Communicating with Diagrams and Gestures

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There are many ways to communicate. Some forms of communication, like words, are symbolic; the relationship between the content and the form of a message is arbitrary. Other forms, like visualizations and gesture, are at least in part iconic; the relationship between the content and the form can be resemblance. Resemblance confers an immediacy to communications; they can be directly understood rather than through symbolic mappings. Visualizations and gestures share iconicity, though the former primarily uses space and the other primarily time. They differ in other ways; indeed, they can complement each other so that integrating both enhances communication. To see how, we first consider how visualizations communicate.

Advantages of visualizations. Depictions of all kinds are ancient, dispersed across the planet, predating written language. Paintings in caves, tallies in clay, carvings in wood, inscriptions on bone, and imprints on stone are some that have survived. Depictions are externalize knowledge; they are cognitive tools, created to enhance the human mind. As cognitive tools, they play many roles, memorial, communicative, and spiritual among them. In modern times, depictions abound in newspapers, public places, instructions, textbooks. They serve as a permanent record of ideas, one that can be inspected and reinspected by individuals and by groups. They can function as an external store of the contents of working memory, increasing the number of items that can be considered as well as fostering mental processing of those items. They capitalize on human ability to make rapid inferences about space and the things in it, distance, direction, length, area, shape, and more, and to perform mental transformations and operations on objects in space, like adding, subtracting, or combining, changing shape, size, orientation, and location, comparing, and more (see Tversky, 2005b). They can map abstract as well as concrete elements and relations in the world to elements and spatial relations on paper thereby expanding their domain to ideas that are metaphorically spatial. They externalize thought, rendering it visible to a thinker for understanding, expression, and revising as well as making inferences and discoveries. They render thought visible to a community for the same ends. When designed by groups, they become a joint creation, not the creation of one individual, so each and all can take pride and feel ownership. Part of the power of external visual representations derives from their iconicity; in many cases, external visual representations bear similarities, figurative as well as literal, to what they are intended to represent. This feature is especially important in science, for teaching, for understanding, for exploring. Because visualizations bear iconic or metaphoric similarity to what they represent, they are more readily understood than purely symbolic media.

Visual communication. Depictions, visualizations, diagrams are part of a larger class of external representations that includes artifacts, natural or manufactured, models, and the like. Many serve the ends described above. Each, however, has its' own advantages and disadvantages. Visual-spatial external representations are rarely pure; that is, most contain words or symbols. Although language is often regarded as purely symbolic, it, too, when regarded wholly, is multi-media and has iconic channels, notably, gestures. Gestures are ubiquitous in humans. Blind children who have never seen gestures and cannot see their own, gesture, especially when describing space (Iverson and Goldin-Meadow, 1997). Gestures, like diagrams, have many purposes, both for the person gesturing and for the recipients of the gestures. Gestures, for example, can serve to externalize thought, alleviating and structuring working memory (e. g., Kessell and Tversky, 2006); counting on one's fingers is an ancient and widespread example. Gestures help speakers find words and formulate messages (e. g., Krauss and Hadar, 1999). As shall be seen, they also serve to promote understanding and memory in both those making them and those observing them (Lozano and Tversky, 2006; Lozano and Tversky, submitted; Tversky and Lozano, in press).

Visualizations extract essences. Effective graphics are schematic. They do not, cannot, include all the information, so they select only that needed for the task. In addition to abstracting information, they select the information that is relevant and important; they often distort the essence for emphasis and clarity. Maps serve as an example. Roads on road maps are not usually shown in proper scale; if they were, they wouldn't be visible. Roads are typically straightened as small twists and turns might clutter and confuse, and are the minor twists and turns are not usually needed. Aerial photographs, which preserve much more information than most maps, not only contain too much information to be useful for navigation, they contain much information that is not helpful, such as the tops of trees and buildings. The selectivity and distortion of graphics can matter or not matter, depending on the pragmatics, the implicit understandings of the groups using them. For example, good route sketch maps provide clear indications of the turns at landmarks needed to arrive at the endpoint, but leave out considerable detail and may distort distance and directions, among other things (e. g., Lee & Tversky, 1998, 1999). Because route maps have been created and comprehended by communities of users, the distortions are less likely to cause problems. This may not be the case for other diagrams, and that opens the doors to misunderstandings.

