Chapter 2

Location and Space

"The concern about the conceptualization of space seems to be undoubtedly at the root of geography," suggests Nunes (1991, p. 15) in a survey from within giscience that is unusually broad in its engagement with wider currents in geographical thought. Or again, space is "the basic organizing concept of the geographer" (Whittlesey, 1954, p. 28). Geography as a discipline has not been particularly good at accounting for its existence, but space often features in elevator pitches for what geography brings to the table relative to other fields. This tendency is amplified when giscience and GIS are introduced to the conversation, when space and location become central for enthusiasts and skeptics alike. "GIS are particularly powerful and useful computer-based data-handling, analysis and mapping systems that have the capacity for integrating spatial data of any kind," according to John Pickles (2004, p. 155), a trenchant critic of GIS. More recently language about the value of a spatial perspective has been superseded by *location*: "ArcGIS Desktop is the key to realizing the advantage of location awareness"[1] is a typical marketing claim. The mantra "location, location, location" could as easily be the GIS professional's as the realtor's.

[1] https://desktop.arcgis.com/en/ in January 2023.

It makes sense then to start by looking more closely at notions of space in geography and giscience. We start with the (not so) simple idea of location as it is embedded in contemporary GIS and other geospatial computing platforms. GIS is explicitly built on a notion of space as primarily defined by *location*, itself represented by an association between spatio(-temporal) coordinates $\mathbf{S} = (x, y[, z, t])$ and a collection of attributes $\mathbf{A} = \{a_1 \ldots a_n\}$. This tuple $\langle \mathbf{S}, \mathbf{A} \rangle$ has been presented (Frank & Goodchild, 1990; Goodchild et al., 2007) as the atomic form of geographic information—the *geoatom*—a fundamental building block out of which all geographical representations in GIS are built.

This representation is so central to giscience that it is almost invisible, and therefore deserves closer scrutiny. What are the possibilities and also the limitations of such representations? What alternative foundational representations might different kinds of GIS be built on? What is the relationship between space-as-location on the one hand, and the rich ontologies of space that geographers more widely deploy in their attempts to understand and explain the world?

THE NATURE OF SPACE

The geoatom perspective on space is congruent with what Whitehead disparagingly terms "simple location" ([1925] 1967, p. 50). His disdain for simple location derives from the fact that this approach suggests that

> [t]he characteristic common both to space and time is that material can be said to be *here* in space and *here* in time, or *here* in space-time, in a perfectly definite sense which does not require for its explanation any reference to other regions of space-time ([1925] 1967, p. 50).

Further, Whitehead continues,

> as soon as you have settled [...] what you mean by a definite place in space-time, you can adequately state the relation of a particular material body to space-time by saying that it is just there, in that

> place; and, so far as simple location is concerned, there is nothing more to be said on the subject ([1925] 1967, p. 50).[2]

Whitehead's disparaging tone about simple location notwithstanding, as a practical matter, we should recognize that simple location is far from simple. We are accustomed to having our phones instantaneously position us as precisely located points on maps. But the underlying machinery of the Global Positioning System (GPS) that makes this happen is astonishing in its intricacy, complexity, and scale. Around 30 satellites spanning over 50,000 km, carrying high precision atomic clocks, precisely synchronized, paired with complex microprocessing capability in billions of receiving units. The accuracy requirements of the system are such that the atomic clocks on board the satellites are set to run slow to offset the relativistic effects of their 4 km/s orbital velocity. Even setting aside the Rube Goldbergian[3] intricacies of GPS, which might be considered a third millennium aberration, precisely determining a location on Earth's surface has never been simple (Sobel, 2007; Rankin, 2016; Evans, 2017; Pike, 2018).

That the foundations of GIS are built on the notion of precise coordinates bears directly on discussions in geographical theory considering space as *absolute*, *relative*, or *relational* and which of these is the most productive for geographical thinking. David Harvey provides a wonderfully concise statement of these varieties of space in the introduction to *Social Justice and the City*:

> If we regard space as absolute it becomes a thing in itself with an existence independent of matter. It then possesses a structure which we can use to pigeonhole or to individuate phenomena. The view of relative space proposes that it be understood as a relationship *between* objects which exists only because objects exist and relate to each other. There is another sense in which space can be viewed as relative and I choose to call this relational space—space regarded, in the fashion of Leibniz, as being contained *in* objects in the sense

[2] In place of simple location Whitehead ([1927] 1978) offers "region" as a more apt spatial primitive, a topic we return to in Chapter 5, and also in Chapter 8.

[3] Heath Robinsonian in British English.

> that an object can be said to exist only insofar as it contains and represents within itself relationships to other objects (1973, p. 13).

The following short sections expand on each of these in turn as they have been further elaborated on in the literature, although it is hard to add greatly to the spare outline above.

Absolute Space

The absolute space perspective conceives of space as an empty container in which the stuff of the world—objects, things, phenomena—are located (see Figure 2.1). Given this perspective on space, the primary information required to describe the world is the location and nature of the objects in the space. This quickly leads to the geoatom or something very like it. Locations are indexed by coordinates and objects are described in terms of their properties. Implicit in the framework is the impossibility of more than one entity occupying a particular spatial location at the same time, so that entities are individuated in space-time. As described by Harvey, absolute space is associated with Euclidean geometry, and a fixed immovable frame of reference.

This perspective is so deeply embedded in post-Newtonian scientific thought, which in turn is so hegemonic in Western thought, that it is initially difficult to see much wrong with it. But even taken on its own terms questions arise. What is space itself? Is it an empty void? Apparently not, since "[i]t is not true that a Vacuum is nothing; it is the Place of Bodies; it is Space; it hath Properties; it is extended in Length, Breadth and Depth" (de Voltaire, [1738] 1967, p. 180). In the depths of interstellar space these kinds of considerations obviously carry some weight. On Earth, with which geographers are concerned, there is no void, there is stuff everywhere. Nevertheless, an absolute model of terrestrial space is frequently deployed as if we were dealing with empty space, and enumerating or defining objects within it.

