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Arrows in Comprehending and Producing Mechanical Diagrams

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Abstract

Mechanical systems have *structural* organizations—parts, and their relations—and *functional* organizations—temporal, dynamic, and causal processes—which can be explained using text or diagrams. Two experiments illustrate the role of arrows in diagrams of mechanical systems. In Experiment 1, people described diagrams with or without arrows, interpreting diagrams without arrows as conveying structural information and diagrams with arrows as conveying functional information. In Experiment 2, people produced sketches of mechanical systems from structural or functional descriptions. People spontaneously used arrows to indicate functional processes in diagrams. Arrows can play a powerful role in augmenting structural diagrams to convey dynamic, causal, or functional information.

Ketwords: Arrows; Diagrams; Diagrammatic reasoning; Mechanical knowledge

1. Introduction

Diagrams have been used for millennia to convey information in myriad domains, from everyday and ancient depictions of geography and cultivation to modern sophisticated visualizations of protein structure and rocket design. Developing principles for designing effective diagrams has been a concern of graphic designers (e.g., Horn, 1998; Mijksenaar & Westentorp, 1999; Tufte, 1983, 1990, 1997), cognitive scientists (e.g., Carswell & Wickens, 1990; Kieras & Bovair, 1984; Kosslyn, 1994; Larkin & Simon, 1987; Narayanan & Hegarty, 1998; Novick, 2001; Pinker, 1990; Stenning & Oberlander, 1995; Tversky, 1995, 2001; Tversky et al., in press), statisticians (e.g., Cleveland, 1985; Wainer, 1984; Wilkinson, 1999), semioticians (Bertin, 1983; McCloud, 1994), computer scientists (e.g., Card, Mackinlay, & Shneiderman, 1999; Glasgow, Narayanan, & Chandrasekeran, 1995; Ware, 2000), classicists (e.g., Netz, 1999; Small, 2003), and educators (e.g., Mayer, 2001; Winn, 1987). Here we focus on diagrams of mechanical systems, a domain of interest in many cognitive, computer, and educational inves-

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tigations (e.g., Hegarty & Just, 1993; Kieras and Bovair, 1984; Mayer & Gallini, 1990). Complex systems have two levels of organization, presenting a challenge for diagram design. Mechanical and other complex systems have a *structural* organization, consisting of parts in a particular arrangement and a *functional* organization consisting of a sequence of actions and events, usually dynamic operations of parts, and their consequences.

Comprehending functional processes is especially difficult for novices, but essential for experts in many domains (e.g., Hmelo-Silver & Pfeffer, 2004; Suwa & Tversky, 1997). We use the term *functiona*l to refer to the sequence of operational steps of the system. Functional explanations may refer to the actions or behavior of the system, as well as the causal outcomes of the behaviors. To the extent that function entails the movement or changes or operations of parts on other parts, function depends on structure. It is not necessary, however, that a mental model of the function of a system include all the parts of a system or refer to the exact arrangement of the parts. Similarly, a mental model of the structure of a system includes the spatial array of the parts but does not typically include the operation of the parts. A mental model of function is needed for understanding the operation of a device, for making inferences, and for solving problems, in short, for expertise (e.g., Kieras & Bovair, 1984).

Diagrams are ideal for conveying structural organization, as they use elements and spatial relations in diagrammatic space to convey elements and spatial or conceptual relations in the system, thereby capitalizing on people's experience interpreting spatial relations (e.g., Larkin & Simon, 1987; Tversky, 1995, 2001). Language is also effective in conveying structure (e.g., Mani & Johnson-Laird, 1982; Taylor & Tversky, 1992)—probably the main reason that well-crafted text is often as effective as diagrams in conveying structure (e.g., Winn, 1987). Diagrams cannot convey function as directly as they can convey structure, simply because depicting function may entail depicting movement, changes of state, forces, goals, and outcomes, all more difficult to portray in static depictions than structure. Text can convey function, but text loses the natural mapping of diagrams from elements and configurations of a system to elements and configurations on paper. To convey function in diagrams requires other means.

