Chapter 4

Spatial Schemas in Depictions

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4.1 Overview

Depictions, such as maps, that portray visible things are ancient whereas graphics, such as charts and diagrams, that portray things that are inherently not visible, are relatively modern inventions. An analysis of historical and developmental graphic inventions suggests that they convey meaning by using elements and space naturally. Elements are based on likenesses, "figures of depiction" and analogs to physical devices. Spatial relations are used metaphorically to convey other relations, based on proximity, at nominal, ordinal, and interval levels. Graphics serve a variety of functions, among them, attracting attention, supporting memory, providing models, and facilitating inference and discovery.

4.2 Introduction: A Brief History of Graphics

We take it for granted that human beings have crafted tools to improve their physical well-being from the beginning of humanity. More recently, it has become apparent that other primates do the same (e.g., Goodall, 1986; Whiten, Goodall, Mc Grew, Nishida, Reynolds, Sugiyama, Tutin, Wrangham and Boesch, 1999). These tools augment our physical capacity, they allow us to obtain food and protection more effectively than our bodies alone could do. Less noticed is the fact that we craft tools to augment our mental capacity as well (e.g., Donald, 1991; Norman, 1993). The fabrication of cognitive tools by other primates has not been shown. One of the oldest of these tools is graphics, from maps in the sand to neon on the Ginza. The key to these is using space and elements in it to convey meaning.

Long before there was written language, there were depictions, of myriad varieties. Only a few of the multitude of cave paintings, petroglyphs, bone incisions, graffiti, clay impressions, stone carvings, and wood markings that people created and used remain from ancient cultures. Some of these depictions probably had religious significance, but many were used to communicate, to keep track of events in time, to note ownership and transactions of ownership, to map places, and to record songs and sayings (e.g., Coulmas, 1989; De Francis, 1989; Gelb, 1963; Mallery, 1893/1972; Schrnandt-Besserat, 1992). As such, they served as permanent records of history, commemorations of cultural past. Because pictures represent meaning more directly than alphabetic written languages, we can guess at their meanings today. In rare cases, we have the benefit of contemporaneous translations. While collecting petroglyphs and other examples of pictographic communications from native Americans in the last century, Mallery was able to speak with many still using them (1893/1972). Several of these left by a Native American who lived near Long Lake in Maine in the mid-nineteenth century appear in Figure 4.1. They are leave-taking notices posted on bark to inform visitors where he had gone.

In many places in the world, the use of pictures to communicate developed into complete written languages. All such languages invented ways to represent concepts that are difficult to depict, such as proper names, abstract entities, causality, quantification, negations, and the like (e.g., Coulmas, 1989; DeFrancis, 1989; Gelb, 1963). As pictures evolved into written languages, two things occurred: they became schematized and they lost their transparency. Figure 4.2 shows how Sumerian characters that began as fairly transparent sketches of the concepts they conveyed became schematized in writing and lost any resemblance to those concepts. Some originally pictoric written languages transformed to use written marks to represent sound rather than meaning directly. This had two simultaneous advantages: it reduced the numbers of pictographs that had to be learned and it solved the problem of representing concepts difficult to depict. The spread of the alphabet and, much later, the invention of the printing press decreased reliance on pictures for communication. With the increasing ease of reproducing written language and increasing literacy, depictions became more decorative than communicative.

Now, pictures, depictions, and visualizations as communications are on the rise again. As with the proliferation of written language, this is partly due to technologies for creating, reproducing, and transmitting pictures.

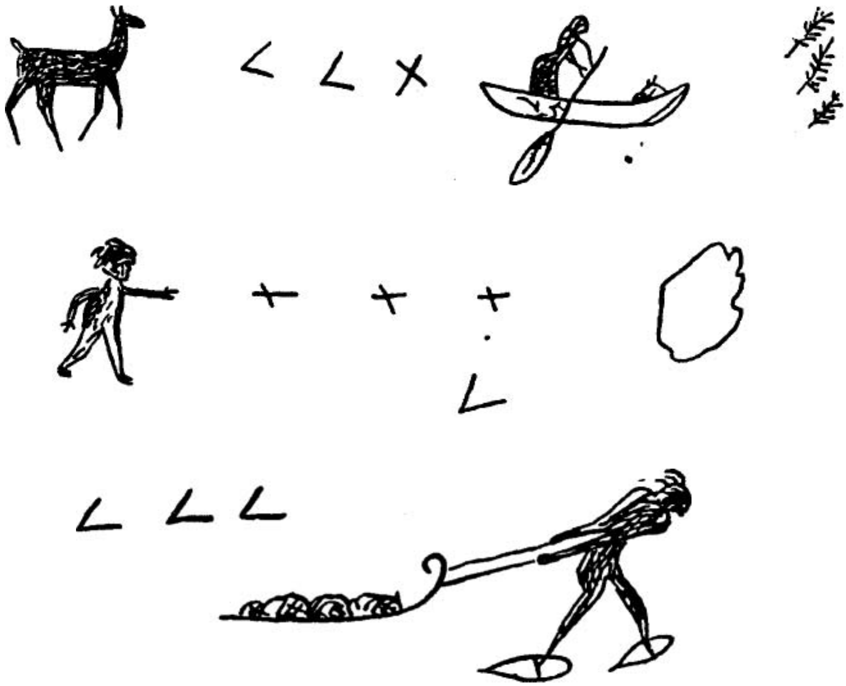

Figure 4.1
Birch bark leave notices left by a Native American living near Long Lake, Maine in the mid-1800's. Top panel: I am going across the lake to hunt deer. Middle panel: I am going towards the lake and will turn off at the point where there is a pointer before reaching the lake. Lowest panel: I am going hunting and will be gone all winter. From Mallery (1972, 331).

And as with the proliferation of written language, some of the spread of depictions is due to intellectual insights. For this, the basic insight is using depictions to represent abstract meaning by means of visual and spatial metaphors and figures of depiction. Using space also capitalizes on people's extensive experience learning about space and making spatial inferences.

Although space in depictions has long been used to convey concrete ideas, the use of space to convey abstract ideas is more recent. Early uses of space in depictions for the most part portrayed things that were inherently visualizable, such as objects, buildings, or environments, in pictographs, architectural plans, or maps. Maps appear in many forms, many taking liberty with spatial metrics, such as the T-O maps popular in

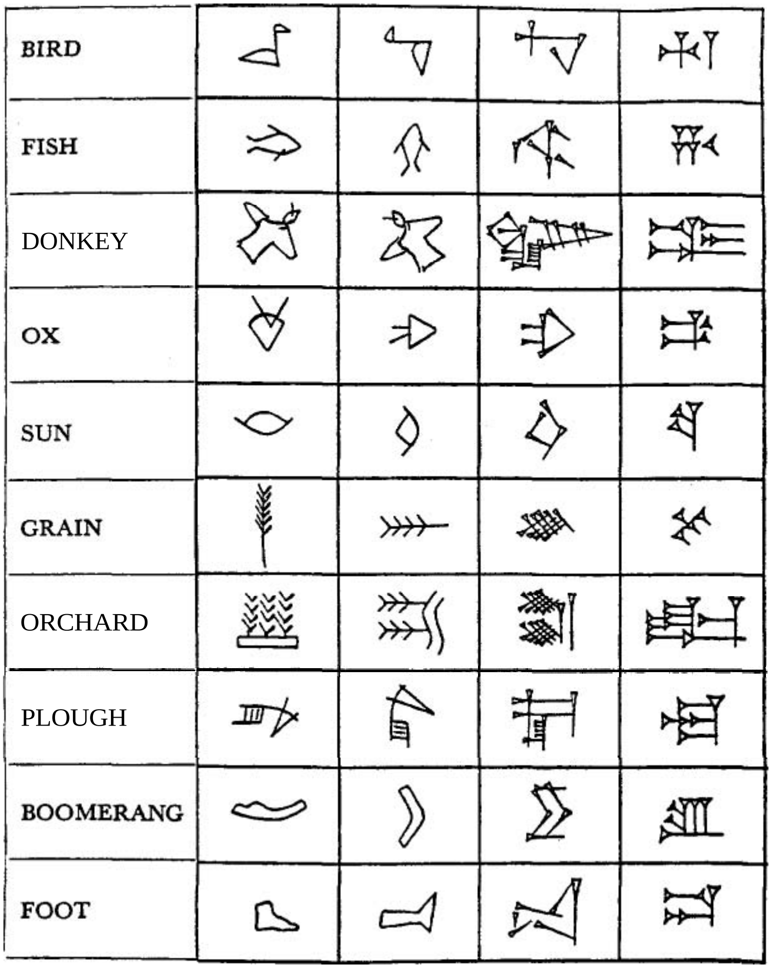

Figure 4.2
Pictorial origins of ten cuneiform signs. Note the rotation the forms underwent to accommodate production. From Gelb (1963, 70).

medieval times, so-called because they were 0-shaped, with an internal T. An example appears in Figure 4.3. In these maps, East, the Orient, the rising sun, Asia, was at the top, above the crossbar of the T, which was formed by the Dan and Nile Rivers. Below the crossbar to the left was Europe and to the right, Africa, separated by the Mediterranean forming the vertical bar of T. Maps are necessarily schematic; at the least, they omit information, presumably retaining the information relevant to their expected use. Maps may even mix perspectives, as in landmark maps, appearing as early as medieval times, where countries, rivers, and roads are laid out as if from above, with landmarks portrayed frontally superimposed. Figure 4.4 shows one of these (for more examples of maps ancient and modern, see Brown, 1979; Harley and Woodward, 1987, 1992, 1994; Southworth and Southworth, 1982). In contrast to these ancient depictions, many contemporary depictions are visualizations of things that are not inherently visualizable, such as temporal, quantitative, causal, or social relations. These depictions depend on analogy rather than schematic miniaturization or enlargement.