Visualizations in science. Communicating science is hard, in part because scientific thinking is hard. Part of what makes science hard is that it is abstract. Diagrams can make the abstract concrete. Although graphics have been used for millennia to convey concepts that are inherently visuospatial, such as maps, building plans, depictions of cultivating crops, making bread, and military campaigns, their use in conveying abstract concepts is modern, and has not undergone the fine-tuning that years of informal user testing has done for maps. Many scientific concepts are more complex than that the information conveyed in maps; they may require understanding of things at different scales, where each scale involves different objects, relations, and processes. They may require different perspectives or complex transformations of objects and relations. Scientific concepts may entail understanding of concepts that are not inherently visible such as force, weight, temperature, and energy. For these reasons and more, visualizing scientific concepts often require expertise to produce and to understand.

Meaningful geomtric forms: Lines, blobs, boxes, and arrows. Most diagrams are multi-modal if only because some information is difficult to convey visually, even metaphorically visually. Crucial to conveying non-visual aspects of concepts, scientific and other, are symbolic information, such as words and equations, and geometric forms. Unlike symbolic information, geometric forms, such as lines, boxes, and arrows, frequently have meanings suggested by their geometric or Gestalt properties that allow them to be readily understood in context (e. g., Tversky, Zacks, Lee, and Heiser, 2000). A familiar example is route maps, where one-dimensional lines are produced and understood as paths and two-dimensional blobs are produced and understood as places or landmarks (Tversky and Lee, 1998, 1999). Lines can be combined to indicate different kinds of intersections, T's, L's, and +'s, and concatenated, along with blobs, to form routes.

Graphic language for routes. Three aspects of route maps are of general interest as they can be extended to other diagrams as well, understanding as well as designing them. First, route maps have a grammar: lines and blobs and a few other forms constitute their semantics and the rules of concatenation constitute their syntax. Route maps also have a pragmatics, conventions of use, including a shared understanding that distance, direction, and shape are only approximate, not to be taken literally. Next, the skeleton of route maps, nodes and links where distance, direction, and shape are simplified, corresponds to people's mental representations of routes (e. g., Tversky, 1981, 1993). Both diagrams and mental representations schematize, typically in the same ways. This implies that understanding peoples', especially experts', mental representations of a domain (most of us are experts in routes) is key to creating effective diagrams for that domain as the mental models suggest what information to include and what to omit. What's more, people's productions of diagrams simultaneously reveal their mental models as well as diagrammatic devices for conveying them (Tversky, Agrawala, Heiser, Lee, Hanrahan, Phan, Stolte, and Daniel, 2007).

Graphic Languages. The research revealed that diagrams for routes have a simple semantics, syntax, and pragmatics. The semantics are the graphic elements for the components, primarily paths, intersections, and landmarks. The syntax is the rules for stringing them together, and the pragmatics concerns their use. The language used to describe routes is structured similarly. Route depictions and descriptions differ in pragmatics. For example, in route descriptions, if one segment ends at a path, that path is the start point for the next segment. Because it can be inferred, it can be omitted from the description of the subsequent segment. In maps, the end and start points are explicit (Tversky and Lee, 1999). It seems likely that graphic languages can be constructed for other domains as well, and that the semantics and syntax will have parallels in verbal language, just as for route maps. Assembly diagrams are a good candidate for another domain amenable to a graphic language, as they consist of a set of parts, a set of actions required to assemble the parts, and a sequence of steps combining the parts and the actions (Tversky, et al., 2007). This underlying cognitive structure was revealed in people's productions of verbal instructions, diagrammatic instructions, and gestural instructions, just as for routes (Lozano and Tversky, 2006; Tversky and Lee, 1999; Tversky, et al., 2007; Tversky and Lozano, submitted). Effective assembly diagrams show the assembly actions step-by-step using a perspective that shows the action, and adding arrows to indicate actions and guidelines to indicate placement of parts. Consistent with the research on segmenting events, each new assembly diagram shows the addition of another part. The vocabulary of assembly diagrams consists of each of the parts, indicated by an iconic drawing of each part as it is inserted into the increasingly assembled object, and the actions, usually indicated by arrows.

