Lines, Blobs, Crosses, and Arrows:

Diagrammatic Communication with Schematic Figures

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Abstract. In producing diagrams for a variety of contexts, people use a small set of schematic figures to convey certain context specific concepts, where the forms themselves suggest meanings. These same schematic figures are interpreted appropriately in context. Three examples will support these conclusions: lines, crosses, and blobs in sketch maps; bars and lines in graphs; and arrows in diagrams of complex systems.

1 Some Ways that Graphics Communicate

Graphics of various kinds have been used all over the world to communicate, preceding written language. Trail markers on trees, tallies on bones, calendars on stellae, love letters on birch bark, maps on stone, and paintings in caves are some of the many remnants of graphic communications. Many graphics appear to convey meaning less arbitrarily than symbols, using a number of spatial and pictorial devices. Maps are a prime example, where graphic space is used to represent real space. Graphic space can also be used metaphorically to represent abstract spaces. Even young children readily use space to express orderings of quantity and preference (Tversky, Kugelmass, and Winter, 1991). Space can be used to convey meanings at different levels of precision. The weakest level, the categorical level, uses space to separate entities into groups, such as lists of players on two baseball teams or, in writing, the letters belonging to different words. Greater precision is needed for ordinal uses of space, as in listing restaurants in order of preference or children in order of birth. Often, the distances between elements as well as their order is indicated, as in the events of history or the skill of athletes where the differences between events or athletes are meaningful in addition to the ordering between them.

Space is not the only graphic device that readily conveys meaning. The elements in space do so as well. Many elements bear resemblance to the things they convey. Both ancient and modern examples abound. Ideographic languages conveyed things, beings, and even actions through schematic representations of them, just as airport signs and computer icons do today. Ideograms and icons also represent through figures of depiction, concrete sketches of concrete things that are parts of or associated with what is to be conveyed, as a scepter to indicate a king or scissors to indicate delete.

2 Meaningful Graphic Forms

Our recent work on diagrams suggests another kind of element that readily conveys meaning in graphics, more abstract than sketches of things and beings, yet more concrete than arbitrary symbols like letters. In his self-proclaimed, but also generally recognized, "authoritative guide to international graphic symbols," Dreyfuss (1984) organized graphic symbols by content, such as traffic, geography, music, and engineering. But Dreyfuss also organized symbols by graphic form, notably circle, ellipse, square, blob, line, arrow, and cross, all in all, only 14 of them, some with slight variants. These graphic forms appear in a number of different contexts, with meanings varying appropriately. Circles, for example, represent gauges, plates, warnings, and nodes, among other things. Lines stand for barriers, piers, railroads, streets, limits, boundaries, divisions, and more. We will call this class of graphic forms that readily convey more abstract meanings "meaningful graphic forms."

Why only a dozen or so forms, and why these forms? One characteric of these forms is their relative simplicity. They are abstractions, schematizations, without individuating features. They have a useful level of ambiguity. As such, they can stand for a wide variety of more specialized, more individuated forms. A circle can stand for closed spaces of varying shapes, two- or three-dimensional. When the individuating features are removed from a closed form, something like a circle is left. A line can stand for a one-dimensional path or a planar barrier, of varying contours. When the individuating features are removed from a path, something like a line remains. A cross can represent the intersection of two lines. These abstract forms can take on more particular meanings in specific contexts. Using them seems to indicate that either the individuating feature omitted are not relevant or that the context can supply them. In many cases, the forms themselves are embellished with more individuating features, especially when similar forms appear in the same context.

Another perspective is to regard graph readers as implicit mathematicians in interpreting depictions. In other words, they interpret the primitive shapes in terms of their mathematical properties. A circle is (a) the simplest, and (b) the most efficient form (shortest path) that encloses an area of a given size. Thus interpreting a circle in a diagram invites the inference that nothing more is to be specified than that it depicts a closed area. A blob departs from simplicity and efficiency in an unsystematic fashion. Thus, it invites the additional inference that the area depicted is not a circle or other systematic shape. Similarly, a straight line is the simplest and most efficient form connecting two points. Thus using the thinnest reasonable line invites the inference that an edge is indicated rather than an area, and making it straight invites the inference that nothing more is to be specified than that the ends are connected/related. A squiggle departs from simplicity and efficiency in an unsystematic fashion. Thus it invites the additional inference that the area depicted is not a straight line or other systematic shape.