This approach is undeniably useful, for example, when planning a kitchen, constructing a high-speed rail network, or even defining the boundaries of nation-states. Applied to colonization, enclosure, and the

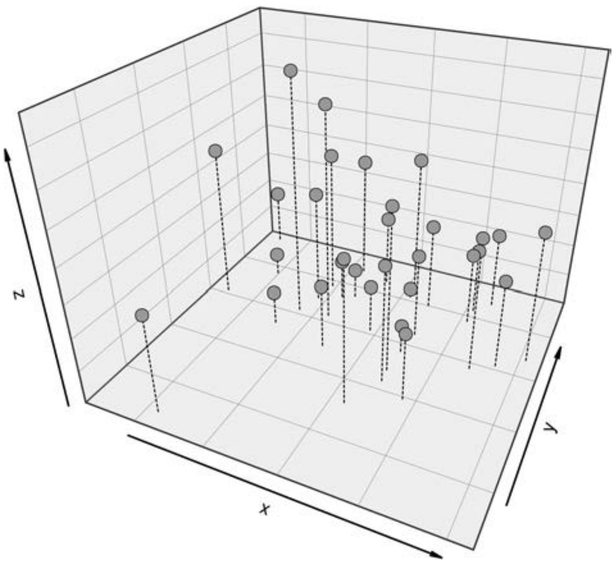

Figure 2.1. A representation of an absolute space, showing a coordinate frame as is usually associated with this perspective on space. Points in this space are completely defined by a set of coordinates specifying their simple location.

exercise of state and corporate authority generally, conceptions of absolute space can also be considered responsible at some level for many of the world's ills. While a political-economic order similar to late capitalist modernity might be built on a different conception of space, many key aspects of that order are intimately bound up with an absolute model of space, particularly property rights in land (the cadastre), the notion of the individual self (the point objects of human dynamics), and the geographically bounded nation-state (Pickles, 2004).

An absolute space perspective is also bound up with "the god trick of seeing everything from nowhere" (Haraway, 1988, p. 581). Space is a neutral container, where everything is simply where we know it to be, as shown on page or screen. Maps and GIS routinely deploy this pretense of omniscience presenting themselves as neutral and authoritative, when they are anything but. Maps and GIS data are complex outcomes of many selectively chosen acts of observation, recording, encoding, simplification, and so on. These processes are especially well hidden when even the frame inside which things are presented is taken for granted and singular. Whether relative or relational perspectives entirely avoid this failing is open to question, but they at least acknowledge that different perspectives are possible.

Relative Space

Relative spaces exist relative to entities and their relations to one another. Directly opposing the notion that space is a thing in itself, Leibniz argued that "Space without matter is something imaginary" (quoted in Elden, 2013, p. 297). This insight leads to the conclusion that there can be no fixed frame of reference applicable in all cases to all entities and all subjects of concern. At cosmological scales this framework yields Einstein's relativistic universe where all motion is measured relative to the frame of an observer, and space-time bends to accommodate an absolute limit on the speed of light.

At the more mundane scale of terrestrial measurements, we recognize that the times, distances, and rhythms of daily commutes in a particular urban region are governed by different measurement systems than global capital flows, or ecological movements, and that no single frame of reference can make these different relative distances commensurable. From a relative perspective, space and time are intimately bound up with one another, and distance collapses into a concept more like the cost in time, energy, or resources of overcoming the friction of distance. These are spaces that Bill Bunge considered in his meta-cartographic "traverse" of distance (Bunge, 1962, pp. 52–61) and Tobler (1961) was grappling with in broadening the concept of map projections, at the outset of the quantitative revolution. A relative perspective on space greatly complicates—and enriches—our picture of the world, by recognizing that many different distance metrics are needed for many different purposes, and further that each metric is encountered or experienced differently by different observers. Thus, for example, we can construct potential travel time maps centered on a particular location, but those maps will vary by mode of transport, by cost, by time of day, and so on (see Figure 6.14 and also Chapter 7).

It is worth considering the degree to which absolute and relative perspectives on space really diverge from one another or not. There is after all no single absolute frame of reference with respect to which an attempt has been made to apply a monolithic and singular absolute space. The nearest thing is the geocentric system of latitude and longitude but, in practice, local coordinate systems usually take priority over geocentric coordinates, even when the metric in use is one of simple distances. Thus, absolute space as deployed in practice is generally a complicated overlapping set of different coordinate reference systems (Clarke, 2017; Rankin, 2016), although this does not really detract from the absolute spatial mode of thought at work and it is generally possible to resolve discrepancies between such reference frames by technical means.

When other metrics than simple distance are deployed, resolving discrepancies becomes much more challenging or even impossible. By their nature, simple distance measurements can be triangulated and are internally self-consistent. The same is not necessarily true of other measurements of the cost in time, energy, money, or whatever, of traversing the space between two entities. More complex geometries than those that can occur in two- or three-dimensional Euclidean space may appear (Sheppard, 2002). It might take longer to travel from A to B than from B to A. Shortcuts may be available but not from all places or at all times. In general, resolving such complex geometries and presenting them as conventional maps is impossible, and this presents interesting technical problems to giscience, challenging our geographical imaginations (see L'Hostis & Abdou, 2021). Nevertheless, *in principle*, absolute and relative space are not so different. Any mapping of a collection of things in an absolute space implies a set of relative spaces measurable from the perspective of each of those things (or from any other empty location in the space). Any relative space can be portrayed (if only approximately) as an absolute space. Many of the techniques for tackling such problems were a central focus for quantitative geography after initial optimism about simple Euclidean geometry as the language of space dissipated (Forer, 1978; Gatrell, 1983).

Relational Space

From a relational perspective, there can be no empty space, devoid of entities, and space only exists contingent on entities. Conversely, entities only exist in relation to other entities, those relations being expressed through the processes that give rise to those entities. From a relational perspective, we no longer think in terms of entities, but instead in terms of processes. As processes unfold they make and remake space, while space in turn acts back on processes, altering and shaping their unfolding. Viewed relationally space is not a container within which processes occur, but *is itself a process*, actively made and remade over time. Entities do not exist as such, but rather are more or less enduring features of the processes that produce them. This perspective is central to Whitehead's *process philosophy* ([1927] 1978, see also Chapter 8) and also appeared much earlier in Leibniz's monadology (but see Malpas, 2012).

