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CHAPTER 2

PROLEGOMENON TO SCIENTIFIC VISUALIZATIONS

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Abstract. Visualizations are central to many tasks, including instruction, comprehension, and discovery in science. They serve to externalise thought, facilitating memory, information processing, collaboration and other human activities. They use external elements and spatial relations to convey spatial and metaphorically spatial elements and relations. The design of effective visualizations can be improved by insuring that the content and structure of the visualization corresponds to the content and structure of the desired mental representation (Principle of Congruity) and the content and structure of the visualization are readily and correctly perceived and understood (Principle of Apprehension). Visualizations easily convey structure; conveying process or function is more difficult. For conveying process, visualizations are enriched with diagrammatic elements such as lines, bars, and arrows, whose mathematical or abstract properties suggests meanings that are often understood in context. Although animated graphics are widely used to convey process, they are rarely if ever superior to informationally equivalent static graphics. Although animations use change in time to convey change in time, they frequently are too complex to be apprehended. Moreover, because people think of events over time as sequences of discrete steps, animations are not congruent with mental representations. Visualizations, animated or still, should explain, not merely show. Effective visualizations schematize scientific concepts to fit human perception and cognition.

INTRODUCTION

People invent tools to enhance their physical comfort--clothing, shelter, implements for obtaining and preparing food. People are not unique in creating tools for food or shelter. People, however, seem to be unique in creating tools that enhance their mental well-being; they keep track of things by counting on their fingers or on calculators, they remember their ways by notching trees or sketching a route, they convey ways to others by drawing them in the sand or on paper. Altering the external world to facilitate memory, information processing, and communication is ancient, preceding written language. The modern visualizations critical to scientific understanding, explanation, and discovery are an extension of these ancient devices. How do they do their job?

Maps serve as a paradigm, an instructive example. They are ancient and modern, they appear in cultures all over the world, they are created by children and adults, both schooled and unschooled. Effective maps schematize, they are not "realistic." They select the information that is needed for the task at hand, simplifying, even distorting, it to make it more accessible. Roads, for example, are not large enough to appear in many road maps if they were drawn to scale. The zigs

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and zags of crooked roads are simplified. Effective maps omit the information that is not needed, so churches appear in tourist maps but not in maps for drivers, topography appears in maps for hikers but not for drivers. Tourist maps aid sight-seers by presenting impossible perspectives, overviews of roads, frontal view of destinations. Maps typically add information that is not visual, place names, boundaries, distance scales, heights, and depths.

Until the late 18th century, most visualizations conveyed information that was naturally visual, maps, architectural plans, flora and fauna, mechanical devices. Only recently have visualizations been designed to convey concepts that are not inherently visual, such as balance of trade and population growth (Beniger and Robyn, 1978; Tufte, 1983). Two centuries later, most graphs depict what they did when invented, change over time (Cleveland and McGill, 1985). Until recently, most diagrams conveyed only the structure of things, often exquisitely. Depicting how structure changes, that is, how things function, is a more contemporary phenomenon. Witness the paucity of arrows in earlier diagrams and their proliferation now (e. g., Gombrich, 1990; Horn, 1998). Perhaps not coincidentally, arrows entered diagrams to convey motion at about the same time as graphs portraying abstract information. Arrows, as we shall see, readily convey function.

COMMUNICATION: SPATIAL RELATIONS

Maps and other visualizations, like spoken language, are structured; they consist of elements and the spatial relations among them. In maps, the elements may be dots or lines or other shapes meant to be cities or streets or building or countries; the spatial relations on paper reflect the distances and directions among the elements in actual space. Contrast maps with tree diagrams, such as corporate charts or evolutionary trees or linguistic trees. For these, the elements are the nodes, the corporate roles or species of plants or animals or languages. The spatial relations among the elements in a tree are typically not metric distance; rather, they convey order or subset relations among the entities. Thus for visualizations of things not inherently visualizable, the spatial relations stand for abstract relations that are metaphorically spatial.

The spatial relations in visualizations preserve different levels of information from abstract relations. Many bar graphs and tables map only categorical information, for example, the number of cases in each category, as in the numbers of students in each discipline or the numbers of plants of each variety. Trees and some graphs may map abstract relations ordinally, for example, kinds of kinds of kinds or rankings of hues by wave length or risks by fatalities. Finally, visualizations may preserve information at the interval level, where not only the order of elements but also the distances between elements are meaningful, or at the ratio level, where zero, as well as order and interval, are meaningful. Graphs of all sorts are typically used to convey interval and ratio relations.