Graphs are perhaps the most prevalent example of depictions of abstract concepts, and were invented as recently as the late eighteenth century (e.g., Beniger and Robyn, 1978; Carswell and Wickens, 1988; Tufte, 1983), although they probably had their roots in mathematical notation, especially Cartesian coordinate systems. Two Europeans, Playfair in England and Lambert in Switzerland, are credited with being the first to promulgate their use, for the most part to portray economic and political data.

Notably, those early graphs, X-Y plots with time as one of the variables, are still the most common type of graph in scientific journals (Cleveland, 1984). This is despite the continuing clever inventions of visualizations from Florence Nightingale's polar plots of mortality across hospitals (Cohen, 1984) to box plots and stem-and-leaf diagrams (Tukey, 1977) to starfields, cone trees, and hyperbolic trees (e.g., Card, Mackinlay and Shneiderman, 1999) to the latest presentations at the InfoVis meetings or in Newsweek. Some of these visualizations have been widely adopted. Bar graphs and pie charts are common for representing quantitative data, with flow charts, trees, and networks widely used for qualitative data. Icons appear in airports, train stations, and highways all over the world, and menus of icons on information highways over the world. Many are used to portray concepts and information that are difficult to

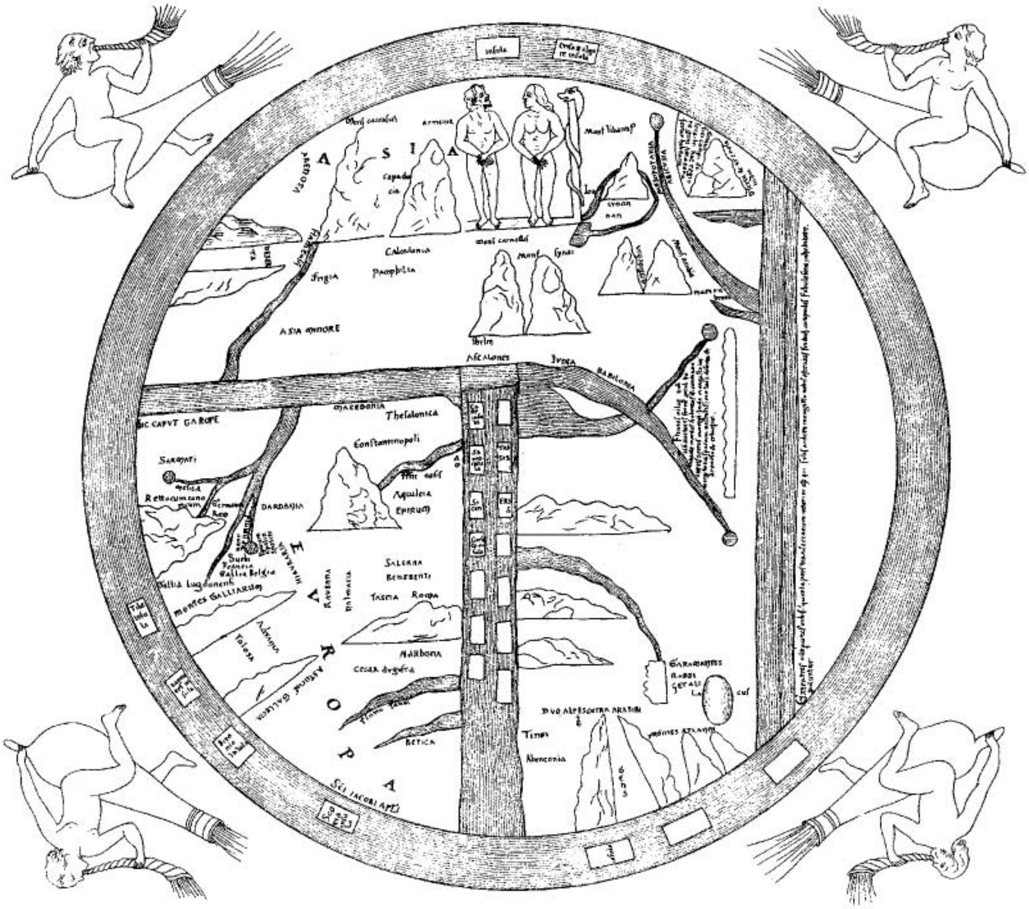

Figure 4.3
A T-O map, popular in the Middle Ages. Asia (east) is at the top, Europe (north) to the left, Africa (south) to the right. From Brown (1977, 118).

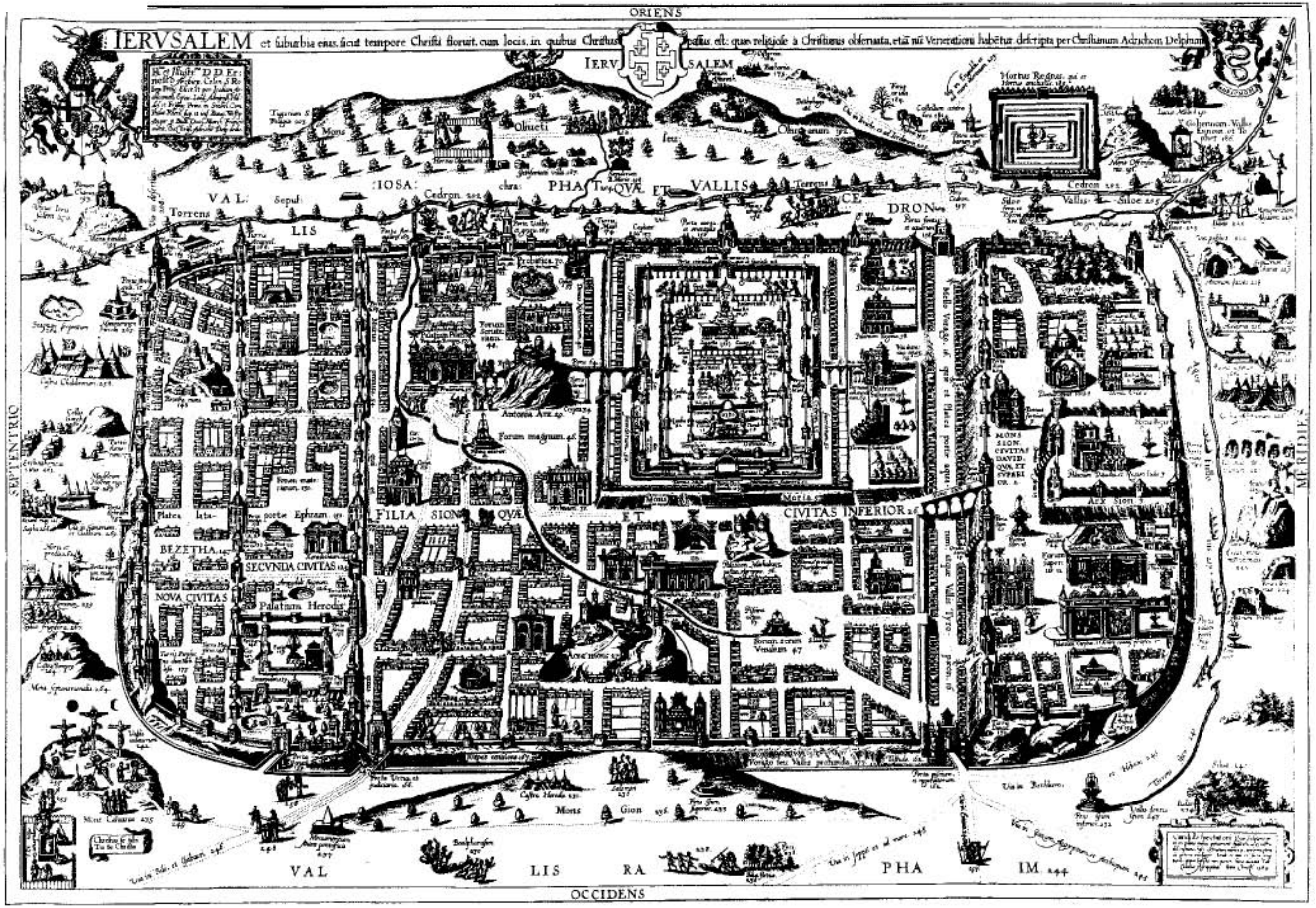

Figure 4.4
A map that mixes perspective to show both the street plan and the frontal views of landmarks. From Southworth and Southworth (1982, 74). Reprinted with permission of the Division of Rare and Manuscript Collections, Cornell University Library.

visualize, such as large data bases. Creating an effective visual webrowser continues to challenge the ingenuity of many.