From the relational perspective, everything contains to some degree its relations to everything else (Leibniz insisted that everything contains everything else). An object is not simply the object, but also the social, economic, political, and material relations and processes that came together to produce it. The laptop I am writing on was produced somewhere, designed somewhere else, assembled from parts manufactured and designed in other places. My possession of it is a function of my role as a professor in a university at a particular place and time. All of these social and economic relations are embedded in the laptop, along with innumerable complicated histories of the materials out of which all the components of the laptop are made. And so on, and on. It is difficult and even a little unnerving to start seeing the world in this way. Pragmatically, it is much easier just to take things at face value, for what they appear to be. But when we really want to understand what's going on around us, this kind of relational thinking in space and time becomes essential.

This tripartite classification of space into absolute, relative, and relational is not unambiguous. In Harvey's account relational space is only cursorily defined (through objects) as existing "only insofar as [each object] contains and represents within itself relationships to other objects" (1973, p. 13).[4] Revisiting these definitions later (Harvey, 2006, pp. 123–24), the difference between relational and relative space is more clearly conceptualized with respect to how processes define their own spaces, so that it becomes essential to consider not only space, but space-time.

A processual, space-time perspective on space is often assumed in any discussion of space, although Cox (2021) argues that human geography in fact remains stuck on a relative perspective, where space is a more or less fixed structure of relative locations at which things are placed. Cox further claims, "[t]here is an inevitability about the relation of space to process in physical geography that seems to be absent in human geography" (2021, p. 11). This means, Cox suggests, that physical geographers work with relational space concepts (without necessarily giving it much explicit thought in such terms), while human geographers discuss abstract notions about space, but, lacking the same concrete embedding of processes in space, remain stuck with relative space, whether they realize it or not. For example, market relations and processes may be conceptualized as outside of space, with no necessary specific relationship to space (see Sayer, 1985).

Whatever the merits of this argument, it clarifies a little the intention behind distinguishing relative and relational concepts of space. Relative spaces can be thought of as more or less fixed structures in which things are embedded in relation to one another, and are in this sense not so different from absolute spaces. At the same time relative spaces, to the extent that their measures of relation are contingent on movement, flows, perceptions, and so on associated with processes, approximate to the relational spaces of those processes. Thus, relative spaces can be either absolute, relational, or perhaps even both, depending on your point of view! This might help explain why the term "relative space" has fallen

4 Harvey offhandedly acknowledges with respect to relational space that he "neglected [. . .] to explicate its meaning," some 23 years later (1996, p. 250). See also Chapter 8.

into disuse since early discussions, with many authors favoring a binary of relational space presented as in opposition to absolute space.

Harvey (2006, Figure 1) offers a tabulation of contexts where the threefold perspectives on space might apply. Some of these are difficult to make sense of. For example, it is unclear why "circulation and flows of energy, water, air, energy" exist in a relative space, while "electromagnetic energy flows and fields" are relational. Other distinctions are clearer. "Cadastral and administrative maps" clearly inhabit absolute space, while "thematic and topological maps (e.g. London tube system)" are relative space representations.

Whatever we make of these abstract ideas about space, it is important before considering space in giscience to emphasize that these three conceptualizations are just that: conceptualizations. As ever with models of any kind, no model is correct, but all we need is for them to be useful (Box, 1979), and each of these models—absolute, relative, relational—however hard it might be to separate them, has its uses. As Harvey further notes, "[t]he problem of the proper conceptualization of space is resolved through human practice with respect to it. In other words, there are no philosophical answers to philosophical questions that arise over the nature of space—the answers lie in human practice" (1973, p. 13).

SPACE IN GISCIENCE

Absolute Space in GIS

What, then, does the human practice of giscience make of space? Perhaps unsurprisingly, particularly as it manifests in GIS and other mapping platforms, giscience presents us with a would-be absolute space.

For many giscientists, the most direct consideration of how space is represented is the *raster-vector debate*, which revolves around technical questions of which approach to the representation of geographic phenomena is preferable (Peuquet, 1984). But as Helen Couclelis suggests, "the *technical* question of the most appropriate data structure begs the *philosophical* question of the most appropriate conceptualization of geographic space" (1992, p. 65). For Couclelis, the philosophical question revolves around whether the world consists of a collection of objects or is a continuously measurable field of values, whether of land elevation, air temperature, population density, or other quantifiable phenomena. The object view—equated with vector representations—forces the world to conform with its precisely defined geometric points, lines, and polygons, while the field view remains more agnostic, instead requiring the user to detect patterns in data to identify features (Tomlin, 1994). Many aspects of the human world fit reasonably well into the vector-object perspective, while many aspects of the natural world are more readily accommodated by the raster-field perspective. But seen through the lens of absolute, relative, and relational models of space, the two views are essentially the same, both depending on a fixed coordinate frame within which points or cells can be referenced.

Further, even novice GIS users are aware that one of the most important first steps in the planning and execution of any project is determining an appropriate map projection for the task at hand. Put differently, the coordinate system for the absolute space within which analysis will be conducted must be determined. In almost all cases the primary consideration governing the choice of projection is associated with the severity of the geometric distortions to the phenomena at hand due to the chosen projection (see also §Scale and Map Projection, Chapter 3). Next-generation GIS may assume a priori that geodetic (i.e., latitude–longitude) coordinates are the correct frame of reference, given that advances in computation render many advantages of planar projected coordinates moot, but short-circuiting the choice of coordinate system in this way runs the risk of distancing giscience further still from geographic thinking about space.