From route maps to networks. The skeleton of route maps can be generalized to area maps as well as to metaphoric maps, which are common across many domains. Route maps typically depict only the needed path from a richer area map, but area maps are similarly conceived so the node and link grammar can be extended to diagrams and mental conceptions of area maps as well (Fontaine, Edwards, Tversky, and Denis, 2005). Reduced to nodes and links, the network, hierarchy, and box and link diagrams so common in science and engineering are structurally maps, maps by analogy. Schematic node and link diagrams that depict connections in geographic space serve as convenient metaphors for connections in abstract spaces.

Lines and bars. Lines serve key roles in visualizations. In route maps, they represent roads or more abstractly, connections. The power of lines to represent connections is clear from research investigating how people understand and produce line and bar graphs. Lines connect. In contrast, bars contain and separate. In a simple graph of two values, A and B, such as height of ten and twelve year olds (continuous variable) or men and women (categorical variable), lines say there's a relationship between the two data points, they have different values on the same dimension. Bars say, there are A's and there are B's and they are separate. This reasoning from the gestalt properties of the geometric shapes predicts that lines should be interpreted and produced for trends and bars should be interpreted and produced for discrete comparisons. This, in fact, was the case (Zacks and Tversky, 1999). In fact, the graphic form was a stronger predictor than the underlying data, continuous or discrete, so that some respondents interpreted a line graph of height of men and women as "as you get more male, you get taller."

Form and Transformation. Visualizations are ideal for conveying structural information as they map elements and relations in the conceptual world to elements and space on paper. Indeed, many crucial scientific concepts are structural, hearts, molecules, proteins, atoms for examples. However, no less important to science are concepts of change or transformations, behavior of hearts, bonding of molecules, functions of proteins, smashing of atoms. These are exactly the sort of conceptual information that is difficult to convey in static graphics. Visualizations can still facilitate by off-loading mental representations of form onto paper, but the mind then has to perform the mental operations underlying the change. Some mental transformations of the static information are relatively easy, such as following a route, or mental scanning, but many are difficult, such as mental rotation, mental reflection, mental shape transformations, and mental shifts of perspective, especially when they need to be combined (e. g., Novick and Tversky, 1987; Shepard and Cooper, 1982; Zacks and Tversky, 2005). In fact, bright students with lower spatial ability find it difficult to infer function from diagrams, presumably because they find the requisite mental transformations, movements in varying directions and rotations and reflections, difficult to perform (Heiser and Tversky, submitted). Students with low spatial ability were able to grasp functional information from descriptions. Interesting for what is yet to come, performing motor actions or gestures compatible with the mental transformation facilitates executing the mental transformation (e. g., Schwartz and Black, 1999; Schwartz and Holton, 2000; Wohlschlager and Wohlschlager, 1998).

Visualizing the Invisible: Arrows for Transformations. Conveying transformations, then, is a major challenge for designing effective visualizations. One common device is an arrow. When students are asked to describe diagrams of a bicycle pump, a car brake, or a pulley system that have no arrows, they provide structural descriptions. They describe the parts of the system and where they are located relative to each other. If arrows are added to the structural diagrams, students provide functional descriptions. They describe the function of the system, the causal structure of its' operation from start to finish. Thus, arrows are one way to enrich structural diagrams to convey function (Heiser and Tversky, 2006). Arrows may not be sufficient however, as was the case for students of low spatial ability in the study of Heiser and Tversky (submitted).