How do diagrams convey nonspatial information? Designers use diagrammatic elements to augment structural information. Enriching diagrams with devices that are less iconic to convey ideas not easily depicted is commonplace. Even the most spatial of diagrams, maps, use such devices—for example, elements to signify kinds of sites—archeological, commercial, religious—or shading to indicate altitude or colors to denote legal boundaries. To sketch a route, a goal-directed sequence of turns at landmarks, people superimpose a line on a map. One compelling candidate for conveying change over time, movement, and causality in a diagram is an arrow. Arrows belong to a class of privileged diagrammatic elements, along with lines, boxes, crosses, and circles (Tversky, 2005; Tversky, Zacks, Lee, & Heiser, 2000). These are schematic geometric figures that convey meanings related to their gestalt or geometric properties. For example, lines, as used in route maps, graphs, networks, and flowcharts, link or associate. They signify that a relation exists between the entities they link. Arrows can link as well, but they are asymmetric, indicating an asymmetric relation. Arrows can express many relations, among them pointing or connecting, sequence, change over time, path, or manner of movement or forces, and more (e.g., Horn, 1998; Tversky et al., 2000). In the case of maps, arrows indicate the direction of the route, the sequence of actions required to reach the destination. In the case of diagrams of complex systems, arrows can be used to indicate temporal sequence, the order of the operation of the components to accomplish the overall goal of the system. Arrows can also show aspects of motion. It is noteworthy that all of these concepts, and more, require separate words, but can be expressed by a single graphic device, an arrow. Because diagrams of complex systems readily convey structure, but not function, enriching them to convey function effectively is desirable.

Diagrams are frequently used to supplement text in teaching complex systems. Illustrations that focus learners on the key elements of devices such as a bike pump or car brake benefit learners; combinations of text and labeled illustrations improved performance on problem solving (Mayer, 1989). To investigate formats that might promote construction of mental models of systems, Mayer and Gallini (1990) compared three types of diagrams, those portraying the parts of the system, the steps of the system, or both the parts and the steps. Benefits of the diagrams depended on the prior knowledge of the learner. For students high in prior knowledge, none of the diagrams improved recall or transfer performance. For students with low prior knowledge, only the diagrams with both parts and steps were helpful. However, the steps diagram used arrows as well as added text to explain the process of the system. Thus, this design cannot isolate the role or aspects of diagrams per se in promoting mental models of the systems. In a study comparing text, diagrams, or both in conveying a pulley system, Hegarty and Just (1993) found that either text or diagram was sufficient to comprehend the configuration of the system, but the conjunction of text and diagram was needed to understand the processes involved in a pulley system. Altogether, understanding system process or function or kinematics has proved to be harder than understanding configuration. The studies reviewed found that both text and diagrams are helpful, but this could be because function has typically been conveyed only by text (e.g., Hegarty & Just, 1993; Hegarty & Sims, 1994).

How does language convey structure and function? Consider a structural description of a bicycle pump: "The bicycle pump is a tall cylinder with a handle extending from the top that can move up and down. Attached to the bottom of the handle in the middle of the cylinder is the piston. Next to the piston is the inlet valve that can open and close. Below the inlet valve is the chamber. Extending outward from the chamber at the bottom is the outlet hose. Between the chamber and the hose is the outlet valve, which can open and close." Now compare this to the functional description of the car brake: "From the brake fluid reservoir, brake fluid enters and travels sideways and down the tube. As the brake fluid accumulates at the bottom of the tube in the center of the brake, pressure is exerted on the small pistons inside the wheel cylinders which extend sideways from both sides of the tube. This causes the pistons to push outwards, exerting pressure on the brake shoes. The brake shoes then move outward toward the brake drum. The outward movement of the brake shoes causes friction along the inside of the brake drum, slowing the rotation of the wheel." The major distinction is the verbs. Functional descriptions are dynamic; as such, they are similar to route descriptions of environments and tend to use verbs of motion and transitive verbs, such as *enter, open, close,* and *travel.* Functional descriptions also include verbs that express outcomes and causes, such as *accumulates, exerted, push, slow,* and even *causes.* Not only do these verbs directly describe function, they are also likely to be the verbs used in testing knowledge of systems.

Here we investigate how depictions and descriptions convey structure and function of complex systems. From the work of others, we chose three mechanical systems: a car brake, a bicycle pump, and a pulley system (e.g., Hegarty, 1992; Mayer, 1989). For the learner, what is critical is the nature of mental models engendered by diagrams with different formats and text with different perspectives. In the first experiment, we ask whether adding arrows to structural diagrams changes the way they are interpreted. In the second experiment, we examine whether the perspective of the text, structural or functional, affects the diagrams participants produce.