It is important to recognize here that there is nothing in particular preventing coordinate systems that portray relative spaces being used with conventional GIS platforms (Bergmann & O'Sullivan, 2017). Most geospatial toolkits perform geometry operations, such as intersection, the measurement of length and area, and point in polygon tests, in a planar, two-dimensional Euclidean coordinate space, and not in the (approximately) spherical coordinate space of Earth's surface. This design choice was made early in the development of GIS as automated cartography

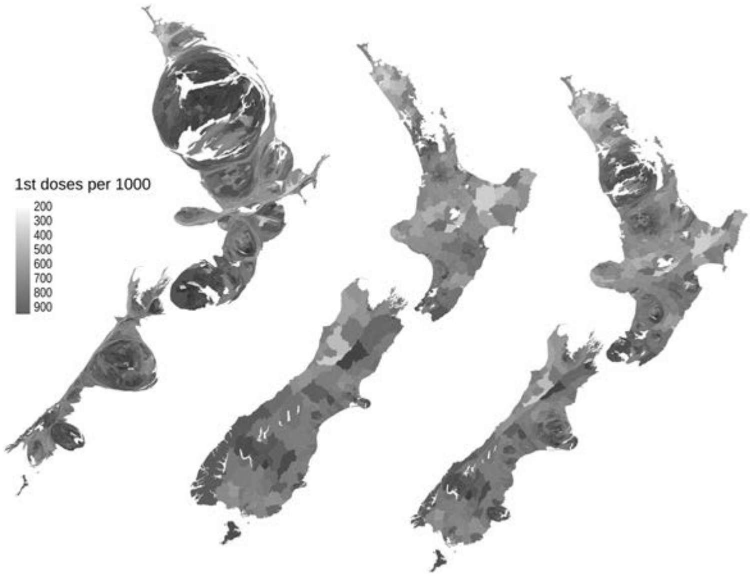

Figure 2.2. Three views of Aotearoa New Zealand SARS-CoV-2 vaccination uptake (at October 6, 2021). In the middle is a conventional map view. The left-hand map is a cartogram scaled to population of statistical areas, while the right-hand map is a cartogram scaled to $\sqrt{A}$ where A is the area of each census district. The last of these reduces the visual dominance of the large but sparsely populated rural areas while making it easier to discern detail in urban areas. Assembling different spaces like this is not straightforward with contemporary geographical computing tools.

(Goodchild, 2018). Even as more globe-centered approaches based on spherical or ellipsoidal geometry develop,[5] it is unlikely that support for Euclidean geometry will be dropped (and see Chrisman, 2017, on the challenges of spherical geometry).

[5] For example, in the *R-Spatial* ecosystem, the package `sf` (simple features) has an option setting `sf_use_s2` which can be easily toggled to switch between calculations based on a spherical approximation to Earth surface, and more traditional Euclidean geometry.

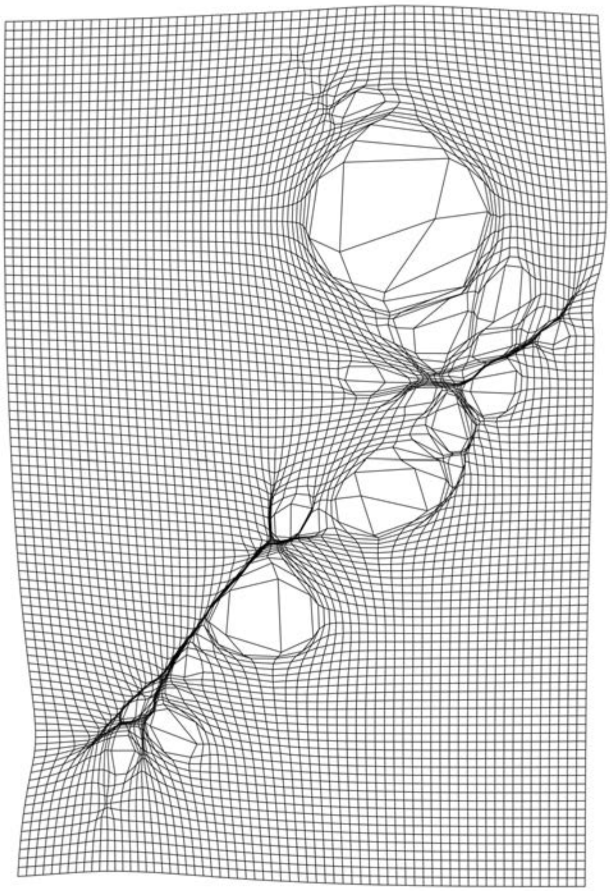

Figure 2.3. The cartogram deformation grid for the first cartogram in Figure 2.2. This grid contains all the information needed to project other layers into the cartogram map space, if they are sourced in the same projection as the original data layer.

As an example, tools for easily generating cartograms have become more widely available in recent years,[6] so that type of map transformation can now be readily generated. The example in Figure 2.2 shows three different cartogram spaces (the middle one a standard map) in which a conventional choropleth map might be displayed. While it is relatively simple to make such maps, it is difficult to work with the resulting data layers using standard geospatial tools. Tools struggle to recognize whether or not data are projected or have no known projection. This may make it difficult to do things as simple as reading them, or having read them, to display them alongside other views.[7] *ScapeToad* can project other layers into the cartogram map space at the time of cartogram calculation. It also generates a deformation grid output (see Figure 2.3), but later taking the information contained in this grid and using it to project other data layers into the cartogram space is not supported. In sum, if a user wants to define an entirely new map transformation relative to their particular context of inquiry (their "practice"), and then use geospatial platforms to manipulate data in that projection, it can be difficult and frustrating.

Cartograms may seem like a special case, but as is clear from the previous section, it has long been accepted in geography more widely that "distance can and must be measured in terms of cost, time, social interaction, and so on, if we are to gain any deep insight into the forces moulding geographic patterns" (Harvey, 1969, 210, referencing Watson, 1955). Another common use case is working with historical base maps. While such maps may not meet the expectations for geodetic accuracy of modern map projections, they often represent contemporary understandings of space more faithfully, and are thus relevant to the questions at hand. Rather than being able to use the contemporary, historical base map, a GIS user is expected to *georeference* their map, warping it to match modern, anachronistic map projections that conform to an essentially

[6] See *ScapeToad* http://scapetoad.choros.place/.