These schematic forms, then, seem to depict abstractions, as if denoting concepts such as closed form or path. Yet they are not arbitrary symbols like the word concepts they loosely correspond to. Rather their very forms suggest those more general concepts. A circle is a closed form, and something like a circle would be obtained from averaging shapes of many closed forms. Similarly, a line is extended in one-dimension or on a plane, and something like a line would be obtained from averaging many one-dimensional or planar extensions.

3 Sketching Route Maps: Lines, Curves, Crosses, and Blobs

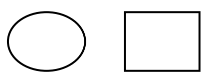
Depictive Element	Use in Diagram	Descriptive Element
	landmark	name of building or path
	straight path	"go down"
	curved path	"follow around"
	various intersections	"turn," "take a," "make a"

Fig. 1: Core Elements of Route Depictions and Descriptions

The sketch maps that people provide when asked to give directions to some destination look quite different from regional maps. Like route descriptions, route maps provide only the information needed to get from point A to point B, eliminating information extraneous to that goal. Tversky and Lee (1998, 1999) stopped students outside a dormitory and asked if they knew how to get to a nearby fast-food restaurant. If they responded affirmatively, they were asked to sketch a map or write directions to the place. The maps and directions they produced were analyzed according to a scheme developed by Denis (1997) for segmenting route directions. For both route maps and route directions, a small number of elements were used repeatedly by most participants. Moreover, these elements mapped onto one another. See Figure 1 for the map elements and the corresponding discourse elements.

The primary elements of route maps seem to be landmarks, paths, and intersections. Although the landmarks varied in size and shape, they tended to be represented by blobs, circle-like closed contours of indistinguishable shapes. Presumably, such blobs are intended to convey that there is a striker, but that the exact form of the structure is not important. Although the streets varied in curvature, they were represented by either a straight line or a curved one. Again, the exact curvature does not seem to be an issue. Interestingly, the verbal descriptions made a two-way distinction as well. The straight lines corresponded to "go down," whereas the curved lines corresponded to "follow around" in the descriptions. A similar phenomenon occurred for intersections. They tended to be portray as crosses or partial crosses (T's, L's) depending on the number of streets in the intersection. However, the angle of the intersection was not reliably represented.

The depictions, then, schematized information about shapes of structures, curvatures of paths, and angles of intersections. Although the depictions had the potential to represent the spatial elements in an analog fashion, they did not. In fact, the depictions made very few, if any, critical spatial distinctions that were not made in the descriptions, a symbolic rather than spatial medium. On the whole, the depictions and the descriptions represented the same spatial elements and made the same distinctions among them. This suggested to us that it might be feasible to translate automatically between route depictions and descriptions. As a start in that direction, we gave participants either depictive or descriptive tool kits, containing the basic elements of the route directions. We also gave them a large set of routes, spanning large and small distances, complex and simple paths, and told them to use the tool kit to construction directions for them, supplementing the tool kits wherever necessary. In fact, for the vast majority of cases, the tool kits were sufficient, suggesting that the semantic elements frequently used in route directions and route maps are the essential elements for representing known routes.

4 Graphing Data: Bars and Lines

Line and bar graphs are the most frequent visualizations of data in popular as well as technical publications (Zacks, Levy, Tversky, and Schiano, in press). In many cases, they are used as if equivalent, though the purists insist on lines for only continuous variables and bars for discrete variables. By contrast, people—college students, that is—use bars and lines consistently but according to a different principle. Bars are closed forms and can be viewed as containers; they enclose one kind of thing, separating that kind of thing from other kinds of things, which may be in another bar. Lines, on the other hand, can be viewed as paths or connectors. Since bars contain and separate, it seems natural for them to convey discrete relationships. And since lines form paths and connect separate entities, it seems natural for them to convey trends.