People seem to spontaneously think about abstract relations in spatial terms. Languages are packed with spatial metaphors, we say we feel *close* to friends or to solving a problem, that a new *field* is *wide open*, that a student is at the *top of the heap*. Not only is spatial distance used to convey abstract distance, but also certain directions, namely the vertical, are loaded. Upwards is used to convey better, more, stronger. Gestures reflect spatial thinking as well, good things get a thumbs up or a high five, bad things get a thumbs down. The space of visualizations conveys meaning in exactly the same way, distance on paper reflects distance on abstract dimensions, and upwards reflects positive dimensions. A survey of common visualizations in science textbooks confirms this (Tversky, 1995). All but one or two of the diagrams of the evolutionary tree had man (yes, *man*) at the top, and those of geologic eras had the present at the top.

The prevalence of spatial metaphors in language and gesture suggests that mapping abstract relations onto spatial ones is natural and spontaneous. Querying children is one way to address this. Children from pre-school through university from three language cultures, English, Hebrew, and Arabic, were asked to place stickers on paper to indicate the meals of the day or various sized containers of candy or books or liked or disliked food and TV shows (Tversky, Kugelmass, and Winter, 1991). These are concepts that can be readily ordered by time or quantity or preference. Would the children order them such on paper? Would their placement of stickers reflect distance on these dimensions? The mappings of stickers to concepts of even the youngest children reflected order on each of these dimensions. However, the mappings reflected distance or interval in only older children. What about direction of the orderings? For quantitative and preference, children of all languages mapped increased left to right, right to left, or bottom to top; they avoided mapping increases downwards. For temporal concepts, direction of increasing value followed direction of writing.

Spontaneous mappings of abstract relations onto space are neither random nor arbitrary. Rather they reflect *meanings* that are consistent across cultures and across age. As shall be seen, meanings of elements are often readily interpretable as well.

COMMUNICATION: ELEMENTS

Icons. Visualizations use elements as well as spatial relations to convey their messages. One time-tested kind of element is an icon, a depiction that resembles the thing that it represents. Written languages all over the world began this way. Not every concept can be depicted, of course. Common in ideographic languages are figures of depiction, such as synecdoche, where a part represents a whole as in the head of a cow to stand for a cow, or metonymy, where a symbol represents a whole as in the staff of office to represent a king or scales to stand for justice. These figures of depiction are as modern as those in computer menus, scissors for delete, a trashcan for eliminating files, a floppy disk (remember those?) for saving files.

Morphograms. Visualizations use another kind of element for conveying meanings, simple schematic, geometric figures, something we termed *morphogram*s. Examples include lines, crosses, arrows, boxes, and blobs. Their geometric forms and Gestalt properties suggest general meanings, which contexts can clarify. Lines are one dimensional, they connect or form paths from one point to another. As such, they suggest a relationship between the points. Arrows are asymmetric lines, suggesting an asymmetric relationship. Blobs are amorphous and two-dimensional, suggesting areas where exact shape is irrelevant. Let us now turn to research illustrating how these are understood in context.

Graphs: Bars and Lines. Bar graphs and line graphs are popular both in scientific and lay publications. They are often used interchangeably, though purists recommend reserving lines for interval data. People's interpretations of the forms of representation are not interchangeable; rather, they depend on geometric properties of the forms (Zacks and Tversky, 1999). Bars are containers; they separate. Lines are links; they connect. Bars for X's and Y's suggest that all the X's share a property and all the Y's share a different property. A line connecting X and Y, however, suggests that X and Y share a dimension but have different values on that dimension.

If people respond to those geometric properties, then their interpretations of data presented as bars should be as discrete comparisons and their interpretations of data presented as lines should be as trends. In fact, when asked to interpret an unlabeled bar graph, people said that there are more Y's than X's or that the Y's are higher than the X's. For unlabeled line graphs, people said that there's an increase from X to Y or a rising trend from X to Y. When the graphs were labelled with continuous variables, such as the height of 10 and 12 year olds, or with discrete variables, such as the height of women and men, the graphic form played a larger role in interpretations than the underlying nature of the data. Some students interpreted a line graph connecting the height of women and men as, "if you get more male, you get taller." Form also overrode content when students were asked to produce graphs from descriptions of data. Students produced bar graphs for data described as discrete comparisons and line graphs for data described as trends. Geometric form and conceptual interpretations of bar and line graphs are tightly linked.