[7] A common workaround (at the time of writing) involves converting to the shapefile format and deleting the associated `.prj` file containing projection information. It is also not unusual to have to repeatedly delete this file during a workflow to prevent tools from assigning a default geocentric coordinate system to the data!

arbitrary absolute spatial notion of accuracy, relative to questions of interest. This seems the opposite of what would be desirable for supporting the needs of these GIS users, when the contemporary understanding of space, already embedded in the source materials, surely has interpretive value. Ironically, it is exactly the data included in the deformation grid shown in Figure 2.3—a series of mappings of known control points from one coordinate system to the other—that are needed and that are used when basemap imagery is georeferenced that would be required to support this functionality. The only change necessary to geospatial tools that can perform georeferencing (in other words, any GIS) to allow support for arbitrary projections in any desired space would be to remove the expectation that the coordinates in datasets be in some known projected coordinate system (see Bergmann & O'Sullivan, 2017).

Relative Space in Quantitative Geography

The narrowness of spatial representation in GIS is unfortunate, because a great deal of work in quantitative geography and spatial analysis *effectively adopts a relative model of space*, even as GIS tools do not. Much of spatial analysis boils down to incorporating a *spatial weights matrix* tailored to the particular questions at hand into otherwise fairly standard statistical concepts of correlation, similarity, difference, and so forth (O'Sullivan & Unwin, 2010; Bailey & Gatrell, 1995). A spatial weights matrix is a compact summary of the relations among a collection of entities, determined from their locations in space, generally derived from some function of their Euclidean distances of separation.

A simple example is provided by distance-based approaches to point pattern analysis (Ripley, 1981; Stoyan, 2006). Consider the two sets of points, located in a two-dimensional absolute space, shown in Figure 2.4. One pattern appears evenly spaced or dispersed, while the other appears clustered or aggregated. One way to make the difference in the patterns clear is to measure the distance from each point to its nearest neighbor in the pattern, and to examine the distribution of the resulting *nearest-neighbor distances*. This is shown in the histograms alongside each pattern where the contrast is clear.

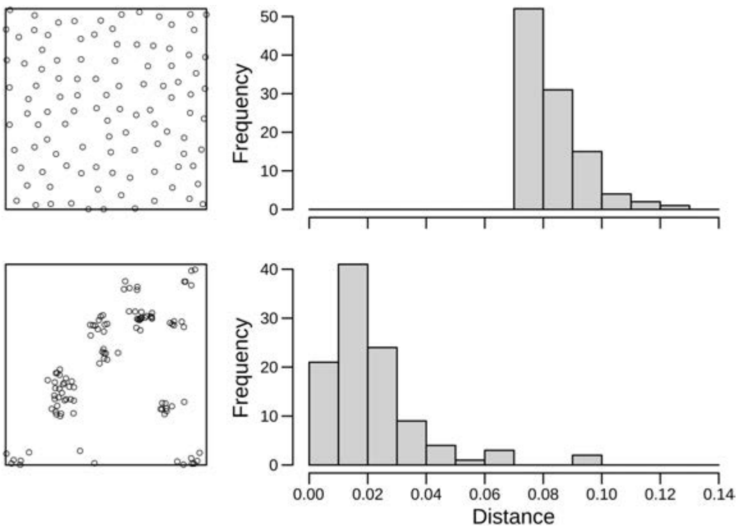

Figure 2.4. Two point patterns in absolute space characterized using nearest-neighbor distances. The difference between the upper evenly spaced pattern and the lower clustered pattern is apparent when we measure the nearest distances for every point in each pattern, as shown in the distributions plotted on the right.

Such a distance-based measure of point pattern draws on a relative concept of space insofar as what is analyzed is not the absolute location of points relative to a fixed frame of reference, but the position of each point relative to its nearest neighbor. Of course, the approach also depends on the points having coordinates relative to a fixed absolute frame of reference, and also some agreed-upon approach to measuring their separation distances (there is no shortage of possibilities; see Deza & Deza, 2016). Shuttling back and forth between an absolute and a relative perspective on space in this way is commonplace, but almost always a context-specific choice, which may be difficult to replicate given the poor support geospatial tools provide for spaces not in standard projections.

PROSPECTS FOR RELATIVE/RELATIONAL GISCIENCE

Despite the dominance of absolute space in GIS platforms, the prevalence of relative space approaches in spatial analysis holds out some hope. Therefore, it is useful here to review approaches that, similar to the point pattern example, push giscience in the direction of relative, perhaps even relational conceptualizations of space. Many of these are both widely known and widely used by giscientists, but have not necessarily become embedded in platforms in the same way that absolute space has in GIS.

Data Structures That Include Adjacency

We should first note that many data structures incorporate adjacency and by implication a (limited) relative space model. These include early formats such as GBF/DIME, TIGER, and POLYVRT (Cooke & Maxfield, 1967; Peucker & Chrisman, 1975; Broome & Meixler, 1990), on which Esri's Arc/INFO coverages were based, as well as more recent examples such as TopoJSON.[8] These formats were developed to address technical and practical issues in the management of polygon data layers.

The obvious approach to storing a polygon is as a sequence of point locations, along with an indication that the points are the vertices of a polygon. Any software handling these data can then handle the series of points as the corners of a polygon. A typical format of this *simple features* kind is GeoJSON,[9] an example of which is shown in Figure 2.5.[10] Here, a two-part polygon is stored as two lists of coordinate pairs, with points listed in counterclockwise order. The GeoJSON format requires the first vertex to be stored twice to close the polygon. Other formats may leave closure of the polygon implicit.