To establish whether people associate bars with discrete comparisons and lines with trends, we ran two kinds of experiments: interpretation and production. In the interpretation experiments, students were shown line or bar graphs of height as a function of either a discrete variable, men or women, or as a function of a continuous variable, age 10 or 12 years (Zacks and Tversky, 1999). Examples of the graphs appear in Figure 2.

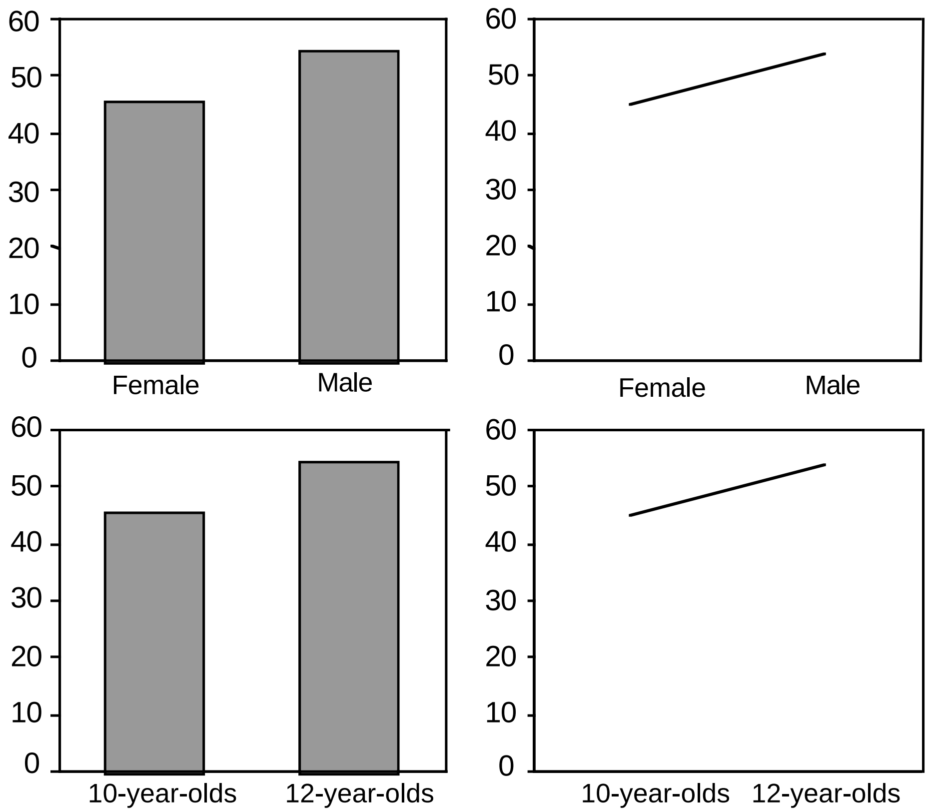


Fig. 2: Y-axes show *height* in inches. Bar and line graphs are presented to students for interpretations (Zacks and Tversky, 1999).

In fact, both the form of the depiction and the nature of the independent variable affected people’s interpretations of line and bar graphs, but, surprisingly, the effect of form of depiction was greater. As determined by blind coders, bar graphs elicited proportionately more discrete comparisons. Some discrete comparisons were: “male’s height is higher than that of female’s” and “twelve year olds are taller than ten year olds.” Similarly, line graphs elicited more descriptions of trends, such as: “height increases from women to men,” “height increases with age,” and even, “the more male a person is, the taller he/she is".

As before, descriptions of the relationships played a larger role in the graphic form selected than the nature of the underlying variable. When presented with a discrete comparison, such as "height for males (12 year olds) is greater than height for females (10 year olds)," students tended to construct bar graphs. However, when presented with a description of a trend such as "height increases from females (10 year olds) to males (12 year olds)," students tended to construct line graphs.