4.3 How Graphics Convey Meaning

Graphics consist of elements that are systematically arranged in space. The choices of elements and spatial arrangements are usually not accidental or arbitrary. Many graphic conventions have been invented and reinvented by adults and children across cultures and time. Many have analogs in language and in gesture. Many are rooted in natural cognitive correspondences, "figures of depictions," and spatial metaphors, and have parallels in Gestalt principles of perceptual organization. In this paper, I present an analysis of graphic inventions based on how their elements and spatial arrangements are used to convey meaning. The evidence I will bring to bear is eclectic and unconventional, drawing from examinations of historical graphic inventions, children's graphic inventions, and language, as well as more conventional psychological research. Later, I examine how two contemporary graphic inventions, animation and 3-D, communicate, survey the various functions graphics serve, and draw conclusions for their design.

With some exceptions, graphic elements are generally used to represent elements in the world and graphic space is used to represent the relations between elements. One notable exception is mathematics, where elements such as + and – indicate relations. The dichotomy, into elements and relations, maps loosely onto the "what" vs. "where" distinction in vision and in spatial cognition, that is, information related to objects on the one hand and to spatial relations among objects on the other.

The fact that graphic displays are external augments many of their functions. Externalizing a representation reduces demand on memory and facilitates information processing. Spatially organized information can be accessed, integrated, and operated on quickly and easily, especially when the spatial organization reflects conceptual organization. Moreover, external representations are public. Several people can simultaneously inspect the same graphic display, and refer to it by pointing and other devices in ways apparent to all, facilitating group communication (e.g., Engle, 1998).

Elements: Figures of Depiction

Sometimes icons as elements are effective in representing meaning directly, for example, highway signs of a picnic table or a water tap on the route to the location of actual ones. For concepts not easily depicted, icons present challenges. They can, however, represent concepts indirectly, using a number of "figures of depiction," analogous to figures of speech (Tversky, 1995). One common type of figure of depiction is metonymy, where an associated object represents the concept. In computer interfaces, a picture of a folder represents a file of words and a picture of a trash can represents a place for unwanted folders. Analogous examples in language include using "the crown" to represent the king and "the White House" to represent the president. Synecdoche, where a part is used to represent a whole, or a whole for a part, is another common figure of depiction. Returning to highway signs, an icon of a place setting near a freeway exit indicates a nearby restaurant and an icon of a gas pump a nearby gas station. Analogous examples in language include "give a hand" for help and "head count" for number of people. Figures of depiction frequent early pictographic writing (Coulmas, 1989; Gelb, 1963;). For example, early Sumerian writing used a foot to indicate "to go" and an ox's head to indicate an ox. Figure 4.5 presents early ideographs for several concepts from a number of written languages, illustrating metonymy and synecdoche. Children's spontaneous writing and depictions also illustrate these principles (e.g., Hughes, 1986; Levin and Tolchinsky-Landsman, 1989). Like the inventors of pictographic languages, children find it easier to depict objects, especially concrete ones, than operations. For abstract objects and operations, children use metonymy and synecdoche. For example, children draw hands or legs to indicate addition or subtraction. Interestingly, the latter was also used in hieroglyphics (Hughes, 1986). As seen in the examples of public icons in Figures 4.6 and 4.7, depicting objects or things is more direct than depicting relations among objects. The public symbols developed by a different local, national, and international organizations for restaurants and coffee shops are highly similar whereas those developed for purchasing tickets or for baggage claim are less so.

The meanings of these depictions are somewhat transparent. Often, they can be guessed, sometimes with help of context. Even when guessing is unsuccessful, the range of meanings possible is highly limited. Because of their transparency, these icons are easily associated to their meanings, and thus easily remembered (for similar arguments in the context of ASL and gesture, see Macken, Perry and Haas, 1993). The meanings of computer icons cannot always be conveyed by a single word. The alternatives, verbal commands, are not always transparent and frequently need to be

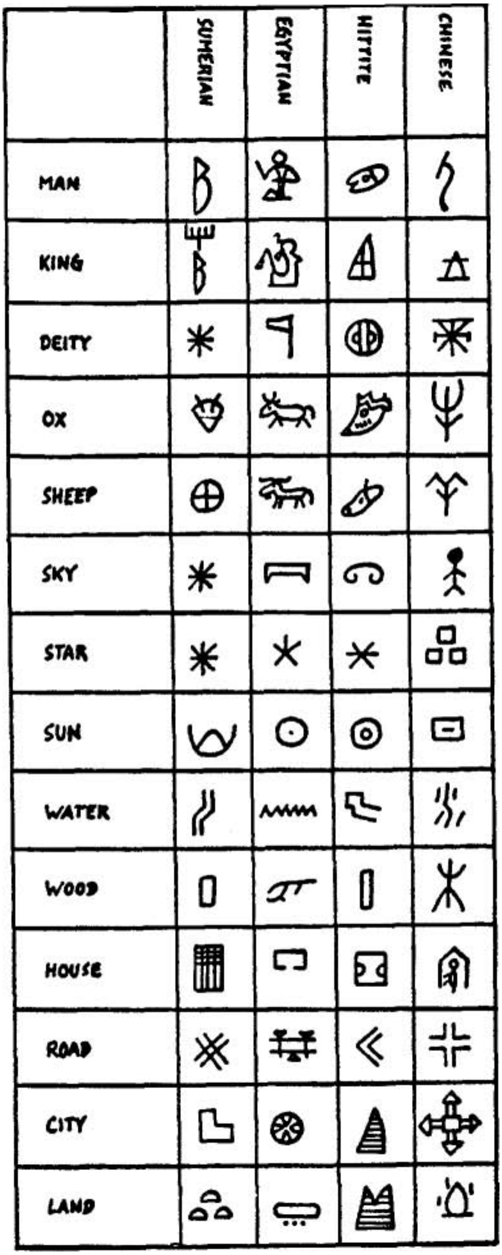

Figure 4.5
Pictorial signs in the Sumerian, Egyptian, Hittite, and Chinese languages. From Gelb (1963, 98).

learned. Does "delete" or "remove" eliminate a file? Do we "exit" or "quit" a program? Depictions have other advantages over words. Meaning is extracted from pictures faster than from words (Smith and McGee, 1980). Icons can be "read" by people who do not read the local language.

A new use of depictions has appeared in email. Seemingly inspired by smiley faces, and probably because it is inherently more casual than other written communication, computer vernacular has added signs for the emotional expression normally conveyed in face-to-face communication by intonation and gesture. These signs combine symbols found on keyboards to denote facial expressions, usually turned 90 degrees, such as :) or ;).

Spatial Arrays of Elements

Graphs, charts, and diagrams convey qualitative and quantitative information using natural correspondcnccs and spatial metaphors, some applied to the spatial elements, and others applied to the arrays of spatial elements. For spatial arrays, the most basic metaphor is proximity: proximity in space is used to indicate proximity on some other property, such as time or value. Spatial arrays convey conceptual information metaphorically at different levels of precision, corresponding to the four traditional scale types, nominal, ordinal, interval, and ratio (Stevens, 1946). These are ordered inclusively by the degree of information preserved in the mapping. Spontaneously produced graphic displays reflect these scale types. Children, for example, represent nominal relations in graphic displays at an earlier age than ordinal relations, and ordinal relations at an earlier age than interval relations (Tversky, Kugelmass and Winter, 1991). For elements, graphic displays use a variety of visual analogs to physical devices to convey information of varying quantitative precision.

Nominal scales Nominal scales are essentially clustering by category. Here, elements are divided into classes, sharing a single property or set of properties. Graphic devices indicating nominal relations often use the simplest form of proximity, grouping. This form, like many of the uses of spatial arrangement to convey meaning, capitalizes on Gestalt principles of perceptual grouping. In perception, things that are near by in space tend to be grouped and separated from things that are distant. To use this for conveying abstract meanings simply requires placing things that are related in close proximity and placing things that are not related farther away in space. One use of this device that we take for granted are the