2. Experiment 1: Describing diagrams with and without arrows

2.1. Participants and design

Participants were 80 students in an introductory psychology course at Stanford University, fulfilling a course requirement. Thirteen participants did not complete the questionnaire, leaving 67 participants. Thirty-four participants described diagrams without arrows. Of those participants, 8 described a car brake, 14 described a bicycle pump, and 12 described a pulley system (see Fig. 1 for example of car brake diagram). Thirty-three participants described diagrams with arrows; 8 described a car brake, 12 described a bicycle pump, and 13 described a pulley system.

2.2. Procedure

Participants were given a single piece of paper (8.5 × 11 in.) with one of three diagrams; a car brake, bicycle pump, or a pulley system. These diagrams either included arrows indicating the temporal sequence of the system or did not include arrows. Below the diagram was the instruction, “Please examine the diagram above. On the lines below, write a description of the

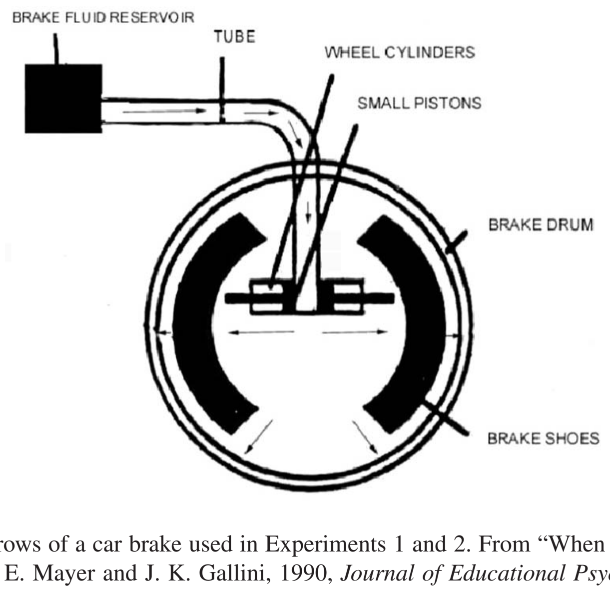

Fig. 1. Diagram with arrows of a car brake used in Experiments 1 and 2. From “When is an illustration worth a thousand words?” by R. E. Mayer and J. K. Gallini, 1990, *Journal of Educational Psychology, 82,* p. 715–726. Copyright 1990 by the American Psychological Association. Adapted with permission.

system in the diagram." Participants were also asked to rate their mechanical ability on a 1 to 7 scale (1 = *poor,* 7 = *excellent*). In addition, they were asked to rate their prior specific knowledge of the mechanical system being portrayed in the diagram on the same scale. They were instructed to spend approximately 3 to 5 min on the entire task.

2.3. Coding descriptions

Descriptions of diagrams were coded blindly. Two coders first divided statements into propositions, that is, the smallest unit of meaning in a sentence, and then decided whether those propositions described the structure or the function of the mechanism. Descriptions of the system structure or explanations of the features of the components (i.e., the shape of a part) counted as structural information. Descriptions of the operations of the system, the causal consequences of operations, the function of individual parts, or the way the parts work together, counted as functional information. For example, in the sentence, "The liquid brake fluid travels down the tube" there are two propositions: "The brake fluid is liquid" and "The brake fluid travels down the tube." The first is structural and the second functional. Furthermore, the functional units were coded as describing the motion of parts or causal sequences. Coders agreed 94%, and the disagreements were settled through discussion. Distinguishing propositions referring to motion or behavior from those referring to causes did not prove useful. As the functional description of the car brake illustrates, descriptions of actions or operations and causal consequences are typically interleaved in functional descriptions. This was complemented by an objective coding of the verbs as passive, *to be,* or transitive.

2.4. Results

As predicted, participants who described diagrams with arrows produced significantly more functional units ($M = 2.24$, $SD = 1.3$) than participants who described diagrams without arrows ($M = 1.26$, $SD = 1.1$), $F(1, 61) = 10.9$, $p < .01$. Similarly, participants who described diagrams without arrows generated significantly more structural units ($M = 1.65$, $SD = 1.65$) than those who described diagrams with arrows ($M = .52$, $SD = .62$), $F(1, 61) = 13.67$, $p < .01$ (see Fig. 2). As expected, the finer coding of the functional units (motion, causality) did not reveal any additional significant differences. There were also no main effects or interactions of diagram content, self-rated ability, or total number of propositions across conditions.