Simple features formats have a number of problems. Because they are effectively just lists of polygons, which might be presented in any

[8] See https://github.com/topojson/topojson-specification.
[9] See https://tools.ietf.org/html/rfc7946.
[10] A useful tool for getting a feel for GeoJSON can be found at https://geojson.io.

```
{
  "type": "FeatureCollection",
  "features": [
    { "type": "Feature",
      "properties": {},
      "geometry": {
        "type": "Polygon", "coordinates": [
          [
            [113.2, -22.3],
            [116.1, -35.1],
            [133.8, -32.1],
            [142.2, -38.9],
            [149.7, -37.5],
            [153.8, -27.0],
            [142.3, -10.3],
            [140.1, -17.8],
            [133.5, -11.1],
            [113.2, -22.3]
          ],
          [
            [144.5, -40.9],
            [147.0, -43.6],
            [148.4, -40.7],
            [144.5, -40.9]
          ]
        ]
      }
    }
  ]
}
```


Figure 2.5. A GeoJSON file including a single multipart polygon.

order, any time we want to deal with the relationships between polygons, inefficiencies are inevitable. Finding other polygons near a given polygon requires searching through the list of all polygons. Spatial indexes can make it easier to restrict a search to only those polygons known to be nearby and are one solution to this search problem (Samet, 1990), that requires no changes to the simple features data model.

An even more basic issue arises when polygons are expected to mesh together to completely cover a region, without any gaps, as is required in many situations, such as cadastral databases. Because every polygon edge is stored twice, every coordinate on a boundary between two polygons is also stored twice. If any inconsistencies between the two copies of each point arise, then corresponding overlaps and slivers occur in the polygon layer. An example is shown in Figure 2.6. Inconsistencies might arise

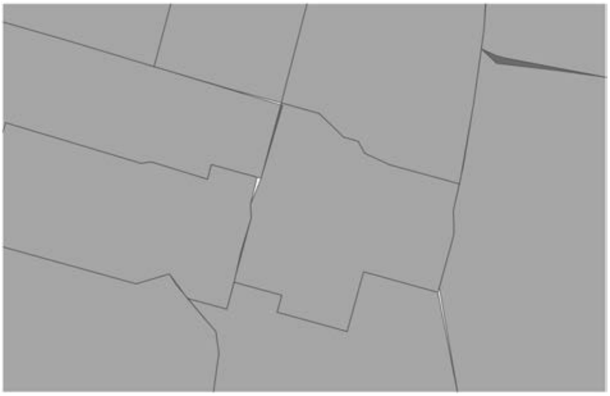

Figure 2.6. Slivers and gaps in a set of polygons. These can arise in data structures that store each polygon independent of all others.

as a result of polygons being independently edited, or when procedures such as automated generalization (see §Scale-dependencies, Chapter 3) are applied.

A solution to this problem is to organize information about polygons so that each vertex is only stored once. There are a number of ways to do this. For example, all vertices can be stored in a table, assigning each vertex an ID number. Each boundary between two polygons can then be stored as a sequence of point IDs with specified start and end points, and also, in most implementations the identity of the polygon that is to the right and left of the edge, when it is traversed from the start to the end node. Finally, polygons are stored as a sequence of edges (Peucker & Chrisman, 1975, is an accessible early description of the approach). If a vertex location is changed, then it changes in all polygons to which it belongs, resolving the overlaps and slivers problem. Details of the exact implementation vary from format to format. The underlying ideas and variants are discussed by Worboys and Duckham (2018, pp. 177–87). While this data format is considerably more complicated than simply storing a list of lists of coordinate pairs, it enforces topological consistency, and offers numerous advantages.

In addition to enforced boundary consistency, the approach allows rapidly finding the neighbors of any selected polygon, since traversing the polygon edges will return a list of all the neighboring polygons. It is surprising that in the 1990s Esri's shapefile format—which does not offer either of these advantages—became dominant in the GIS world, presumably because it was assumed that increased processing capability meant that calculation of polygon neighbors and so on could be performed rapidly as required.[11] Whatever its limitations, because the 1990s were the decade when GIS really took off, the shapefile became a de facto standard, and simple features, without topology, remain dominant, including more recent examples like the GeoJSON and GeoPackage formats. As a result, it is not uncommon to encounter issues with slivers and overlaps in datasets, even those maintained by official sources.

Topological data formats are implicitly relative in their representation of space, since every polygon is stored along with relations to its neighbors. It is important not to overstate the significance, since the only relations recorded are trivial immediate adjacencies. Also, the motivation for such formats is practical not theoretical. These formats appeared in the context of handling datasets representing a quintessentially absolute spatial perspective where all land is unambiguously assigned to specified zones for administrative or commercial reasons. Thus while it is technically convenient, for the reasons discussed, to work with data formats that impose topological consistency, it is important to recognize that they emerge out of an absolute perspective on space.[12]

[11] A slightly bemused David Theobald suggested it was because shapefiles can be drawn on screen more quickly; see "Understanding topology and shapefiles" at https://www.esri.com/news/arcuser/0401/topo.html.

[12] An interesting challenge to the logic of this perspective is provided by Gordon Matta-Clark's artwork *Reality Properties. Fake Estates*; see Manolescu (2018, pp. 180–85). It is interesting to consider the degree to which the slivers of land this work highlights may have been an unintended side effect of the lack of topology in shapefiles!

The Voronoi Model of Space

An extension of the topological approach to polygon data has been proposed by Christopher Gold (1992) making use of *Voronoi polygons* (see Okabe et al., 2000). Voronoi polygons—also known variously as Thiessen polygons or proximity polygons—are a partitioning of a region of space, based on a set of entities (most often points) where each polygon is a subregion of the space that is nearer to its generating entity than it is to any other entity in the set. An example is shown in Figure 2.7.

The Voronoi tessellation is frequently used in spatial analysis. For example, in facility location problems, large Voronoi polygons in the tessellation derived from existing facility locations are diagnostic of underserved areas. In point pattern analysis the Voronoi polygons associated with a set of points can help in identifying areas of high-intensity clustering or the outer edge of clusters (Estivill-Castro & Lee, 2002).

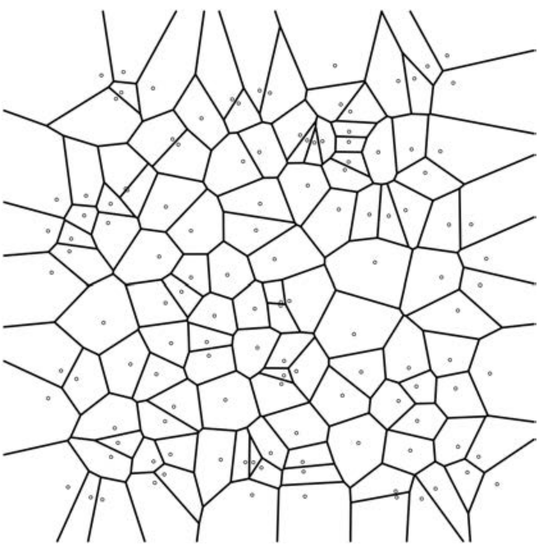

Figure 2.7. Voronoi polygons associated with a set of point locations.