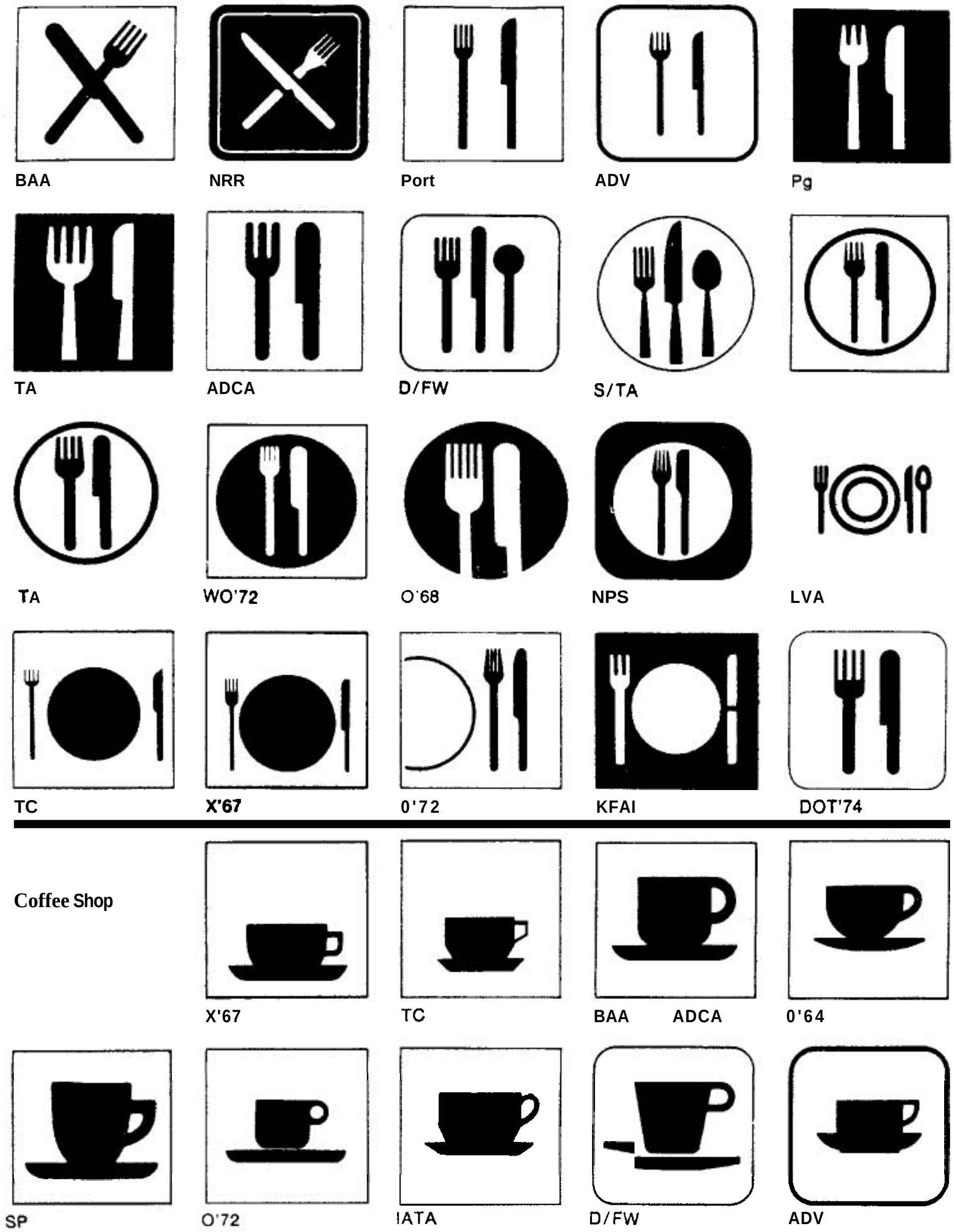

Figure 4.6
Various icons developed by civil authorities for restaurant and coffee shop. From Modley (1976, 67).

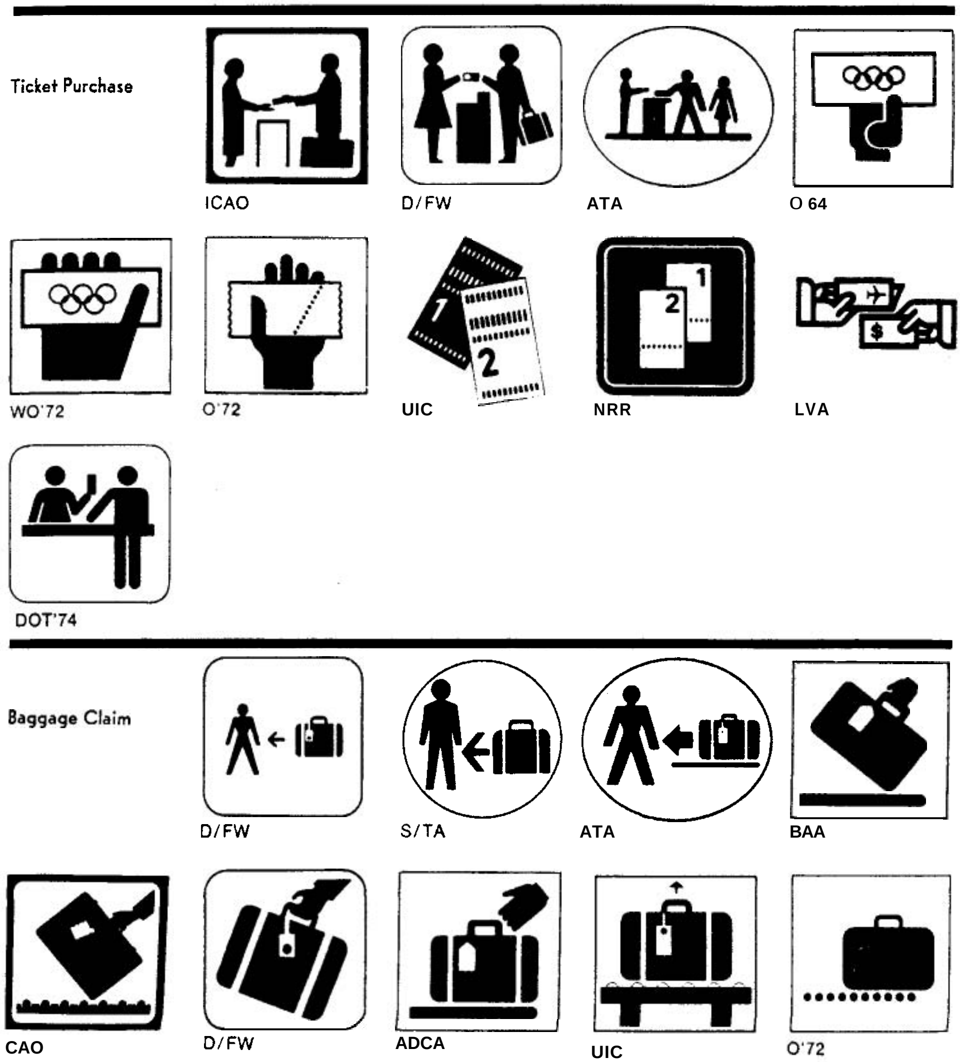

Figure 4.7
Various icons developed by civil authorities for ticket purchase and baggage claim. From Modley (1976, 70).

Table 4.1
Visual and spatial devices used to convey categorical and nominal relations

Categorical/Nominal Relations
spaces between words
spacing by rows and columns
( ), [ ], boxes, circles, Venn diagrams
visual devices: color, shading, cross-hatching
Ordinal
Simple subordination
indentation
size
superposition
highlighting
punctuation
Complex subordination
order
trees (hierarchies)
——

spaces between words in writing. Although it is easy to overlook spacing as a graphic device, early writing did not put spaces between words. The Roman alphabet for the most part maps sounds to written characters, but beyond the alphabet, many conventions of writing are based on spatial correspondences, not sound correspondences. Indentation and/or spacing before a new paragraph is another example of using separation in space to indicate separation of ideas. Some of the spatial and visual features used to convey nominal and ordinal relations appear in Table 4.1.

Another spatial device for delineating a category is a list, where all the items that need to be purchased or tasks that need to be done are written in a single column or row. Items are separated by empty space, and the items begin at the same point in each row, indicating equivalence. For lists, there is often only a single category; organization into a column indicates that the items are not randomly selected, but rather, share a property. Multiple lists are also common, for example, the list of chores of each housemate or a shopping list divided by departments or stores. A table is an elaboration of a list, using the same spatial device to organize both rows and columns (Stenning and Oberlander, 1995). A table cross-classifies items by several categories simultaneously. Items within each column and within each row are related, but on different features. In many cases, tables combine categorical and quantitative information. Examples include a list of countries with their GNP's for each of the last ten years, or a list of schools, with their average achievement scores on a variety of tests. Tables cross-classify. Items within each column and within each row are related, but on different features. Train schedules are yet another example, where the first column is typically the stations, the places where the train stops, and subsequent columns are the times for each train. For train schedules, a blank space where there would ordinarily be a time indicates a non-event, that is, this train doesn't stop at that station. Using spatially-arrayed rows and columns, tables group and juxtapose simultaneously.

Empty space is not the only spatial device used to indicate grouping. Often special signs, usually visual ones rather than strictly spatial ones, are added. These seem to fall into two classes, those based on enclosure (cf. Gestalt Principle of Grouping) and those based on similarity (cf. Gestalt Principle of Similarity). Signs used for enclosure resemble physical structures that enclose actual things, such as bowls and fences. On paper, these include parentheses, circles, boxes, and frames. Tables often add boxes to emphasize the structures of rows and columns or to enclose related items and separate different ones. Newspapers use frames to distinguish one classified ad from another. Parentheses and brackets in writing are in essence degenerate enclosures The curved or bent lines, segments of circles or rectangles, face each other to include the related words and to separate them from the rest of the sentence.

Complete circles have been useful in visualizing syllogisms and in promoting inference as in Euler or Venn diagrams or in contemporary adaptations of them (e.g., Shin, 1991; Stenning and Oberlander, 1995). Circles enclose items belonging to the same set. Circles with no physical contact indicate sets with no common items, and physically overlapping circles indicate sets with at least some common items. The classic Euler circles have been used as a reasoning heuristic as they are not sufficient for actual deduction. There are ongoing attempts to develop completely diagrammatic reasoning systems. One attempt has been to enrich Euler diagrams with spatial signs based on similarity, such as filling in similar regions with similar and dissimilar regions with different marks, color, shading, cross-hatching, and other patterns (e.g., Shin, 1991). Others have been developing heterogeneous reasoning systems based on a a combination of graphics and language, utilizing each for the contents and contexts in which inferences are easiest (Barwise and Etchemendy, 1995).