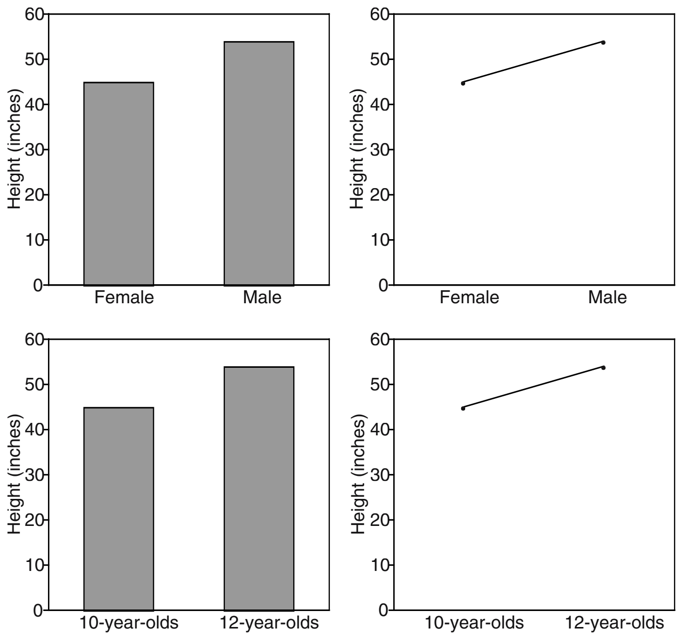

Figure 1. *Examples of bar and line graphs used by Zacks and Tversky (1999).*

Route Maps: Lines, Curves, Crosses, and Blobs. The visual devices of route maps are also tightly linked to linguistic devices. To compare route maps and route descriptions, we asked students outside a dormitory if they knew how to get to a nearby fast-food restaurant. If they did, we asked them to either sketch a map or write directions to get there (Tversky and Lee, 1998). We got a broad range of responses, some long, some short, some overflowing in detail, some crisp and elegant. Underneath the variability, however, was a structure common both to sketch maps and to written directions.

The structure underlying maps and directions extended a scheme developed by Denis (1997) for a large corpus of route directions. He found that directions consisted of strings of segments with four components: a start point, a reorientation, a progression on a path, and an end point. Like Denis' corpus, our corpus of directions consisted of segments with the same four components, though in many cases, some were implicit rather than explicit. For example, if the previous segment ended in an end point, the next segment often began with a reorientation, under the assumption that the end point of one segment served as the start point of the subsequent segment. Sketch maps also consisted of strings of segments with the same components, but the pragmatics of sketch maps, unlike the pragmatics of words, do not allow ellipsis.

Table 1. *Examples of Route Directions - (From Tversky & Lee, 1998)*

DW 9
From Roble parking lot
R onto Santa Theresa
L onto Lagunita (the first stop sign)
L onto Mayfield
L onto Campus drive East
R onto Bowdoin
L onto Stanford Ave.
R onto El Camino
Go down few miles. It's on the right.
BD 10
Go down street toward main campus (where most of the buildings are as opposed to where the fields are) make a right on the first real street (not an entrance to a dorm or anything else). Then make a left on the 2nd street you come to. There should be some buildings on your right (Flo Mo) and parking lot on your left. The street will make a sharp right. Stay on it. That puts you on Mayfield road. The first intersection after the turn will be at Campus drive. Turn left and stay on campus drive until you come to Galvez Street. Turn Right. Go down until you get to El Camino. Turn right (south) and Taco Bell is a few miles down on the right.
BD 3
Go out St. Theresa
Turn Rt.
Follow Campus Dr. way around to Galvez
Turn left on Galvez.
Turn right on El camino.
Go till you see Taco Bell on your Right