When dense control points are available, natural neighbor interpolation (Sibson, 1981), derived from Voronoi polygons, can be very effective.

As Gold (1992) points out, the Voronoi model can be extended to *any* set of generating entities, whether points, lines, or polygons, although the computational geometry becomes a little more complicated. An approximate approach is to convert all spatial objects in a scene to points while retaining the original object IDs, and then perform the Voronoi transformation on the complete set of points (see Fleischmann et al., 2020). The resulting Voronoi polygons can then be dissolved together based on the object IDs. An example is shown in Figure 2.8. Gold (1992) and Edwards

Figure 2.8. Voronoi polygons associated with lines and polygons approximated by conversion to closely spaced points. A road (dark gray) and building footprints (gray) have evenly spaced points (black) assigned along their length. These are used to generate Voronoi polygons (gray outlines), which are dissolved based on entity IDs, to give Voronoi polygons for the line and polygon objects. The resulting black outlines seem to match well with intuitive notions of the neighborhood of those entities.

(1993) argue that such polygons correspond well with human ideas of where the neighborhoods of such objects are. Although this claim has not been verified in any systematic way, it appears plausible on examination of maps the technique yields.

Object Fields

Some authors have suggested a hybrid of the vector-object and raster-field perspectives in the guise of *object-fields* (Cova & Goodchild, 2002; Goodchild et al., 2007; Yuan, 2022). In this formulation, every location in a space, at some resolution, can be associated with an arbitrarily complex spatial object. For example, at every location across a space the other locations visible from each location can be approximately determined by a visibility analysis that associates an *isovist* with each location. These results can be summarized in a field of isovists where isovists are represented as a collection of points, as a (multi-)polygon, or as a set of pixels in a raster. Exploration of an object-field might display the associated isovist polygon when a mouse hovers at the associated location.

It is interesting that merging the object and field perspectives in this way leads to an approach that might be considered relational from the perspective of the earlier discussions. For example, an object-field of isovists is exactly equivalent to the visibility graph described by Turner et al. (2001) and O'Sullivan & Turner (2001), where relations between places are explicitly captured by the relational structure of a graph (see also Chapter 6). Although there is no necessity for an object-field to be relational in this way, the idea lends itself directly to the construction of networks of second-order relations among locations. Each location has an associated more or less complicated spatial object, and the associated spatial object may in turn have relations either to other locations or to their associated objects. When adopting an object-field approach, it makes sense to think of locations in terms of how they relate to other locations in some way. Although Cova & Goodchild (2002) present mocked-up examples, the approach has not been implemented as a default in any platform I am aware of.

Graph Databases

Although the database technology that underpins geographical information systems, *relational database management systems* (RDBMS), is "relational," this is a misnomer from the perspective of this chapter. The relational in RDBMS refers to the relations that compose the database, but relations in this context are what are more generally considered data tables (Codd, 1970). Ironically, relational databases are poor at dealing with relations in the more usual sense of the word.[13] In an RDBMS, geographical entities are necessarily individuated. Each row in a table represents a single geometry—whether point, line, polygon, raster cell, or some more complicated type, like a multipolygon. Data-rich entities will tend to have an associated data table in an RDBMS and the focus of the data model is on those entities and their properties. Relations between entities are expressed by matching attribute values of entities in different tables, where (for example) the ID of a school that a student attends might appear in the `students` table as a *foreign key*. To summarize information about the schools attended by students, a temporary *join* between the `students` and `schools` matches students and schools into an extended table, based on the foreign key in the `students` table.

In this light a GIS is a relatively limited extension to an RDBMS that can accommodate attributes that are geometric entities, such as points, lines, or polygons. Further, a GIS can support matching geometric entities according to various geometric operations such as intersection, containment, overlap, and so on. That a GIS is really this simple extension of RDBMS is clear on considering PostGIS, which is "a spatial database extender"[14] that augments a conventional database by adding geometric objects. Similarly, the geospatial ecosystems in programming languages such as R and Python are based around packages that take a standard data table format and allow for storage and manipulation of geometries as a special kind of column in the data table. This is the approach taken in both `sf` (in R) and `geopandas` (in Python).

---

[13]It is a further irony that RDBMS superseded the network data store model, which centered the relations between data items. See Haigh & Ceruzzi (2021, pp. 274–75).

[14]See https://www.osgeo.org/projects/postgis/.

Because relations between entities in RDBMS are based on temporarily matching attributes between data tables, relations as such have only second-order status in the model—they exist only by implication, rather than being explicitly represented. The conceptual frame of the model is that entities exist and are independent of one another. In *graph databases*, by contrast, relations are first-order concepts that have equal standing with entities. This means that graph databases can take advantage of algorithms based on ideas from network science (see §Network Science, Chapter 6) to enable more efficient exploration of data understood as a complex interconnected collection of entities. Where the designer of an RDBMS focuses on data-rich entities, the designer of a graph database will consider both entities and the relations that may exist between them. Where the basic element in RDBMS is the tuple of attributes describing each entity in a table, in a graph database the basic element is a triple of a subject, an object, and the relation between them. This triple is also central to the Resource Description Framework (RDF) for the exchange of semantic information on the web.

Graph databases have become more commonplace since the mid-2000s, with a great deal of hype around "leveraging complex and dynamic relationships in highly connected data" (Robinson et al., 2015, p. xi), although they are still much less widely used than RDBMS. They remain underexplored in giscience and GIS, where the data table with a geometry column model remains dominant, to the detriment of richer, situated representations of geographical knowledge (Bergmann, 2016; Gahegan & Pike, 2006). RDF-based approaches to the exchange of geospatial information are an alternative pathway toward a more relational model of space in giscience (Claramunt, 2020). The role of network science with respect to more relational perspectives on geography is explored in more detail in Chapter 6.