Lines and closed figures, namely bars, have readily available interpretations in the context of graphs, as trends or as discrete comparisons. These interpretations stand in sharp contrast to the interpretations lines and closed figures would be given in the context of other graphic forms, such as maps. In maps, lines are interpreted as and produced for roads or boundaries and closed figures are interpreted as or produced for structures.

5 Diagramming Complex Systems: Arrows

The early uses of arrows in diagrams remain obscure, but they did appear in diagrams to indicate direction of movement by the 18th century (e. g., Gombrich, 1990). There seem to be at least two physical analogs for arrows that indicate directionality. One is the arrow shot from a bow. The second is the arrow-like junctures that occur as liquid flows downhill (Tversky, in press). Inferring direction from arrows seems like a small leap. Similarly, it seems a small leap to infer temporal direction from spatial direction. After all, much of the way we talk about time comes from the way we talk about space (e. g., Clark, 1973; Lakoff and Johnson, 1980). Yet a more abstract but related use of arrows is in the sense of implication as in logic and in the sense of causality as in diagrams. Indeed, temporal necessity is often regarded as a prerequisite for causal necessity. Philosophy aside, Michotte (1963) has elegantly demonstrated that people readily make inferences from appropriate temporal relations to causal ones. One dot moves next to another; if the second dot moves quickly in the same direction, the first dot is seen as "launching" or causing the movement of the second dot, much like billiard balls. Arrows, then, seem well designed to indicate direction in space, time, and causality.

Uses of arrows have not been restricted to direction in space and time. In his extensive survey of diagrams, Horn (1998) counted 250 meanings for arrows, including and metaphoric uses, such as increases and decreases. Mapping increases to upward arrows and decreases to downward arrows is cognitively compelling. Increasing quantities make higher piles, piles that go upwards.

Diagrams of complex systems, such as those in Figures 3, 4, and 5, are common in textbooks and in instructions for their operation.