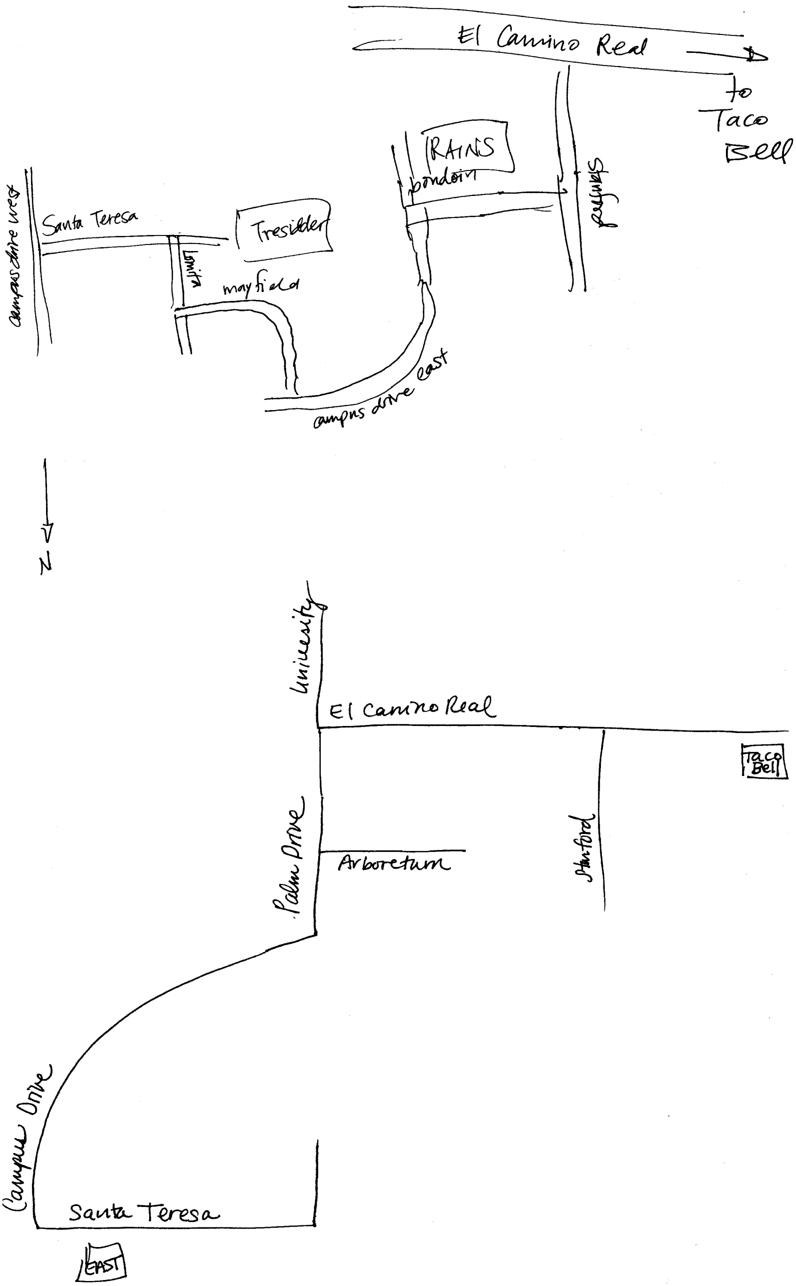

Figure 2. *Sketch maps from Tversky & Lee (1998)*

Although differing in pragmatics, the semantics and syntax of the route descriptions and the route depictions had noticeable correspondences. Start points and end points were landmarks in both, sometimes a street name, sometimes a building, named in directions, depicted by a blob in depictions. Reorientations disregarded amount of turn in both cases. In maps, they were +'s or T's or L's or Y's depending on the actual shape of the intersections. In directions, they were indicated by "take a," "make a," or "turn," followed by "left" or "right." Road shape was either straight or curved in depictions; straight corresponded to "go down" in directions, and curved corresponded to "follow around." It is important to note here that although the route maps could be analog, they were not. In fact, they made the same distinctions that language did for the most part. Similarly, exact distance was not represented in either. Distance in both seemed to reflect complexity. Descriptions got longer for complicated reorientations just as depictions got larger. Long, straight stretches on the highway didn't take space in either depictions or descriptions.

The correspondence between elements of directions and elements of depictions suggest that they both derive from the same underlying cognitive structure. The structure of routes is a sequence of actions at intersections or links and nodes, where exact reorientation and exact distance are not important. Why can this information, which seems critical, be omitted? Most likely because the information is sufficient for the situations in which the directions are used. If the angle of the turn is unspecified or different from the angle in the world, the traveller will follow the road. Similarly, the traveller will reorient when the landmark signifying reorientation appears, irrespective of the distance. In fact, when the distance is long, people indicate that on both maps and directions by adding landmarks along the route that are not associated with reorientations. Significantly, the schematisation apparent in route maps and directions parallels the schematisation of memory (Tversky, 1981). People remember turns as closer to right angles, roads as closer to parallel, roads as straighter than they actually are.