Other visual features of diagrams can be used to convey categorical relations. Maps use colors as well as lines to indicate political boundaries and geographic features. For geographic features, many of the correspondences are natural ones. For example, deserts are colored beige whereas forests are colored green, and lakes and seas are colored blue. Colors can also be used to convey quantitative information, for example, deeper (darker) blues indicating deeper water. Color categories and gradations can be used metaphorically as well. Examples include the use of colors to indicate degree of excitation in PET or fMRI images of the thinking brain. In addition to color, other visual features, such as size, shape, and font, can be used to signify groups based on similarity.

Ordinal relations Ordinal relations can vary from a partial order, where one or more elements have precedence over others, to a complete order, where all elements are ordered with respect to some property or properties. There are two separable issues in mapping order onto space. One is the devices used to indicate order, and the other is the direction of order. The direction of indicating order will be discussed after interval relations, as the same principles apply.

Now to ways of indicating order, first using space. Many of the devices used to indicate groupings can be adapted to indicate order. Writing is ordered, so one of the simplest spatial devices to indicate rank on some property is to write items according to the order on the property, for example, writing countries in order of GNP, or people in order of age. Empty space is used to convey order, as in indentation in outlines, where successively subordinate items are successively indented relative to superordinate items.

Visual devices are also useful for indicating order. Primary among them are lines. Lines form the skeletons of trees and graphs, both of which are commonly used to display ordered concepts, to indicate asymmetry on a variety of relations, including kind of, part of, reports to, and derived from. Examples include hierarchical displays, as in linguistic trees, evolutionary trees, and organizational charts. Other visual and spatial devices used to display order rest on the metaphor of salience. More salient features have more of the relevant property. Such features include size, color, highlighting, and superposition. Some visuo/spatial devices rely on what can be called natural cognitive correspondences. For example, high temperatures or greater activity are associated with "warm" colors and low temperatures and lower activity with "cold" colors, in scientific charts. This association most likely derives from the colors of things varying in temperature, such as fire and ice.

Arrows are a special kind of line, with one end marked, inducing an asymmetry. Although they have many uses, a primary one is to indicate direction, an asymmetric relation. Like bars and lines, arrows seem to be based on physical analogs. One obvious analog is the physical object arrow, invented by many different cultures for hunting. It is not the hunting or piercing aspects of physical arrows that have been adopted in diagrams, but rather the directionality. Hunting arrows are asymmetric, as a consequence of which they fly more easily in one direction than the other. Another more abstract analog is the idea of convergence captured by the > ("V") of a diagram arrow. Like a funnel or river straits, it directs anything captured by the wide part to the point, and straight outwards from there. Arrows are frequently used to signal direction in space. In diagrams, arrows are also commonly used to indicate direction in time. Production charts and computer flow diagrams, for examples, use arrows to denote the sequence of processes. Terms for time, such as "before" and "after," and indeed thinking about time, frequently derive from terms for and thinking about space (e.g., Boroditsky, 1999; Clark, 1973; Gentner, this volume).

Interval and ratio relations Interval and ratio relations apply more constraints of the spatial proximity metaphor than ordinal relations. In graphic displays of interval information, the distances between elements are meaningful; that is, greater space corresponds to more on the relevant dimension. This is not the case for ordinal mappings. Ratio displays of information, are even more restrictive. For them, zero and the ratios of the distances are meaningful.

The most common graphic displays of interval and ratio information are X-Y plots, where distance in the display corresponds to distance on the relevant property or properties. Musical notation is a specialized interval scale that makes use of a limited visual alphabet corresponding to modes of execution of notes as well as a spatial scale corresponding to pitch. Finally, for displaying ratio information, pie charts can be useful, where the area of the pie corresponds to the proportion on the relevant variable.

Expressing mixed cases: bars and lines Most graphs display two variables simultaneously, average rainfall over months, school achievement scores by district, chocolate ice cream sales by stores, and so on. Bars charts are a common way to convey quantities of discrete sets. They are useful for displaying quantities for several variables at once where the height or length of the bar corresponds to the quantity on the relevant variable. Isotypes were invented by Otto and Marie Neurath in the 30's as part of a larger movement to increase communication across languages and cultures. That movement included efforts to develop picture languages and Esperanto. Isotypes combine icons and bar charts to render quantities on different variables more readily interpretable (Neurath, 1936). For example, in order to display the yearly productivity by sector for a number of countries, a unit of output for each sector is represented by an isotype, or icon that is readily interpretable, a shaft of wheat for units grain, an ingot for units of steel, an oil well for units of petroleum. The number of icons per sector is proportional to output in that sector. Because of their physical resemblance to a product of each sector, icons facilitate comparison across countries or years for the sectors.

When two variables are displayed simultaneously, one may be categorical and the other quantitative. Going from categorical grouping to conceptual ordering requires a conceptual leap. Grouping entails seeing that items in Group A share one or more properties and items in Group B share one or more different properties. Group A and Group B do not have to be related in any way; they are the proverbial "apples and oranges." Different school districts and different ice cream stores can be regarded as separate and different entities with different properties. Ordering entails seeing that Group A and Group B differ on a property (or properties) that itself differs systematically. Specifically, the systematicity underlying an order requires a property that is similar enough across groups that it can be arranged as including more or less of the property. Put differently, categorical relations depend on within group property similarity and between group property difference. Ordinal relations depend on graded property similarity between groups. Note that the division into categorical and quantitative relations depends in part on perspective. Let us return to the school district example. One way of looking at separate school districts is as separate entities. Another way of looking at them is to order them by parental income, thus turning a categorical variable into a (sensible) quantitative one.

Categorical relations separate and ordinal ones connect. Visual devices that indicate boundaries or containers are natural analogs for categories just as visual devices that indicate connections are natural analogs for orders. Visual boundaries and containers include the brackets and circles and frames discussed in the section on categorical relations. Like those, visual devices that indicate connections resemble physical structures that link things, like outstretched arms, paths, chains, and ropes. Like paths or outstretched arms, lines link one concept to another, bringing non-contiguous things into contiguity, making distal items proximal. Lines, sometimes whole and continuous (——), sometimes partial or broken (········) are used to link related items.

That categorical or discrete concepts are naturally mapped to entities that contain and ordinal concepts are naturally mapped to entities that connect seems to underlie the use and interpretation of bars and lines in graphs (Zacks and Tversky, 1999). Bars are container-like and lines connect. Zacks and Tversky (1999) distinguished two related uses. The use that is statistical lore, and sometimes explicit advice, is the bar-line data use: display discrete data with bars and continuous data with lines. But we have already seen that the same data can be viewed in different ways. The more subtle use is the bar-line message use: interpret/produce bars as discrete comparisons and lines as trends.

Evidence not only for data use but also for message use of bars and lines appeared in graphic productions and interpretations. One set of participants wrote interpretations for graphs of height of males/females, a discrete domain, or 10 year olds/12 year olds, a continuous domain. Examples appear in Figure 4.8. Discrete interpretations used terms like "higher," "less," and "fewer," whereas trend interpretations used terms like "rising" and "decreasing," and sometimes "function," "relationship," and "trend." More line graphs were interpreted as trends than bar graphs, consistent with the bar/line message use. More trend interpretations were produced for the continuous domain than for the discrete domain, consistent with the bar/line data use. Another set of participants produced graphs for discrete or trend descriptions of height in males/females or 10 year olds/12 year olds.

As for interpretations, productions showed the effects of both data and message uses of bars and lines. More line graphs were produced for trend descriptions that used terms like "increasing" than for discrete descrip-

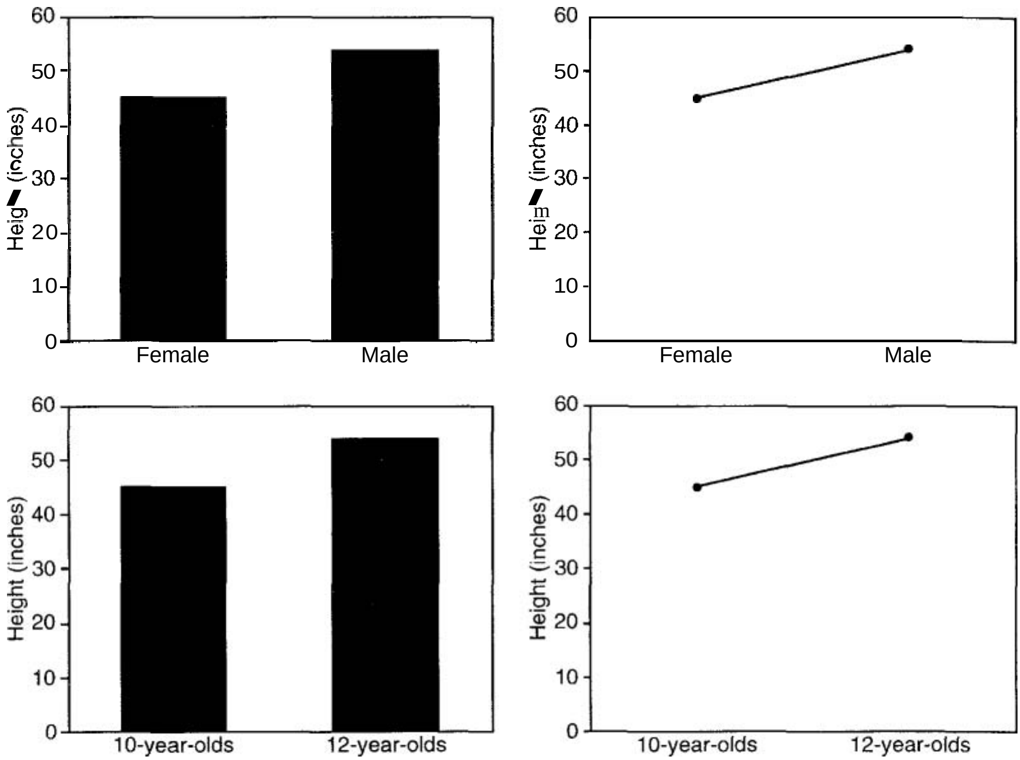

Figure 4.8
Bars and lines used by Zacks and Tversky (1999) for eliciting descriptions of relations. Despite content, informants tended to describe relations portrayed as bars in terms of discrete comparisons and those portrayed as lines in terms of trends. From Zacks and Tversky (1999).

tions that used terms like "greater," supporting the bar/line message use. More trend descriptions were produced for the continuous (age) domain than the discrete (sex) domain, supporting the bar/line data use. Overall, the effects of the graph form, bar or line, were stronger than the effects of the conceptual domain, discrete or continuous.