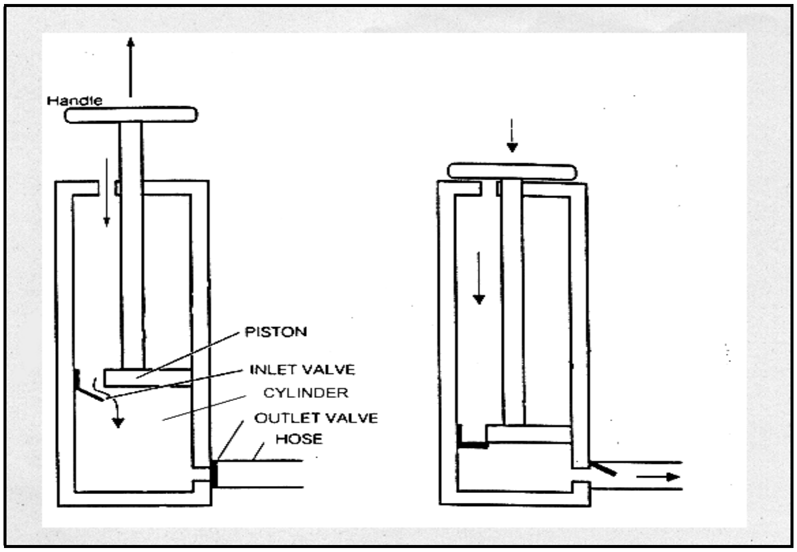


Fig. 3: Diagram of bicycle pump with arrows

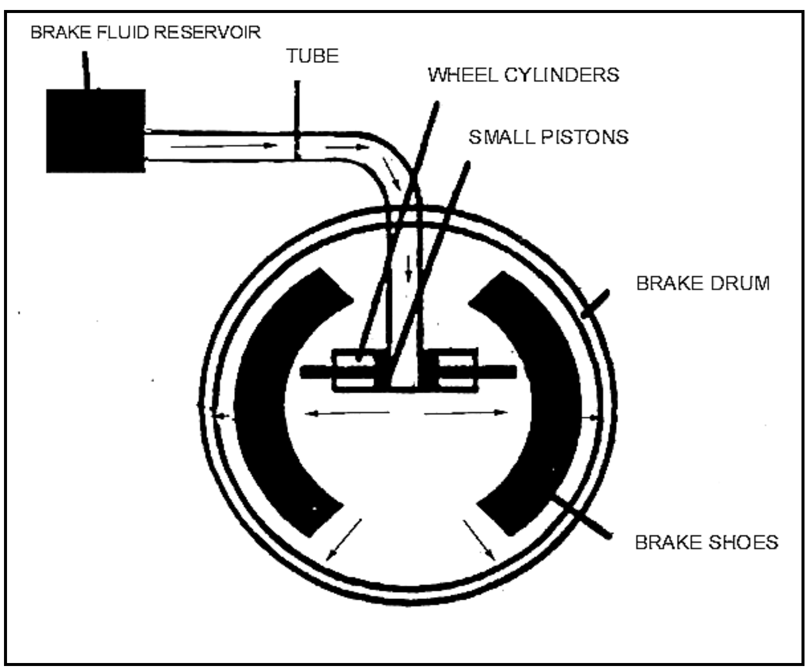


Fig. 4: Diagram of a car brake with arrows

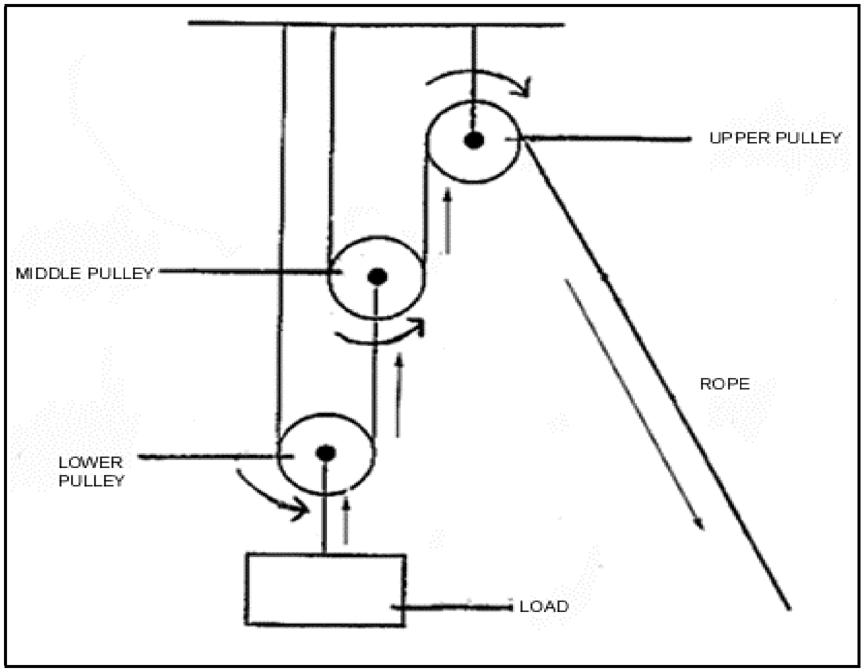


Fig. 5: Diagram of a pulley system with arrows

Note that each of these diagrams contain arrows. The arrows function to show the route and sequence of events in the operation of the system. Without the arrows, the diagrams primarily illustrate the structure of the systems; that is, what the parts are and how they are spatially interrelated. With the arrows, and some mechanical knowledge, the temporal sequence of events in the operation is more apparent. Together with the structure, the temporal sequence of events is a strong clue to the functioning of the system. Put differently, from the temporal sequence, combined with general knowledge, the causal chain of events in the operation of the system can be inferred.