Converging evidence was found in a count of the verbs types that were used in the descriptions. Participants describing diagrams without arrows should use structural predicates, specifically, more forms of the verb "to be," whereas those describing diagrams with arrows should use more action predicates, specifically, verbs of motion and causation, such as *push, lift,* or *travels.* This hypothesis was confirmed. Descriptions from the no-arrow condition contained significantly more static expressions using forms of the verb *to be* ($M = 1.87$, $SD = 1.86$) than descriptions from the arrow condition ($M = .84$, $SD = .95$), $F(1, 81) = 10.496$, $p < .01$. Furthermore, descriptions from the arrow condition contained significantly more active expressions using motion, action, and cause verbs ($M = 3.26$, $SD = 2.07$) than descriptions in the no-arrow condition ($M = 1.78$, $SD = 1.35$), $F(1, 81) = 14.66$, $p < .01$.

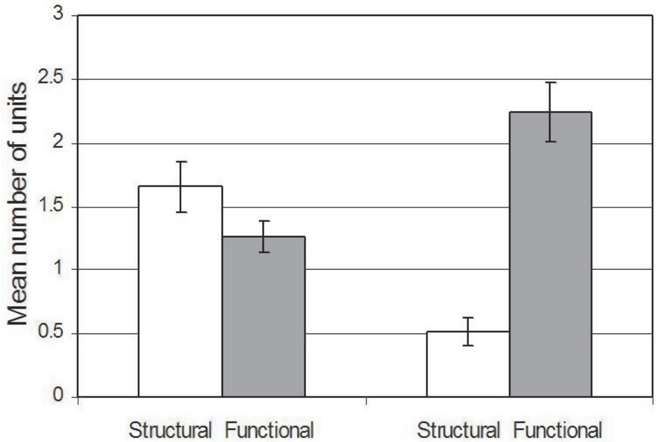

Fig. 2. Mean number of structural and functional units per description of diagrams with and without arrows (Experiment 1).

2.5. Discussion: Comprehending diagrams

When asked to describe diagrams of a car brake, bike pump, or pulley system, participants' produced primarily structural descriptions. When arrows were added to the diagrams, descriptions were primarily functional. Arrows imposed on the structure of a mechanical system effectively convey the order of operations of the system, which people interpret as intending to convey how the system works. Arrows can also signal the direction, path, and manner of motion and, hence, the operation of the device. Without arrows, diagrams suggest the structural configuration of the device. As expected, the language of structural and functional descriptions differed. Structural descriptions used more static verbs, especially forms of *to be,* whereas functional descriptions used more transitive verbs and verbs of motion and cause.

3. Experiment 2: Producing diagrams from structural or functional descriptions

People interpret diagrams without arrows primarily structurally and diagrams with arrows primarily functionally. Will this correspondence hold for the mirror-image task, producing diagrams from text that is structural or functional? In this experiment, participants read a structural or functional description of one of the three systems. They were asked to sketch a diagram of the described system.

3.1. Participants and design

Two hundred forty students in an introductory psychology course at Stanford University participated for course credit. Forty-four participants either did not draw a diagram or did not complete the questionnaire, leaving 93 participants in the functional description group and 103 in the structural description group, distributed fairly evenly across the three systems.

3.1.1. Stimuli

Structural and functional descriptions were written for each of the three systems—car brake, bicycle pump, and pulley system. Descriptions of the car brake appear in Table 1. Structural descriptions contain details of parts and their spatial relations, primarily using forms of the verb *to be* or verbs of fictive motion. Functional descriptions contain actions and consequences primarily using active verbs of motion.

3.2. Procedure

Participants were given a single piece of paper (8.5 × 11 in.) with one of three descriptions, appropriately labeled at the top of the page. Participants were asked to both rate their mechanical ability on a 1 to 7 scale (1 = *poor,* 7 = *excellent*) and rate their specific knowledge of the mechanical system conveyed in the description on the same scale. Participants were then asked to "Please read the following description. In the space provided below the description, please construct a diagram of what you think the description is trying to convey." They were instructed to spend approximately 3 to 5 min on this exercise.

3.3. Coding

Two independent coders coded the diagrams for conventional diagrammatic elements that were used to augment the depictions. These were primarily arrows and lines. The number of arrows and lines, in addition to the placement (inside or outside the diagram) and function (labeling, sequence, motion) were coded. There were no disagreements in coding (see Figs. 3 and 4).