The near sufficiency of these semantic elements was demonstrated in a task in which students were asked to use verbal or pictorial toolkits consisting of these elements to construct a large number of routes, short and long, simple and complex (Tversky and Lee, 1999). They were told that they would probably have to supplement the tool kits with elements of their own design. In fact, most students succeeded in generating verbal and visual directions with only the tool kit provided.

The common underlying structure was instantiated as cognitive design principles to guide development of an algorithm to automatically generate route maps on demand (Agrawala and Stolte, 2001). Users reported vastly preferring these maps to the more typical output from websites, highway maps with routes overlaid. The common underlying structure also raises the possibility of automatic translation between route directions and route maps.

Mechanical Diagrams*:* **Arrows**. Arrows are lines, connectors, but asymmetric ones, so they suggest asymmetric relationships. To assess what arrows communicate, we asked students to interpret diagrams with or without arrows (Heiser and Tversky, 2004). The diagrams were of mechanical systems that would be familiar to students, a bicycle pump (see Figure 3), a car brake, and a pulley system. Each student interpreted a single diagram. The arrows led to striking differences in interpretation for all three systems. When the diagrams had no arrows, students wrote structural descriptions, that is a description of the parts of the system and how the parts were connected. When the diagrams had arrows, they wrote causal, functional descriptions, that is, a description of the sequence of actions of parts and the effects of those actions. As for the previous examples, we asked new groups of students to produce diagrams given either structural or functional descriptions. For structural descriptions, students did not use arrows, but for functional descriptions, they did.

In a comprehensive survey of scientific diagrams (MacKenzie and Tversky, 2004), we have found (as have others, e. g., Gombrich, 1990; Horn, 1998; Westendorp and van der Waarde, 2000/2001; Winn, 1987), many different uses of arrows. A common use is to label or point at something, a function served early on by hands in diagrams. Other uses are to indicate direction of movement, manner of movement, sequence, causality, dependency, and more (it is reported that there are close to a dozen uses in chemistry diagrams alone, Peter Mahaffy, personal communication).

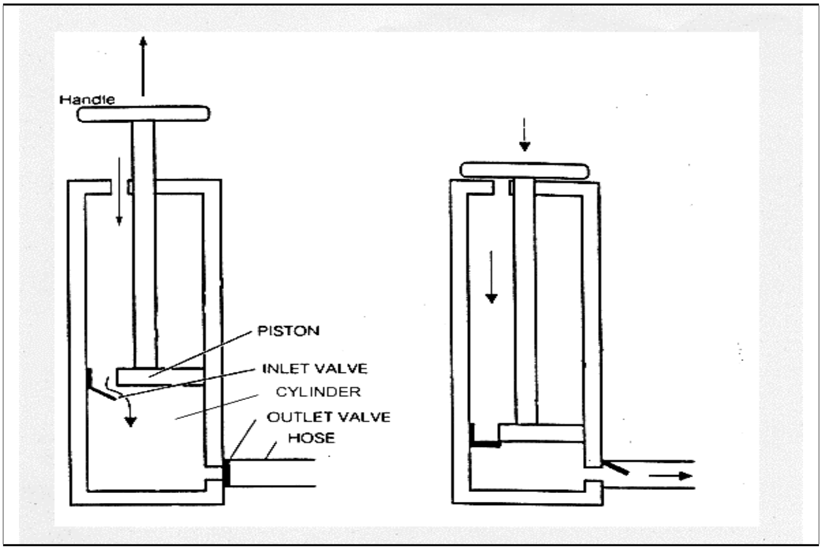

Figure 3. *Bicycle pump with arrows (from Heiser & Tversky, submitted, adapted from Morrison, 2001, adapted from Mayer & Gallini, 1990).*

Morphograms such as lines, blobs, crosses, and arrows are among many simple geometric forms that appear in visualizations of all kinds. Their meanings are often clear in context from their geometric or Gestalt properties. They can be combined not randomly but systematically to create complex graphical messages. As such, they share similarities with words such a *line* or *relationship* or *direction*, which also carry meanings that require context to disambiguate and which can be combined systematically to convey complex meanings. Morphograms, along with icons, figures of depiction, and metaphoric uses of spatial relations explain why many visualizations are easily produced and readily interpretable.