How are arrows used in the interpretation of diagrams? The previous analysis suggests that the presence of arrows should encourage causal, functional interpretations of the diagrams whereas the absence of arrows should encourage structural descriptions of the diagrams. To ascertain the effects of arrows in diagrams, Heiser and Tversky (in preparation) presented one of the three diagrams either with or without arrows to undergraduates. We asked them to examine the diagram and write a description of it. The descriptions were coded without knowledge of diagram condition. Students who observed diagrams with arrows included nearly twice as much functional information as students who saw diagrams without arrows. Conversely, students who saw diagrams without arrows included more than twice the structural information as students who saw diagrams with arrows. For example, one participant who saw a diagram of the bicycle pump without arrows wrote a primarily structural description: "I see a picture of some type of machine or tool that has many different parts which are called handle, piston, inlet valve, outlet valve, and hose. Also the diagram shows a similar tool or machine but the parts are not labeled and are in different positions than the machine on the left. Contrast this with another participant's description of a pulley system, depicted with arrows: "By pulling the rope, which is part of the upper pulley, the clockwise motion of the upper pulley causes the middle pulley to move counter-clockwise. The lower pulley also moves counterclockwise and lifts the load. All the pulleys are connected by the same rope." Or this description of the bicycle pump, by a participant who saw a diagram with arrows: "Pushing down on the handle pushes the piston down on the inlet valve which compresses the air in the pump, causing it to rush through the hose."

Complementary findings were obtained when students were given descriptions of systems and asked to produce diagrams. The descriptions of the bicycle pump, car brake, or pulley system were either structural, that is, they described the parts and their spatial interconnections, or functional, that is, they described the causal sequence of events in the operation of the system. Students who read functional descriptions were more likely to include arrows in their diagrams than students who read structural descriptions.

6 Meaningful Graphic Forms Again

Arrows, then, join the class of diagrammatic forms that readily convey a restricted set of meanings in context. Those meanings seem to derive in part from the graphic form and in part from the context. The forms of enclosed figures like blobs, circles and bars, of lines, of crosses, and of arrows suggest certain physical properties that have cognitively compelling conceptual interpretations. Enclosed figures suggest the possibility of containing certain elements, separating those elements from others. Correspondingly, we have found that people interpret and produce bar graphs for discrete comparisons between variables. Closed figures also suggest two- or three-dimensional objects whose actual shapes are irrelevant, thus schematized. This was revealed in their use to represent landmark structures in sketch maps. Lines suggest connectors, as seen in their interpretation and production for trends in data as well as their use to represent roads and paths in sketch maps. Crosses suggest points where paths intersect, also revealed in sketch maps. Finally, arrows suggest asymmetry, direction, in space, in time, in motion, in causality. Consonant with this, arrows in diagrams encouraged causal, functional interpretations of the systems depicted. Conversely, diagrams of causal, functional descriptions of systems were more likely to contain arrows than diagrams of structural descriptions of the same systems. The graphic forms suggest a class of possible meanings; more precise meanings are developed in specific contexts.

7 In Sum

Diagrams are often composed of schematic figures that serve as graphical primitives. A figure communicates meaning beyond that given by its' location in the diagram and beyond the local conventions established by the diagram. That is, schematic figures carry semantic weight. In sketch maps, blobs, straight lines, curved lines, and crosses are used systematically to convey information about geographical features. In graphs, bars indicate discrete comparisons while lines indicate trends. In mechanical diagrams, arrows signify order of functional operation. In each case, the meaning of the diagram as a whole is conditioned on the individual elements' ability to convey meaning on their own.

Diagrams seem especially suited to conveying a broad array of concepts and conceptual relations. They use characteristics of elements and the spatial arrays among them to convey meanings, concrete and abstract. Abstract meanings are metaphorically based on the concrete ones. Just as spatial language has been adopted to express abstractions, so space and the elements in it readily express abstractions. One reason that diagrams are useful is that they provide cognitively appealing ways of mapping elements and relations that are not inherently visual or spatial. Yet another reason that diagrams are useful is that they capitalize on the efficient methods people have for processing spatial and visual information.

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