Table 1
Example of car brake descriptions used in Experiment 2

Car Brake Structural Description
The brake or brake drum is a circular structure. Directly inside the sides of the brake drum are two thick semicircular structures called the brake shoes. The brake fluid reservoir is located above and to the side of the brake drum. From the brake fluid reservoir, a tube runs down sideways and then down to the middle of the brake drum. Extending from both sides of the tube in the middle of the brake drum are wheel cylinders surrounding small pistons. Brake fluid can move from the reservoir through the tube to the pistons. The small pistons can move outward toward the brake shoes. The brake shoes can move outward toward the brake drum.
Car Brake Functional Description
From the brake fluid reservoir, brake fluid enters and travels sideways and down the tube. As the brake fluid accumulates at the bottom of the tube, pressure is exerted on the small pistons inside the wheel cylinders. This causes the pistons to push outward toward the brake drum. The outward movement of the shoes causes friction along the inside of the brake drum, slowing the rotation of the wheel.

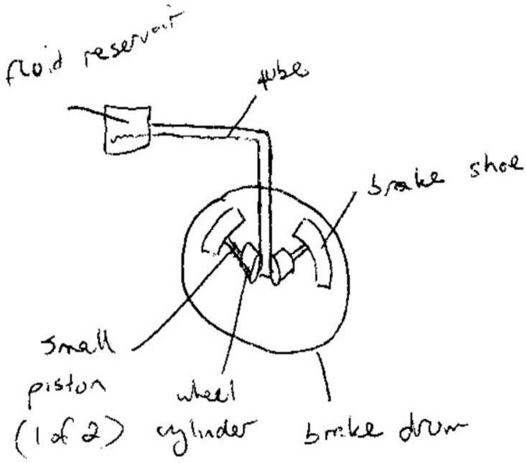

Fig. 3. A participant's sketch of a diagram from a structural description of a car brake in Experiment 2.

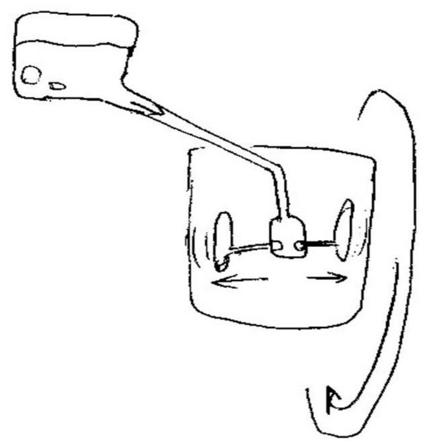

Fig. 4. A participant's sketch of a diagram from a functional description of a car brake in Experiment 2.

3.4. Results

Of the 196 depictions coded, the primary graphical element participants added to depictions were arrows. The arrows appeared to indicate direction of motion of the mechanical system. As predicted, 62/93 (66.7%) of participants who depicted functional descriptions used arrows in their depiction to indicate direction of operation, whereas only 16/103 (15.5%) of participants who depicted structural descriptions included arrows $\chi^2(1, N = 196) = 9, p < .01$; see Table 2. All 16 who included arrows in depictions from structural descriptions were high-ability participants. Sixty-eight participants, 38 who read structural descriptions and 30 who read functional descriptions, added lines to their diagrams to label parts.

Table 2
Number of participants producing diagrams with and without arrows for structural and functional descriptions (Experiment 2)

	Description			
	Structural		Functional	
Arrows in Depiction	*n*	%	*n*	%
No arrows	87	84.5	31	33.3
Arrows	16	15.5	62	66.7
Totals	103	100	93	100

3.5. Discussion: Communicating with diagrams

Here, participants produced diagrams from either structural or functional descriptions of mechanical systems. Mirroring the previous experiment, participants produced diagrams without arrows for structural descriptions and diagrams with arrows for functional descriptions. This corroborates the communicative role of arrows in augmenting structural diagrams to convey function.

4. General discussion

Diagrams use a mixture of devices to communicate. Effective diagrams map elements and spatial relations from the information to be conveyed to elements and spatial relations in the diagram in a cognitively compelling way. Diagrammatic elements can resemble or be associated with the things they represent as in file folders, trash cans, and scissors in computer interfaces. Proximity in diagrams is used to convey proximity on concrete and on abstract dimensions. Diagrams take advantage of human experience making spatial inferences (e.g., Larkin & Simon, 1987; Pinker, 1990; Tversky, 1995). But not all information can be portrayed in this way, so diagrams are often supplemented with text as well as other depictive devices.