These correspondences between choice of graphic representation and choice of interpretation appeared despite the fact that few people in the informant population are aware of the bar/line data use, and even fewer of the bar/line message use. The choice of visual devices for discrete, categorical concepts and for ordinal or continuous ones appears to be naturally derived from physical devices that contain or connect.

Directionality In spite of the uncountable number of possibilities for indicating order in graphic displays, the actual choices are remarkably limited. In principle, elements could be ordered in any number of orientations in a display. Nevertheless, graphic displays tend to order elements either vertically or horizontally or both. Similarly, languages are written either horizontally or vertically, in rows or in columns. There are reasons grounded in perception for the preference for vertical and horizontal orientations. The perceptual world has two dominant axes: a vertical axis defined by gravity and by all the things on earth correlated with gravity; and a horizontal axis defined by the horizon and by all the things on earth parallel to it. Vision is especially acute along the vertical and horizontal axes (Howard, 1982). Memory is poorer for the orientation of oblique lines, and slightly oblique lines are perceived and remembered as more vertical or horizontal than they were (Howard, 1982; Tversky, 1981; for exceptions that depend on graphic interpretation, see Schiano and Tversky, 1992).

Vertical asymmetry Of all the possible orientations, then, graphic displays ordinarily only use the vertical and horizontal. What's more, they use these orientations differently. Vertical arrays take precedence over horizontal ones. Just as for the choice of dimensions, the precedence of the vertical is also rooted in perception (Clark, 1973; Cooper and Ross, 1975; Lakoff and Johnson, 1980; Franklin and Tversky, 1990). Gravity is correlated with vertical, and people are oriented vertically. The vertical axis of the world has a natural asymmetry, the ground and the sky, whereas the horizontal axis of the world does not. The dominance of the vertical over the horizontal is reflected in the dominance of columns over rows. Similarly, bar charts typically contain vertical columns (the exceptions seem to be aimed at conforming to accompanying text).

Natural correspondences with vertical There is another plausible reason for the dominance of the vertical over the horizontal. Not only does the vertical take precedence over the horizontal, but there is a natural direction of correspondence for the vertical, though not for the horizontal. In language, concepts like more and better and stronger are associated with upward direction, and concepts like less and worse and weaker with downward direction (Clark, 1973; Cooper and Ross, 1975; Lakoff and Johnson, 1980). People and plants, indeed most life forms, grow upwards as they mature, becoming bigger, stronger, and (arguably) better. Healthy and happy people stand tall; sick or sad ones droop or lie down. More of any quantity makes a higher pile. The associations of up with quantity, mood, health, power, status, and more derive from physical correspondences in the world. It is no accident that in most bar charts and X-Y plots, increases go from down to up. The association of all good things with up is widely reflected in language as well. Inflation and unemployment are exceptions, but principled ones, as the numbers used to express inflation and unemployment go up. Language reflects these natural correspondences. We speak of someone "at the top of the heap," of doing the "highest good," of "feeling up," of being "on top of things," of having "high status" or "high ideals," of doing a "top-notch job," of reaching "peak performance," of going "above and beyond the line of duty." In gesture, we show success or approval with thumbs up, or give someone a congratulatory high five. The correspondence of pitch with the vertical seems to rest on another natural relation. We produce higher notes at higher places in the throat, and lower notes at lower places. It just so happens that higher notes correspond to higher frequency waves, but that may simply be a happy coincidence.

Horizontal neutral In contrast, the horizontal axis is standardly used for neutral dimensions, most notably, time. Similarly, with few exceptions (curiously, economics), neutral or independent variables are plotted along the horizontal axis, and the variables of interest, the dependent variables, along the vertical axis. This arrangement of variables facilitates inferences of rates of change from line slopes (Gattis and Holyoak, 1996). Although graphic conventions stipulate that increases plotted horizontally proceed from left to right, directionality along the horizontal axis does not seem to rest in natural correspondences. The world is asymmetric along the vertical axis, but not along the horizontal axis. Right-left reflections of pictures are hardly noticed but top-bottom reflections are (e.g., Yin, 1969). Languages are just as likely to be written left to write as right to left (and in some cases, both), but they always begin at the top.

Use of space cross-culturally and developmentally Children and adults from cultures where language is written left to right as well as from cultures where language is written right to left mapped increases on a variety of quantitative variables from down to up, but almost never mapped increases from up to down. However, people from both writing cultures mapped increases in quantity and preference from both left to right and right to left equally often. The relative frequency of using each direction to represent quantitative variables did not depend on the direction of written language (Tversky, Kugelmass and Winter, 1991). Despite the fact that most people are right-handed and that terms like dexterity derived from "right" in many languages have positive connotations and terms like sinister derived from "left" have negative connotations, the horizontal axis in graphic displays seems to be neutral. Consistent with that, we refer to one side of an issue as "on the one hand," and the other side as "on the other hand," which has prompted some politicians to ask for one-handed advisors. And in politics, both the right and the left claim the moral high ground.

Children's and adults' mappings of temporal relations showed a different pattern from their mappings of quantitative and preference relations (Tversky, Kugelmass and Winter, 1991). For time, they not only preferred to use the horizontal axis, they also used the direction of writing to determine the direction of temporal increases, so that people who wrote from left to right tended to map temporal concepts from left to right and people who wrote from right to left tended to map temporal concepts from right to left. This pattern of findings fits with the claim that neutral concepts such as time tend to be mapped onto the horizontal axis. The fact that the direction of mapping time corresponded to the direction of writing but the direction of mapping preference and quantitative variables did not may be because temporal sequences seem to be incorporated into writing more than quantitative concepts, for example, in schedules, calendars, invitations, and announcements of meetings.

Directionality in charts and diagrams Compatible with the previous arguments and evidence, ordinal charts and networks tend to be vertically organized. A survey of the standard scientific charts in all the textbooks in biology, geology, and linguistics at the Stanford Undergraduate Library revealed vertical organization in all but two of 48 charts (Tversky, 1995). Furthermore, within each type of chart, there was agreement as to what appeared at the top. In 17 out of the 18 evolutionary charts, Homo sapiens, that is, the present age, was at the top. In 15 out of the 16 geological charts, the present era was at the top, and in 13 out of the 14 linguistic trees, the proto-language was at the top. In these charts, in contrast to X-Y graphs, time runs vertically, but time does not seem to account for the direction, partly because time is not ordered consistently across the charts. Rather, at the top of each chart is an ideal. In the case of evolution, it is humankind, regarded by some as the pinnacle of evolution, a view some biologists discourage (e.g., Gould, 1977). In the case of geology, the top is the richness and accessibility of the present era. In the case of language trees, the top is the proto-language, the most ancient theoretical case, the origin from which others diverged. In organizational charts, say of the government or large corporations, power and control are at the top. For diagramming sentences or the human body, the whole is at the top, and parts and sub-parts occupy lower levels. In charts such as these, the vertical relations are meaningful, denoting an asymmetry on the mapped relation, but the horizontal relations are often arbitrary.

4.4 Modern Graphics: 3D and Animation

Advances in computers have made more graphic devices available to professionals and amateurs alike, most notably, 3D and animation. Although both can be useful, they should come with questions: First, how well are these devices perceived and conceived? And second, what sorts of meanings do they naturally convey?

3-D

Different forms of 3-D have been used by artists all over the world. Post-Renaissance Western art has favored 1-point perspective, though modern and contemporary Western art seems to have abandoned that. Eastern art, as well as children's spontaneous art, have used other devices to convey depth, such as occlusion, size, and height in the picture plane (e.g., Braine, Schauble, Kugelmass and Winter, 1993; Willats, 1997).