Spatial Analysis and Spatial Models

We have already seen how spatial analysis deploys spatial weights matrices representing the relations among events in a point pattern, thus invoking a relative model of space.

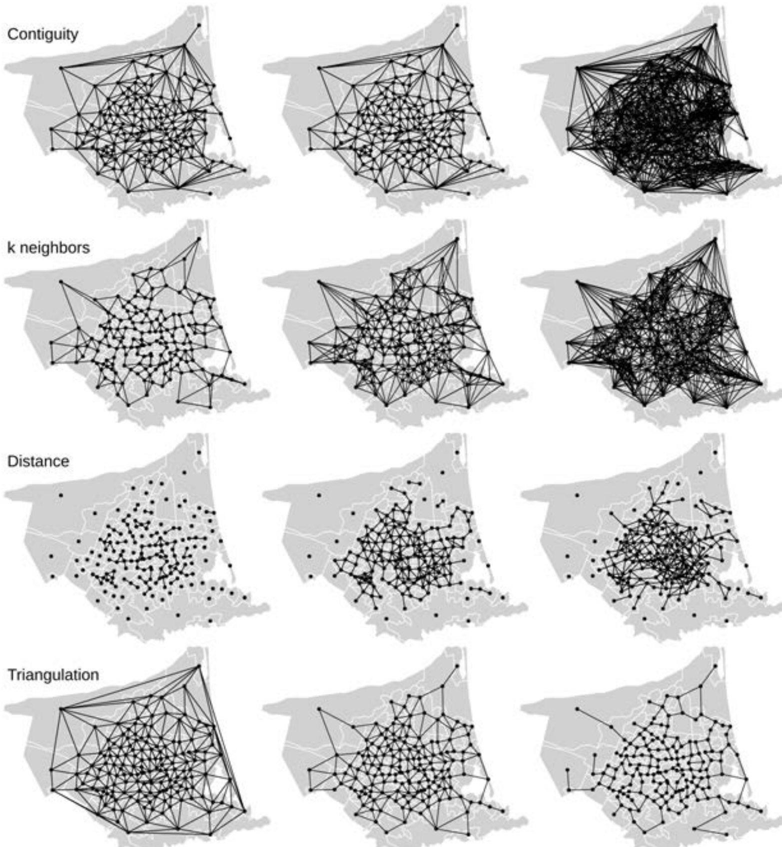

Figure 2.9. A range of spatial weights applied to polygon data. In the top row contiguity criteria are applied: Queen's contiguity, Rook's, and Rook's with lag 2. In the second row k nearest neighbors, 3, 6, 12 based on polygon centroids. In the third row distances between centroids up to 1,000, up to 1,500, and between 1,500 and 2,000 m. Finally, in the bottom row are the Delaunay triangulation, the Gabriel graph, and relative neighbor graphs.

This construct is highly flexible and easily applied to any kind of spatial entity contingent on some rule for measuring the strength of relation between any pair of entities. Examples of purely binary yes/no matrices constructed based on geometric rules are shown in Figure 2.9. It is simple to extend this further to assign relative importance to different strengths of relationship, or even to base relationships not on distance and geometric criteria but on other aspects, such as shared characteristics, commuter flows, and so on. Again, the relationship of these methods to network models is a close one, and is considered further in Chapter 6.

Other kinds of spatial models rely on similar structures. For example, cellular automata (see §Cellular Automata, Chapter 8), both regular and irregular, require a neighborhood to be defined for each cell. Cells exist in a lattice of relations between cells. In regular grids, the relationships between cells are usually identical across the whole space. Couclelis (1997) suggests that the underlying spatial model in this case is neither absolute nor relative but *proximal* (see also Takeyama & Couclelis, 1997; Takeyama, 1997). Proximal space focuses on a difference between sites (locations in absolute space) and situations (locations in proximity or adjacency relations to other locations) and captures aspects of both. O'Sullivan (2001) shows that this concept can be extended to arbitrary spatial entities (not just cells in a grid), resulting in this context in irregular or graph-based cellular automata. We consider these and other dynamic modeling approaches in more detail in Chapter 8 where their processual aspects are also discussed.

FROM SPACE TO EVERYTHING ELSE

Because how space is theorized and represented is foundational to every other aspect of geography and giscience, we have paid close attention to it in this chapter. Many of the themes discussed reappear under different guises in later chapters. In Chapter 4 the vexed relationship between space and place is central, while relationality and relative space are critical aspects of the discussions in Chapters 5 and 6. Relational space-time is a topic taken up again in considering time and dynamics (see Chapter 7) and processual thinking (Chapter 8).

Milton Santos suggested that "[t]echniques are the group of instrumental and social means that people utilize in order to realize their lives, [. . .] to create space" (Santos, [2002] 2021, p. 13). Just so, giscience proliferates computational spaces at every turn, many of which also become spaces in the material world. This may help explain the incomprehension of many giscientists at the suggestion that their ideas about space are naïve and simplistic.

From the foregoing I hope it is clear that giscience as a whole has a firm grip on both absolute and relative space, even if absolute space is central to dominant platforms. Relative space makes things more complicated, but is not in principle any more difficult to handle computationally than absolute space. Data representations almost always start embedded in some absolute frame of reference (usually geodetic coordinates). They may often remain in that space, but equally or more often will be translated into one or several other relative spaces depending on the context and the questions being asked. Often the public face of such work—as maps or other visualizations—remains firmly ensconced in the absolute spaces of familiar map projections, even if the analysis and conclusions inhabit other more abstract spaces of relations.

The further step toward fully relational space in giscience might lie not in any single relative space, but in the moving back and forth among many relative representations, in the ongoing *doing* of giscience, rather than in any particular analysis of a static absolute or relative space (cf. Kitchin & Dodge, 2007, where maps are argued to be processual). Alternatively, the explicit inclusion of movement and change in time geography (see Chapter 7) or of process in simulation models (see Chapter 8) might offer more direct pathways.