Diagrams are particularly appropriate for conveying the structure of complex systems, whether concrete, such as a car brake, or abstract, such as a corporate organization. They use space in diagrams to convey space in a device or system. Function—behavior, action, or causal relations—however, is not readily apparent from a diagram as it depends on a sequence of actions and consequences. Arrows can be added to static structural diagrams to convey function. Experiments 1 and 2 showed that people readily interpret and produce arrows in diagrams to suggest functional properties of complex systems. For car brakes, bicycle pumps, and pulley systems, diagrams without arrows elicited structural descriptions. Conversely, for structural descriptions participants drew diagrams without arrows, but for functional descriptions they drew diagrams with arrows.

The efficacy of arrows in visual communication has implications for the design of diagrams for educational as well as practical uses. One implication is that arrows added to diagrams will be readily interpreted as conveying change, movement, or causality. Using arrows is one of several cognitive design principles that have been developed to apply to algorithms for generating individual diagrams on demand. Computer generation of diagrams is a boon where costs of preparing individual diagrams are high. One project developed cognitive design principles for diagrams for object assembly, informed by experiments that elicited mental models of assembly as well as diagrammatic techniques. A final experiment compared the instructions that came with the object to those of the computer algorithm, which incorporated cognitive design principles, including the use of arrows. Participants using the computer-generated diagrams assembled more efficiently than those using the instructions that came with the object (Heiser, Phan, Agrawala, Tversky, & Hanrahan, 2004).

Arrows belong to a special class of noniconic devices added to maps and other diagrams, schematic figures that have meanings suggested by their geometric forms and gestalt properties, meanings that are general but more refined and interpretable in contexts (Tversky et al., 2000). These include lines in maps, trees, and statistical graphs. Consider the simple line. Lines are one-dimensional; they connect, suggesting a relation. Now consider how lines are used. In maps, they can indicate roads between landmarks; in trees, superset–subset relations; and in statistical graphs, functional relations. These graphic devices are similar to words such as *line, relation,* and *field.* Such words have a multitude of senses, which context disambiguates. An arrow is an asymmetric line, suggesting an asymmetric relation. The arrowhead indicates the direction of the relation, much as an arrowhead used in hunting leads the direction of motion and the *V* formed by water going downstream shows the direction of motion of the water. Like lines, arrows can convey different meanings depending on context (although in many scientific diagrams, the specific senses of arrows are not clarified by context; Tversky, Heiser, Lozano, MacKenzie, & Morrison, in press). That arrows are readily interpreted as conveying function was demonstrated in the context of mechanical systems. When arrows were added to structural diagrams, people interpreted the diagrams functionally. Similarly, when asked to diagram descriptions of functions of systems, people used arrows. What is especially significant in the use of arrows in diagrams of complex systems is that they can convey many different relations, some simultaneously. They can indicate the sequence of steps in the operation of a system. They can show the path of motion, as in pulleys, or the direction of the consequences of the mechanics, as in the direction of air in the bicycle pump. Arrows can also indicate the direction of forces, as in the car brake or bicycle pump. In other contexts, arrows can show the manner as well as the path of motion and forces—for example, a bumpy ride in a comic strip or a curved path in a map. Significantly, many different words are needed to convey what this compact bundle of meaning, an arrow, conveys. Interpretations of diagrams with arrows used a subset of these, including *rotates, pushes,* and *raises.*

Diagrammatic elements, such as lines, arrows, bars, blobs, and crosses, have other parallels to linguistic elements. They can be categorical rather than analog. They can be combined. Diagrams enjoy advantages that language does not have. They use space to convey space. They use elements that resemble their referents. They capitalize on expertise in spatial inferences. Diagrams can be enriched to convey nonspatial information and at the same time retain their spatial advantages in comprehension, judgment, and inference. Spatial relations may be metaphorical as well as literal. And elements may be related to their references associatively, through icons of synecdoche and metonymy, and schematically, through abstract geometric figures. In sketch maps, they can simultaneously convey an environment and a route. In mechanical systems, they can show structure and function at the same time. Diagrams can integrate the functional with the structural, and convey both compactly.

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