Moreover, arrows have many uses in diagrams. They can refer or point as in labeling, they can indicate motion and manner of motion, they convey steps or transformations, they can mean implication or causality (e. g., Tversky, Heiser, Lozano, MacKenzie, and Morrison, in press). Often these uses appear in the same diagram, without disambiguation, causing confusion. As we have seen, lines, too, have many meanings. Ambiguity is not confined to graphic devices. Words, such as *line* or *relationship* are also ambiguous, and writers rely on context to disambiguate *line* of work from *line* on a plane, a romantic *relationship* from a mathematical one.

Animations and its' Discontents. This kind of analysis led us to propose two principles for creating effective graphics. According to the *Congruity Principle*, the structure and content of an external representation should match the structure and content of the desired mental representation (Tversky, Morrison, and Betrancourt, 2002). The congruity principle suggests that animation should be a compatible way of communicating transformations, change over time. Animations use change in time to convey change in time. This idea has been enthusiastically applied across myriad domains. What's been surprising, then, is that in most cases, animated diagrams have not been more successful than informationally-equivalent static diagrams at conveying processes (Tversky, et al., 2002). On closer examination, the failure of animated graphics to improve performance over static ones is less surprising. Animated graphics often fail a second design principle, that of *Apprehension*. According to the Apprehension Principle, external representations should be readily and accurately perceived. In many animations, too much happens too fast to allow accurate perception.

However, even very simple animations, the slow movement of a single geometric figure, where there is no problem with correct apprehension, can fail to improve performance over a static graphic conveying the same information (Morrison and Tversky, submitted). This is most likely due to a more subtle incongruence between animated graphics and understanding of processes that occur over time. People tend to understand those processes, not as continuous, but rather as a discrete sequence of steps (Tversky, et al., 2002; Tversky, Heiser, Lozano, MacKenzie, and Morrison, in press; Tversky, Zacks, Tversky, and Iyer, 2001). Think again of routes through environments. They are continuous and dynamic, yet people think of them as a sequence of actions at choice points, links and nodes. Similarly, even continuous processes, such as the action of a pulley system, are thought of as a sequence of steps, each pulley and its' direction of movement. If people think of events as sequences of discrete steps, then it is congruent to convey them in diagrams that are already segmented into the appropriate steps, rather than requiring the learner to discern them.

There is yet another reason why animations are not more effective in conveying processes that occur over time. Most animations simply *show*; they do not *explain* (Tversky, et al., in press). In the world, we observe many processes that occur over time, flowers bloom, produce seeds, and seeds germinate; bread rises, eggs coagulate when heated; clouds form, thunder sounds, lightning strikes, and rain falls; the moon waxes and wanes. But even detailed observation of change cannot explain why the changes occur. Explanations require more than showing, they may entail changes in perspective and scale, they may use analogies, they may require reducing processes to other kinds of processes, for example, biological ones to chemical and physical ones. The demand to explain and not just show, along with the requirements of congruence and apprehension, presents challenges to the design of effective animations.

Visual communication: Gesture. As noted, visualizations can communicate more directly than purely symbolic media because they use visual elements and spatial relations to convey both concrete and abstract elements and concrete and abstract relations. They also take advantage of resemblance and similarity. There is another mode of communication that has many of those advantages, namely, gesture. There are many kinds of gestures (for excellent overviews, see Goldin-Meadow, 2003, and McNeill, 1992). Some are *emblems*, like the sign for OK, and do not bear similarity to what they represent; like words, they are symbols. Two other categories of gestures are important for explanations, *deictics* and *iconics*. Deictics are pointing gestures, and one of their primary uses is to refer, typically to things in the world. Iconic gestures resemble what they convey, as when someone stretches hands apart to indicate width, or draws a picture in the air. Both deictics and iconics are embodied in the sense that they involve actions of the body and perception of the body, and they are situated in the sense that they make use of the surrounding world to ground the communication. This is in sharp contrast to words, especially words on paper, which are neither embodied nor situated.