COGNITIVE DESIGN PRINCIPLES

The previous review and analysis suggests two cognitive principles for designing effective visualizations (Tversky, Morrison, and Betrancourt, 2002). According to the *Congruence Principle*, the structure and content of the visualization should correspond to the desired mental structure and content. According to the *Apprehension Principle*. The structure and content of the visualization should be readily and accurately perceived and comprehended. Using diagrammatic space to reflect conceptual space, as in mapping increases upwards, illustrates the Congruence Principle, as do successful uses of icons and figures of depictions and morphograms. Route maps are a subtler, deeper example of the Congruence Principle. Spontaneous route sketches do not convey distance and direction accurately. Not incidentally, mental representations of maps schematise the information in the same way. In memory, turns are remembered as closer to right angles than they actually are, and roads as more parallel than they actually are (Tversky, 1981). The much-lauded and much-imitated London subway map makes the same simplifications, and more. Schematising information to reflect schematic cognitive structures facilitates apprehension as well. They simplify the information, but the simplification is systematic, that is, schematic. Schematic visualizations preprocess the actual information, extracting what is needed even distorting it for emphasis, and eliminating what is non-informative. Schematic visualizations remove the irrelevant information that interferes with finding the relevant information.

DIAGRAM NARRATIVES: STRUCTURE AND PROCESS

What kinds of stories do scientific visualizations tell? To answer this, MacKenzie and Tversky (2004) conducted a survey of visualizations in textbooks for a range of disciplines in science. Two types of visualizations dominated: structure and process. Structural diagrams show the parts of a system and their spatial or conceptual relations. Process diagrams show change over time; they often show structure incidentally. Many visualizations combine or expand these types, for example, visualizations that show structure to function or that show structural variants of a category or that show structural hierarchies, parts and subparts. Static diagrams are ideal for conveying structure; they map the elements and spatial relations of a system onto the elements and spatial relations in diagrammatic space.

CONVEYING PROCESSES

Conveying process in static diagrams is not as straightforward. Process or function normally entails change in structure, as in the operation of a pump or cell meiosis or molecular changes, or in the part of the structure that is active as in a circuit diagram or nerve conduction or the nitrogen cycle. Although students high in mechanical ability or expertise are able to infer action or change from static diagrams, students low in mechanical ability/expertise (but high in other abilities) are unable to infer action or change from static diagrams. These students have no trouble understand action from verbal explanations (Heiser and Tversky, 2004). The finding that expertise or ability is needed to infer function from structure is a general finding. Experienced architects can infer change or function, such as traffic patterns and changes in light throughout the day and seasons, from architectural sketches, but novice architects cannot (Suwa and Tversky, 1997).

Fortunately, there are a number of different techniques for conveying process. A frequent one is use of arrows (Heiser and Tversky, 2004). But a close examination of arrows across a range of diagrams reveals many different senses, often in the same diagram, and often not disambiguated. Another is a sequence of static diagrams. A third is animation.

The Principle of Congruence suggests that animations are a natural way of conveying processes, change over time. This is undoubtedly one of the reasons for the enthusiasm for animations. The "gee whiz" factor is another; many animations are esthetic. But are animations effective in instruction? A broad survey of dozens of studies comparing animated graphics to informationally-equivalent static ones did not turn up a single study where animations were superior (Tversky, et al., 2002). This result has been resisted, and requires reflection. On reflection, animations violate both design principles. They are all too frequently too complex to be adequately perceived. They often have many moving parts; what is key is often the exact timing of the changes of the parts, and the eye and the mind cannot grasp them. Beginners don't even know where to look. People do not know how to parse or perceive the animations that life naturally provides. The art museums of the world are filled with paintings of horses galloping with their legs incorrect configured. It was Muybridge's stop-gap photography that revealed the correct configuration (Solnit, 2003). However, even animations portraying a single moving dot are not superior to a static graphic of the path (Morrison and Tversky, in preparation).