For 3D, the first thought is that it is a natural for conveying information, concrete or abstract, that is inherently three-dimensional. Some encouragement for that view comes from work on drawings of objects. People naturally interpret object-like drawings, those, for example, with closed contours and hints of symmetry, as two-dimensional representations of three-dimensional objects (Hochberg, 1964; McBeath, Schiano and Tversky, 1997). Perceiving and comprehending the 3-D details, however, can be problematic from flattened images. Such perceptual difficulties abound, especially for odd views or scenes with multiple objects. The retina itself is essentially flat, and beyond small distances, perception in depth depends on a set of cues such as occlusion, foreshortening, and relative size rather than on stereoscopic vision. Those clues are only clues, however; they are fallible. Their limitations yield error in depth perception and in object recognition alike (e.g., Loomis, DaSilva, Fujita and Fukusima, 1992). 3D interfaces suffer from exactly the same limitations. Even within the bounds of stereoscopy, only one view of an object or scene is present at once. This means that mental representations of the three dimensions must be constructed from separate views. It also means that some objects may be occluded by others, as frequently happens in 3-D depth arrays of bars. Frontal views of 3-D bars often become reversible figures, hard to stabilize in order to inspect.

The difficulties of conceptualizing in three dimensions from a flat display make it no accident that maps of the three-dimensional world are schematized to two dimensions. Nor is it an accident that architects and engineers prefer to design two-dimensional planes of their projects before proceeding to three-dimensional representations (e.g., Arnheim, 1977; Suwa and Tversky, 1996). Not just production, but also interpretation of 3D graphics is difficult for novices (e.g., Cooper, Schacter, Ballesteros and Moore, 1992; Gobert, 1999). Similarly, constructing three-dimensional conceptual representations from two-dimensional graphic representations is also difficult (e.g., Shah and Carpenter, 1995). When asked to provide the information conveyed in a 2-D line graph portraying three variables, respondents described the relations between the in terms of the variables plotted on the X and Y axes rather than in terms of the indirectly represented Z axis.

Although 3D is popular, it is hard to perceive and hard to conceive, even when used for objects and scenes that are naturally three dimensional. But the proliferation of graphics software has allowed creation of 3D graphics even for things that are not naturally 3D, most notably 3-D bar graphs. This practice has been decried by many (e.g., Tufte, 1983; Wainer, 1980). The rising cost of oil, for instance, has been portrayed by proportionately larger oil barrels. Only the relative heights of the barrels are meaningful, but viewers cannot help but respond to the areas or implied volumes. Despite the difficulties of 3-D, users express preferences for 3D bars or lines in certain situations, for example, for showing data for others rather than self, or for remembering data as opposed to examining it (Levy, Zacks, Tversky and Schiano, 1996). Some of these intuitions are not off the mark. Estimates in perception from 3D bars are indeed worse than from old-fashioned 2D bars, but estimates in memory are no worse from 3D than from 2D bars (Zacks, Levy, Tversky and Schiano, 1998).

Animation

Animation, graphics that change, can be eye-catching, as web advertisers have discovered. For conveying real-time on-line processes, simple animations can be informative. Take for example, the bar that appears when accessing a website. It fills at the rate that information is downloaded, allowing the user to estimate how much time it will take to acquire the information. Because animation entails changes in graphics over time, it seems a natural for conveying actions and processes that are inherently dynamic or that take place over time. This should hold for both actions that are concrete, such as the motions of people and machines and for processes that are more abstract, such as weather systems or the temporal/causal relations of algorithms. However, as for 3D, this view does not take into account human perceptions and conceptions of dynamic events. Animations vary in complexity. One simple animation is the path of a point or object. Another is the sequential highlighting of parts of a display. Movements of two- or three-dimensional bodies, especially an irregular ones, and movements along oblique or irregular paths are more complex. Even more complex animations include the movements of parts in relation to one another, such as a system of gears or pulleys or the changes in position of the limbs during walking. Still more complex are the movements of two bodies or systems with respect to one another. For an animation to be effective, it first must be correctly perceived.

Many dynamic events, especially complex ones, take place too quickly for human observers to perceive. For example, generations of artists painted the legs of galloping horses incorrectly until Muybridge's (1957) photographs revealed the correct configuration. This is complex motion, parts moving in complex patterns relative to one another. Yet there is evidence that even the simple path of a pendulum is often misperceived. Observers who select the correct trajectory from an animation may nevertheless fail to draw the correct trajectory (Kaiser, Profitt, Whelan and Hecht, 1992). What's more paths or trajectories of moving objects are often distorted, perceived as closer to horizontal or vertical than they actually are (e.g., Pani, Jeffres, Shippey and Schwartz, 1996; Shiffrar and Shepard, 1991). Even events that are slow enough to be accurately perceived may be conceived of as discrete steps rather than as continuous movement (e.g., Zacks, Tversky and Iyer, in press). In verifying assertions about the behavior of pulley systems, people mentally animate the systems one pulley at a time in sequence rather than imagining the entire system in action (Hegarty, 1992). Put differently, people conceive of the continuous action of a pulley system as a sequence of discrete steps.

In addition to the difficulties of perceiving them accurately. animations have a substantive disadvantage relative to static diagrams. Like speech, animations are transient, ephemeral, and not readily reinspected. A series of static diagrams, freeze frames, can simultaneously portray the sequential stages of an action, like the galloping of a horse's legs or the steps in operating a coffee maker. Similarly, an annotated diagram, such as a flow chart, can show the successive steps of a complex action all at once. Compared to animations, static diagrams can more easily be inspected and reinspected, related and interrelated to insure understanding.

Misperceptions of dynamic events and conceptions of them as sequences of steps rather than continuos activity may account for many of the failures to find benefits of animation in conveying information, concrete or abstract (e.g., Kaiser, Proffitt, Whelan and Hecht 1992; Hegarty, Narayanan, Cate and Holmquist, 1999; Lowe, 1999; Pane, Corbett and John, 1996; Rieber, Boyce and Assad, 1990; Stasko and Lawrence, 1998). There are, however, some cases where animation has been more successful than static diagrams, and these cases are instructive. One notable case is in teaching speed = distance x time problems, where motion was abstracted to a moving point (Baek and Lane, 1988). Two points starting in the same place moving at different speeds and arriving at different stopping points were simple enough to perceive and interpret. In this case, the animation is not only simple, it also abstracts the information essential to solving the problems, the differences in rates of movement. Since the rates are constant and the path a straight line, the events are perceived as continuous, not likely to be conceptually segmented. Another successful application of animation also used simple animations, in this case, sequentially highlighting parts of a diagram to guide viewers' successive foci of attention. This entailed a discrete rather than continuous use of animation. Diagrams can be visually complex, but unlike for reading text, there is no established order of scanning them. Sequential highlighting can provide a sensible order of integrating parts of a diagram. It borrows a device common in language, using linear order to reveal underlying structure. For example, cities scattered spatially on a map can be organized by historical era or by size. Sequential highlighting indeed facilitated organization of a diagram by the highlighted features, determining the character of the mental representation. However, it had no benefits to memory relative to static diagrams (Betrancourt and Tversky, in press). Note that each of these animations is perceptually simple, the smooth horizontal movement of a single point or the sequential highlighting of successive parts. Note also that each animation conveys a cognitively simple idea, the relative speeds of two simultaneously moving objects or the order of spatially scattered elements.

These considerations and findings suggest that graphic animations may succeed with the right combination of information processing ease and cognitive naturalness. Animations can facilitate only when they are simple and slow enough to be perceived. Animations are natural for conveying processes or events that take place in time or for guiding focus of attention over time. Useful animations should reflect people's conceptions of the processes and events they portray; they should be continuous if conceived of as continuous, discrete if conceived of as discrete. Finally, they should abstract and portray the essence of the changes over time.

4.5 Other Approaches

The approach taken here has been to search for ways that space and the things in it have been used to represent both spatial and nonspatial elements and relations, to search for natural correspondences between space and thought. Others have analyzed graphics from different perspectives, among them, linguists, computer scientists, psychologists, statisticians, designers, and philosophers. I review these analyses briefly for the interested reader. Their insights sometimes complement and sometimes parallel the observations and findings put forth here. Some of these researchers have analyzed the graphics themselves, others have examined how people comprehend, use, or construct them, and still others have made recommendations for design. Inevitably, some have focused on more than one of these goals, as the goals interact. Analyses of actual graphics gives clues to how they are used and produced by people and how they are used gives clues to how they should be designed.

In an influential treatise, Bertin (1981) put forth a comprehensive semiotic analysis of the functions of graphics and the processes used to interpret them that established the field and defined the issues. According to Bertin, the functions of graphs are to record, communicate, and process information, and the goal of a good graphic is simplification to those ends. This work was picked up first by statisticians and designers, most notably Tufte and Wainer, and later by psychologists. Tufte (1983, 1990, 1997) has exhorted graphic designers to refrain from "chart junk," extraneous marks that convey no additional information, adopting by contrast a minimalist view that does not take into account conventions or need for redundancy. Wainer (1984, 1992) has gathered a set of useful prescriptions and insightful examples for graph construction, drawing on work in semiotics, design, and information processing.

