated, the result may be no more than a central point representing an extensive line or area. In some cases conventions have emerged for such representative points—a common convention for rivers is to use the location of the mouth, for example. Such databases are vitally important to Web services that search for features based on user input because users will almost always refer to a feature by its name. Many Web services have become very sophisticated at helping the user to identify features, using suggestion and auto-completion, and accommodating spelling errors and alternative syntax. It is also possible to employ sophisticated software to detect place-names in text and to convert them to georeferences (e.g., www.metacarta.com).

4.11 Geotagging and Mashups

Online gazetteers, geocoding sites, and other services for converting georeferences have made it extremely easy to determine the geographic locations associated with many types of online data. It is now easy, for example, to take a mailing list containing street addresses, geocode them, and create maps. Services such as Google Earth, Google Maps, and their Yahoo! and Microsoft cousins provide the mapping capabilities and are readily invoked through their application programming interfaces (APIs). The term *mashup*, which derives originally from the popular-music industry, has been adopted as a way of describing the joining of two or more online services to create something that neither was able to do on its own. One of the best known mashups is www.housingmaps.com, which combines real-estate (property) listings from Craigslist (www.craigslist.org) with cartographic data from Google Maps (maps.google.com). A similar service for the UK is provided by www.nestoria.co.uk, and the www.londonprofiler.org site allows georeferenced property listings to be viewed against a range of thematic data. Today hundreds of thousands of such mashups have been created, many of them dealing with georeferenced data.

In many online services, such as Wikipedia (www.wikipedia.org), georeferences are embedded in text in the form of *geotags*, codes representing latitude and longitude in compressed form. Geotags make it easy to create mashups with mapping services.

4.12 Georegistration

Converting between georeferences is often needed during the process of assembling a database, when two datasets use different and perhaps unknown coordinate systems. For example, two datasets were needed in a study of fire alarms in London, Ontario: the locations of each of several thousand alarms and the boundaries of the tracts defined by the Canadian census. Linking the two datasets would allow the number of alarms to be determined in each tract and to be compared to statistics about the tract's housing and residents. The map of tract boundaries used UTM coordinates, but the map of alarms had been created from a street map using a digitizer (Section 8.3.2.1).

The standard approach in situations like this is to find a number of points that can serve as *registration* points or *tics*, using them to find equations that will convert coordinates. In this case it was convenient to use 10 major street intersections scattered over the city because these could be readily located both in the tract boundaries and on the map of alarms and to use UTM as the common system. Table 4.2 shows the coordinates of these intersections on the alarm map (x and y) and in UTM. Note that the UTM coordinates in meters are rounded to the nearest hundred, an appropriate decision given the limited positional accuracy of street intersections.

To convert the alarm map to UTM, we look for the simplest possible equations and often adopt an *affine transformation* of the form:

$$\text{UTM north} = a + bx + cy$$
$$\text{UTM east} = d + ex + fy$$

where a through f are values to be determined from the tic points. Standard methods exist in GI systems for doing this, yielding the following values:

$$\text{UTM north} = 4744134 + 401.0\,x + 1222.2\,y$$
$$\text{UTM east} = 473668 + 1207.9\,x - 464.6\,y$$

Finally, these two equations are used to convert all the fire alarm data points to UTM so that the analysis can proceed.

Figure 4.23 shows another example of georegistration. The highlighted area was the focus of a proposed project on the campus of the University of California, Santa Barbara, which was intended to restore the area to its natural wetland state. A number of wells were drilled to monitor groundwater and

Table 4.2 Registration points, with coordinates in both systems.