On closer inspection, animations may fail for a deep cognitive reason. People discretize continuous events that take place over time. They think about animated events as sequences of discrete steps (e. g., Hegarty, 1992; Zacks, Tversky, and Iyer, 2001). What's more, the segmentation into steps is systematic and predictable; for example, in the case of mundane human activities, such as making a bed, segmentation is by objects and object parts at a coarse level, and by articulated actions on objects and parts at a fine level (Zacks, et al., 2001). Recall routes; they are segmented by turns at landmarks. If people think about continuous actions as sequences of discrete steps, then visualizations of processes may better serve users by breaking them into the significant steps. Frequently, those steps are marked by changes in object and/or action. In fact, there is evidence that infants, children, and adult novices use large changes in physical actions to infer changes in goals and causes (e. g., Baldwin, Baird, Saylor, and Clark, 2001; Martin and Tversky, 2004; Woodward, Sommerville, and Guarjardo, 2001).

Route maps suggest yet another technique for producing better visualizations of processes that occur in time. Route maps distort space in order to enhance communication. They shorten long straight distances and enlarge short ones with tricky turns; they present turns of all angles as right angles (or diagonals), all in the interest of facilitating navigation. Animations could do the same for time; use time in ways that reflect expert understanding of processes, start, stop, slow down, speed up. Time and space could be altered together to allowing zooming, enlargement, change in perspective—spatial variations—cued by abrupt or continuous temporal changes. But this is not all.

Throughout evolution, humanity has witnessed change, process. The world does not sit still, it is always in flux. Watching things change does not tell us *how* or *why* things change. If it did, there would be little need for science and little scientific progress. How many generations watched water rise in the bathtub or apples fall from trees or the paths of the stars without any *eureka*s? All too many animations just show change. They need to explain it. Concomittant verbal explanations do help students learn from them (Mayer, 2001), but that is not enough. Good explanations do more than annotate the step-by-step action of a mechanical device or biochemical cycle.

VISUAL NARRATIVES

Insights into designing scientific visualizations can come from thinking more broadly about visual narratives. As for other external representations, they are ancient, like the remnants of the frescoes and friezes in Crete and Babylonia, and more recent, like the stained-glass windows and tapestries, and modern, like comic books and children's stories. Each medium tells stories in pictures or in pictures artfully combined with words.

What do good explanations do? Good explanations of the new are based in the old. That is, good explanations capitalize on what their audience already knows. They put things in context. Good explanations interweave the formal information with examples and analogies that elucidate aspects of the formal information. Contrast this to the typical animation, simply showing a process. Showing a process can be thought of as a series of stills snapshots, perhaps at a rate that is perceived as continuous, with temporal links between the stills. Thinking broadly, an explanation can be thought of as a series of stills with many different kinds of links, some temporal, some spatial, some, examples, some analogs, and so on. Verbal explanations can be thought of in the same way, as a string of concepts and relations. In fact, as was shown for routes, analyzing depictions and descriptions of the same content is an effective way of revealing the underlying cognitive structures that need to be communicated. Analyzing experts' depictions and descriptions of scientific concepts should be an effective means of discovering the content and structure that needs to be communicated.

The *Cartoon Guides* that Gonick and his collaborators have written for a variety of scientific and other disciplines are instructive. *The cartoon guide to physics* (Gonick and Huffman, 1990) for example, explains concepts like mechanics and electricity by sequences that zig-zag from general principles articulated in words, to equations, to visualizations of equations that are concrete or in graphs, to depictions of physical examples, and of course, to jokes. The conceptual links are varied and rich; only a minority are temporal. That these guides have been adopted as textbooks in serious courses in first-rate universities is some testimony to the success of this kind of visual explanation. These techniques are waiting to be exploited in scientific animations.

VISUAL COMMUNICATION

Visualizations are an essential element of teaching, understanding, and creating scientific ideas. Visualizations are not unique to the sciences; they belong to a large class of cognitive tools that have been crafted by people from all cultures and all eras for remembering, for reasoning, for discovering, and for communicating a wide range of ideas. Their effectiveness derives from cognitively compelling mappings from real and conceptual elements and spatial relations to elements and spatial relations on paper (or sand). They capitalize on people's extensive experience and facility in making spatial comparisons and inferences.

Visualizations, like language and other cognitive and communicative tools, vary in effectiveness. Effective visualizations take into account human perceptual and cognitive capacities. That means selecting the essential information, removing the irrelevant information, and structuring the essential information so that it can be readily and easily and accurately grasped and understood. Easier said than do, of course. Clarity is paramount for communication. Not so for visualizations for discovery and insight. For these, it cannot be known ahead of time what information is essential nor how to structure it; rather, these are what needs to be discovered. Clutter rather than brevity, ambiguity rather than clarity, excess rather than essence may encourage insight and discovery.

FOOTNOTE

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