Within psychology, the interests of researchers have varied. Ittelson (1996) has called attention to differences in information processing of "markings," deliberate, two-dimensional inscriptions on surfaces of objects and other visual stimuli that may not have communicative intent. Thus, interpreting a graphic depends on understanding that it can represent something other than itself, a concept that children gradually come to appreciate DeLoache, Miller and Rosengren (1997). After an extensive survey of graphics used primarily in education, Winn (1987) analyzed how information is conveyed in charts, diagrams, and graphs. Larkin and Simon (1987) compared sentential and diagrammatic external representations, especially in teaching, highlighting the advantages of diagrammatic ones for tasks where spatial proximity conveys useful information. Continuing this line of thinking, Stenning and Oberlander (1995) presented a formal analysis of the advantages and disadvantages of diagrammatic and sentential representations in drawing inferences. They argue that diagrams allow expression of some abstractions, much like natural language, but are not as expressive as sentential logics.

Several projects have been directly concerned with how people perceive, misperceive, interpret, remember, and produce graphics, raising implications for design. Though a statistician, Cleveland (1984; 1985) has examined the psychophysical advantages and disadvantages of using different graphic devices for conveying quantity, position, angle, length, slope, and more, for efficiency in extracting different kinds of information from displays. He and his collaborators have produced convincing cases where conventional data displays can be easily misconstrued by human users. Kosslyn (1989; 1994), using principles adopted from visual information processing and Goodman's (1978) analysis of symbol systems, has developed a set of prescriptives for graph design, based on an analysis of the syntax, semantics, and pragmatics underlying graphs. Pinker (1990) provided a framework for understanding information extraction from graphics that separates processes involved in constructing a visual description of the physical aspects of the graph from those involved in constructing a graph schema of the mapping of the physical aspects to mathematical scales. Based on Pinker's framework, Carpenter and Shah (1998) proposed a model of graph comprehension in which pattern recognition, translation of visual features to conceptual relations, and determining referents of quantified concepts, are integrated and iterated.

Carswell and Wickens (Carswell, 1992; Carswell & Wickens, 1988; 1990) have demonstrated effects of perceptual analysis of integrality on graph comprehension, and others have shown systematic biases in interpretation or memory dependent on the form of graphic displays (Gattis & Holyoak, 1996; Levy, Zacks, Tversky & Schiano, 1996; Schiano & Tversky, 1992; Shah & Carpenter, 1995; Spence & Lewandowsky, 1991; Tversky & Schiano, 1989).

A number of observers of society have discussed the role of external devices, especially visualizations, in human cognition and behavior. Donald (1991) has speculated on the effects of the creation of mental artifacts on cultural change. Norman (1993) has critiqued modern inventions that, as he says, are supposed to make us smart, but don't always succeed. Kirsh (1995) has analyzed situations, such as preparing meals, playing tetris, and counting money, in which people array artifacts spatially and manipulate those arrays to facilitate memory and inference.

Visualizations have become increasingly important in organizing large data bases and enabling efficient search through them. Navigation metaphors for these tasks abound, both in language and in graphics. Researchers in human computer interaction have also been active in the invention of graphics and visualizations, and in the development of prescriptions for design (e.g., Card, Mackinlay and Shneiderman, 1999). Their "mantra" for creating effective visualizations of large sets of data: Overview first, zoom and filter, then details-on-demand (p. 625). Though there is some support for this mantra, research in cognition on basic level concepts (e.g., Rosch, 1978) and on reasoning (e.g., Cheng and Holyoak, 1985) suggests that an effective entry into a complex system might be a thorough understanding of a concrete example. Once an exemplary example has been mastered, abstraction to generalities and inspection of details are anchored and supported.

The burgeoning interest in both descriptive and prescriptive aspects of comprehension and production of charts, graphs, and diagrams has been addressed in an increasing number of interdisciplinary conferences. Papers from the first of these, along with other seminal papers, were collected in a volume edited by Glasgow, Narayanan and Chandrasekaran (1995) that called the field diagrammatic reasoning. Comics are now regarded as serious literature. They use a variety of pictoric and spatial devices, some readily interpretable, some conventional, to convey motion, emotion, and other ideas (McCloud, 1994). A recent novel, self-described as a "Novel of Business," found it useful to include graphics as part of its' narrative (Bing, 1998).

4.6 Some Functions of Graphic Displays

Despite their variability of form and content, a number of cognitive principles underlie graphic displays. These are evident in the many functions they serve as well as in the way information is conveyed in them. Some of their many overlapping functions are reviewed below. As with functions, goals, and constraints on other aspects of human behavior, so the functions, goals, and constraints of graphic displays sometimes work at odds with each other, and sometimes work in concert.

Attract Attention and Interest

One prevalent function of graphic displays is to attract attention and interest. A related function is aesthetic; graphics may be pleasing or shocking or repulsive or calming or funny.

Record Information

An ancient function of graphics is to provide records. For example, tallies developed to keep track of property, beginning with a simple one-mark one-piece of property relation, developing into numerals as tallies became cumbersome for large sums and calculations (e.g., Schmandt-Besserat, 1992). Various native American tribes kept track of their tribal numbers with icons for members and recorded their history year by year with depictions of a major event of the year (Mallery, 1972).

Memory

A related function of graphic displays is to facilitate memory. This surely was and is one of the functions of writing, whether pictographic or alphabetic. A modern example is the use of menus, especially icon menus, in computer user interfaces. Providing a menu turns what would otherwise be a recall task into a recognition task. Instead of having to call to mind all the possible commands in a program or files on a drive, a user has only to select the command or file that is needed from a list. There is yet another way that graphs promote memory. Menus and icons are typically displayed in standard places in an array. As anyone who has returned to a previous home after a long lapse of time knows, places are excellent cues to memory. Ancient lore, the Method of Loci, and modem research support the intuition that space is not only an excellent cue but also an excellent organizer of memory (e.g., Bower, 1970; Franklin, Tversky and Coon, 1992; Small, 1997; Taylor and Tversky, 1997; Yates, 1969).

Communication

In addition to facilitating memory, graphic displays also facilitate communication. As for memory, this has also been an important function of writing, to allow communication out of earshot (or eyeshot). Graphic displays allow private, mental conceptualizations to be made public, where they can be shared, examined, and revised.

Provide Models of Actual and Theoretical Worlds

Maps, architectural drawings, molecules, circuit diagrams, organizational charts, and flow diagrams are just some of the myriad examples of diagrams serving as models of worlds and the things in them. In general, these are models, and not simply shrunken or expanded worlds. Effective diagrams omit many features of the modeled world and distort others, and even add features that are not in the modeled world. Maps, for example, are not drawn strictly to scale. Roadmaps exaggerate the sizes of highways and streets so that they can be seen and used. Maps introduce symbolic elements, for railroads, ocean depth, towns, and more, that require a key and/or convention to interpret. The essence of creating an effective external representation is to abstract those features that are essential and to eliminate those that are not, that only serve as clutter. For dynamic systems, successful diagrams must illuminate the causal chain of events over and above the parts of the systems and their interconnections (e.g., Kieras, 1992; Kieras and Bovair, 1984; Mayer and Gallini, 1990). Of course, this is not as straightforward as it sounds, partly because it is difficult to anticipate all the uses an external representation will have, partly because successful communication rests on redundancy. Well-designed diagrams facilitate learning and operation of a system but poorly-designed diagrams do not (e.g., Glenberg and Langston, 1992; Kieras and Bovair, 1984; Mayer and Gallini, 1990; Scaife and Rogers, 1996). Current trends in computer graphics go against the maxim of abstracting the essentials. The aim of at least some areas of computer graphics seems to be creating as much detail and realism as possible. At the other extreme are designers (e.g., Tufte, 1983) advocating graphic design that is so minimal that it may not give sufficient clues to interpretation.

Convey Meaning, Facilitate Discovery and Inference

Effective graphics make it easy for users to extract information and draw inferences from them. Maps, for example, facilitate determining routes and estimating distances. A map of cholera cases in London during an epidemic made it easier to find the contaminated water pump (Wainer, 1992). Plotting change rather than absolute levels of a measure can lead to very different inferences (Cleveland, 1985). Indeed, the advice in How *to Lie with Statistics* (Huff, 1954) has been used for good or bad over and over. The format of physics diagrams (Narayanan, Suwa & Motoda, 1994), architectural sketches (Suwa & Tversky, 1996), and graphs (e.g., Gattis, this volume; Gattis and Holyoak, 1996; Shah and Carpenter, 1995) bias users towards some kinds of inferences more readily than others.

4.7 Basis for Metaphors and Cognitive Correspondences

A major purpose of graphic displays is to represent visually concepts and relations that are not inherently visual. Graphic displays use representations of elements and the spatial relations among them to do so. One type of element, common in early writing systems and recent computer interfaces, is an icon, which conveys meaning naturally through resemblance to something in the world or figures of depiction. Another type of element is a schematic pictorial device, such as brackets or frames or lines, which convey meaning naturally through resemblance to physical objects that contain or link. Spatial relations convey meaning naturally by using spatial distance to represent distance on some abstract relation. Ancient graphic creations as well as recent inventions by children and professionals often spontaneously adopt these metaphoric and analogic uses of space and the things in it. People have rich experience observing and interacting with the physical world, and consequently extensive knowledge about the appearance and behavior of things in it. It is natural for this concrete experience and knowledge to serve as a basis for pictorial, verbal, and gestural expression.

This review suggests a perhaps deceptively simple maxim: use spatial elements and relations naturally. Naturalness is found in natural correspondences, "figures of depiction," physical analogs, and spatial metaphors, derived from extensive human experience with the concrete world. It is revealed in language and in gesture as well as in a long history of graphic inventions.

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