The effectiveness of visualizations and of gestures can be increased by using them together, and together with words. Unlike static visualizations, gestures are dynamic, so they can animate; however, in contrast to visualizations, they are fleeting and leave no trace. When asked to explain how a lock works, students given paper and pencil made sketches to show the structure of the lock, and used their hands to demonstrate the action of the lock (Engle, 1998). In another study, pairs of participants worked together to plan an efficient route to rescue wounded after an earthquake (Heiser and Tversky, 2004;

Heiser, Tversky, and Silverman, 2004). Most of the planning took place in the gestures on the map; the talk referred to the gestures. Parallel to the diagrammatic route maps, there were two main kinds of gestures, deictics or points, primarily to landmarks, and iconics, illustrating the paths. The two projects described below examine in greater detail how gestures and words are used in explanations. They provide insight into the roles of gestures in explanations, their semantics and syntax, and their demonstrate their effectiveness in explanations.

Gesture in Explanations. The tasks we chose were modeled on previous work using diagrams: explaining how to assemble a piece of furniture, a TV cart (Lozano and Tversky, 2006; Tversky and Lozano, in press) or explaining how to get from one place to another, a route (Lozano and Tversky, submitted; Tversky and Lozano, in press). Unlike the explanation of many scientific concepts, these are tasks that require no expertise. However, they are representative of the kind of content conveyed in science as they have the structure of many scientific concepts in that they consist of parts, relations among the parts, and actions.

In both experiments, participants first learned the concepts to be explained. For the object assembly, they assembled the object, a TV cart, using the picture on the box as a guide. For the route, studied a map with the route marked. Afterwards, they were asked to make a video explaining the assembly or the route so that someone else could perform it. One group for each task was told that the video would be used by others who didn't understand English. As a consequence, those groups used only gestures and no words in their explanations. The other groups were only told to make a video so others could perform, so they used a combination of words and gestures. Explainers' performance was evaluated differently for the two tasks. For the objects assembly, errors made while explaining were recorded. For the routes, after making the videos, participants were surprised by a request to remember the routes. Performance was evaluated in order to assess effects of explainers' own gestures on their performance. In both experiments, the videos were then shown to other participants, and the performance of those participants was tested as well.

In explaining the assembly of the TV cart, participants using gesture alone made more gestures than those who could also speak. For assembly, explainers, especially those using only gestures, frequently used deictic gestures to point to small parts and exhibit large ones, by holding them up. They often used iconic gestures to model the intended structure of the TV cart. Those who only gestured went further, they often used iconic gestures to model the actions needed to assemble the cart. Thus, gestures can be used to reflect and instill mental models, of structure and of action. The gestures indicating actions turned out to be particularly important. As they assembled the TV cart for the second time, participants often made errors in assembly; some of those errors were corrected, some not. Surprisingly, the participants who were restricted to gesture made fewer assembly errors than the participants who had the more natural task, using speech and gesture as they liked. Moreover, performance correlated with the number of action gestures made. This advantage of iconic gestures illustrating actions was observed in the groups who learned the object assembly as well. One group watched a video in which the explainer only used gestures indicating structure. Another group watched a video in which the explainer's gestures conveying actions. Those who watched the action gestures later performed the task better than those who watched the structure gestures.

In explanations of the routes, explainers using gestures only gestured more than those who could speak. Deictic gestures were used primarily to indicate locations of landmarks on the maps, and iconic gestures to illustrate the turns and paths, though some iconic gestures were used to illustrate landmarks, like shapes of buildings. The participants who explained using speech and gestures tended to use relatively more deictic gestures; this tendency grew stronger across the four routes they each explained. Those restricted to gesture used far more gestures, but used relatively more iconic than deictic gestures, increasingly across the four routes. As for the object assembly, gesture use predicted recall. The participants restricted to gesture made more gestures and recalled the routes better than those free to gesture and speak. Gesture use also accounted for qualitative differences in memory. The quantity of deictic gestures predicted memory for landmarks and the quantity of iconic gestures predicted memory for paths and turns. Specific gestures predicted specific contents of memory.