Intersection	*x*	*y*	UTM north	UTM east
Oxford and Sanatorium	2.90	9.80	4757500	472700
Wonderland and Southdale	4.86	5.96	4753800	476500
Wharncliffe and Stanley	7.32	8.56	4758200	478600
Oxford and Wharncliffe	7.58	9.67	4759800	478400
Wellington and Southdale	8.24	4.90	4754300	481500
Highbury and Hamilton	11.32	6.67	4758200	484100
Trafalgar and Clarke	13.17	7.56	4759700	486200
Adelaide and Dundas	9.49	8.59	4759400	481100
Highbury and Fanshawe	11.50	12.68	4765400	481500
Richmond and Huron	8.28	10.73	4761500	478800

accurately located using GPS. It was then necessary to merge these data with the campus database of detailed fine-resolution imagery and ground elevations, which used a different coordinate system. Registration points were established on features, such as the corners of buildings and streetlights, which could be easily located in both datasets. Note the difficulty in this case of registering the lower part of the highlighted area, where there are no readily identifiable features to use for registration.

The figure shows the result, displayed in Google Earth. Note the obvious displacement between the highlighted area and the Google Earth imagery, but the apparent agreement between the highlighted

Figure 4.23 Registration of a fine-resolution image (highlighted) of part of the campus of the University of California, Santa Barbara, shown as a Google Earth mashup.

area and the Google Earth roads. It seems clear that the roads and the highlighted area are registered much more accurately to the Earth than the Google Earth imagery, which is misplaced by more than 10 m.

4.13 Summary

This chapter has looked in detail at the complex ways in which humans refer to specific locations on the planet and how they measure locations. Any form of geographic information must involve some kind of georeference, and so it is important to understand the common methods, together with their advantages and disadvantages. Many of the benefits of GI systems rely on accurate georeferencing—the ability to link different items of information together through common geographic location; the ability to measure distances and areas on the Earth's surface, and to perform more complex forms of analysis; and the ability to communicate geographic information in forms that others can understand.

Georeferencing was introduced in early societies to deal with the need to describe locations. As humanity has progressed, we have found it more and more necessary to describe locations accurately and over wider and wider domains, so that today our methods of georeferencing are able to locate phenomena unambiguously and accurately anywhere on the Earth's surface. Today, with modern methods of measurement, it is possible to direct another person to a point on the other side of the Earth to an accuracy of a few centimeters. This level of accuracy and referencing is regularly achieved in such areas as geophysics and civil engineering.

But georeferences can never be perfectly accurate, and it is always important to know something about uncertainty. Questions of measurement accuracy are discussed at length in Chapter 5, and Section 5.2.3 deals with techniques for representation of phenomena that are inherently fuzzy, such that it is impossible to say with certainty whether a given point is inside or outside the georeference.

Questions for Further Study

1. Visit your local map library, and determine: (1) the projections and datums used by selected maps; and (2) the coordinates of your house in several common georeferencing systems.
2. Summarize the arguments for and against a single global figure of the Earth, such as WGS84.
3. Access several online mapping services such as Google Maps, Google Earth, or Yahoo! Maps. What projection does each one use, how does it display map scale, and how does map scale vary over the map?
4. Chapter 14 discusses various forms of measurement in GI systems. Review each of those methods and the issues involved in performing analysis on databases that use different map projections. Identify the map projections that would be best for measurement of (1) area, (2) length, and (3) shape.

Further Reading

Bugayevskiy, L. M. and Snyder, J. P. 1994. *Map Projections: A Reference Manual*. London: Taylor and Francis.

Kennedy, M. 2010. *The Global Positioning System and ArcGIS*. 3rd ed. Boca Raton, FL: CRC Press.

Maling, D. H. 1992. *Coordinate Systems and Map Projections*. 2nd ed. Oxford: Pergamon.

Snyder, J. P. 1997. *Flattening the Earth: Two Thousand Years of Map Projections*. Chicago: University of Chicago Press.

Sobel, D. 1994. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. New York: Walker.

Steede-Terry, K. 2000. *Integrating GIS and the Global Positioning System*. Redlands, CA: Esri Press.

Whitaker, R. W. 2004. *The Mapmaker's Wife: A True Tale of Love, Murder, and Survival in the Amazon*. New York: Basic Books.