Why gestures are effective. Why are gestures so effective in explanations, both for those making the gestures and for those learning from them? There are several possible explanations, and they are not contradictory. Gestures provide another code, a motor code, for the information, in addition to verbal and visual codes. Additional codes are known to improve memory. In addition, gestures are actions, and as such, they are especially congruent with the actions or transformations that need to be learned. Gestures are also necessarily abstract and schematic. They cannot convey the pictorial detail that diagrams can convey. For some concepts, detailed pictorial detail may not be informative, and may even be distracting. By schematizing the information, gestures may not only avoid distracting, but also succeed in communicating the necessary abstractions. Finally, gestures are embodied and situated; as such, they build associations between actions and objects, a large part of the crucial information. The most likely reason that the participants who could speak or who learned from language and gesture performed worse is that they used or saw fewer gestures. It's not that speech interferes with learning, but that it reduces the amount of gesturing and changes the kind of gesturing. This leaves us with a puzzle: although gestures are especially effective both for explainers and learners, they are often not used.

This research strongly suggests that gestures should be used in explanations, and may be especially effective for scientific explanations (see Goldin-Meadow, 2003, for more examples of the effectiveness of gesture in teaching). They can go beyond static diagrams of the structure of systems by showing the actions of systems. The semantics of a system suggest what gestures should be used, deictics for referring and locating, for showing form, and, even more important, iconics for showing transformation.

The gestures used in explanations also had a narrative structure, a beginning, a middle, and an end. This was more evident in those restricted to gesture. They often opened by greeting the observer. In the case of object assembly, they showed the parts required.

This was paralleled in the assembly diagrams earlier participants produced, which contained menus of parts, much as a recipe begins with a list of ingredients. For the maps, gesturers sometimes situated the observer in the map, by pointing to the observer and then pointing to the start point of the route. For both the assembly and route tasks, explainers often used gestures to segment the task into steps, indicating when a step began or ended. They sometimes used gestures to group steps into larger steps, creating a hierarchical representation. Finally, they frequently used gestures of presentation to indicate the end of the task. The assembly diagrams did this as well, by putting sparkly lines around the finished object.

The parallels between gesture, word, and diagram for both assembly and route indicate that the three media derive from a common underlying cognitive structure. They use similar semantics, breaking the task into similar parts. They order the parts in similar ways and convey the same sequence of actions, but use different methods for conveying parts, order, and action. They have relative advantages for different aspects of the task, diagrams for structure, gestures for action, and words for supplementary information that cannot be depicted or enacted.

Making communication effective. Depictions are ancient artifacts created to augment the human mind. Gestures are even more ancient, most likely dating to people's primate ancestors. Both gestures and visualizations have an iconic element, they can resemble what they are representing, making them more transparent than purely symbolic media, like language. Iconicity is only one aspect of their effectiveness. They make the abstract concrete, capitalizing on the multitude of metaphoric mappings of abstract to concrete so evident in language: *She's on the top of the heap; he's fallen into a depression*. As such, they take advantage of human ability to make rapid spatial judgments and inferences. Neither depictions nor gestures can convey all the information surrounding an idea or set of ideas; this forces them to extract what is essential, to simplify the ideas, making them easier to comprehend and remember. Visualizations are especially effective for conveying structure, that is, the parts of a system and their relations, spatial or abstract. Conveying dynamic information presents challenges; arrows, successive stills, flow diagrams, and animations are only partial solutions. Gestures are inherently dynamic, and as such, can animate diagrams. As such, visualizations provide form and gestures transform. Even so, there remain concepts that are more readily conveyed in words than by an iconic medium, causality, negation, counter-factual, and possibility are among them. Despite the fact that many meanings can be conveyed well in word, gesture, or diagram, as has been shown here, some meanings are more compatible with one medium than another.

Acknowledgements. The author is indebted to the participants in the Workshop on Diagrams February 10 & 17, 2007, at the Homi Bhabha Centre for Science Education of the Tata Institute for Fundamental Research in Mumbai, India. Preparation of the manuscript and portions of the research were supported by Office of Naval Research

Grants NOOO14-PP-1-O649, N00014011071, and N000140210534, and NSF Grant REC-0440103.

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