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THINKING WITH SKETCHES

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BARBARA TVERSKY
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WHY SKETCH?

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DESIGNERS sketch. One reason they sketch is that they design things that can be seen. A sketch can resemble what the designer wants to create. Unlike the contents of the imagination, a sketch can be seen. Thus, sketches serve to amplify a designer's imagination and relieve limited-capacity working memory. Sketches map on paper things that exist in the world or the imagination and the relations among them, spatial or abstract, to elements and relations on paper: a natural mapping. They can be used to convey concepts that are literally spatial, such as objects, buildings, and environments, as well as concepts that are metaphorically spatial, such as information systems, organization charts, and family trees.

Models can convey objects and spaces as well, perhaps more so than sketches, since models are three-dimensional. Both have a place in design. Early in the design process, sketches have advantages over models, especially when the designer is considering many alternatives, which may be vague or partial. Sketches are just that, *sketchy*; for example, they can represent incomplete objects as blobs, or incomplete connections as wavy lines, so that a designer can consider general configurations before committing to particular connections and specific shapes. Models demand completeness.

Sketching is faster than model-building, and kinder to trial-and-error and revision. Sketches are easier to create and easier to revise. Sketches are two-dimensional, and thinking in two dimensions is easier than thinking in three (e.g., Gobert, 1999; Shah and Carpenter, 1995). Sketches readily enable expressing separate parts, different perspectives, and various scales so the designer can focus on each part, perspective, or scale, viewing them separately or together. A designer can use a sketch to focus on certain aspects of the design, ignoring others that may distract from the problem at hand.

Because sketches are visible they can be inspected and reinspected, considered and reconsidered. Designers can discover new properties and relations from their sketches as they inspect them—properties and relations that emerge from the sketch but were not intentionally put there (e.g., Goel, 1995; Goldschmidt, 1994; Schon, 1983; Suwa, Tversky, Gero, and Purcell, 2001). But sketches can go beyond the visible. They can eliminate detail that is irrelevant and distracting in the service of capturing the essential. At the same time, sketches can exaggerate and even distort the essential. They can be enriched with words and other symbols, enhancing their meaning with ideas and properties not easily expressed pictorially. Yet designers of things that cannot be seen also sketch. Sketches can use elements and relations on paper to represent abstract elements and abstract relations. Designers of experiments and of assembly lines, both of which occur in time, sketch possible sequences of events. Extending sketches from space to time is a natural step, as temporal events are described in part using the language of space, for example, *before* and *after*, *forward* and *back*. But designers of abstract ideas such as corporate organizations and computer operating systems also sketch.

Why can't people work these things out in their heads? To some extent they, especially experts, can, but ideas, whether spatial or abstract, that are complex or detailed are likely to be too massive to hold in one's mind, especially if they need examination, manipulation, or revision—all processes crucial to design. The pragmatics of putting ideas on paper demands a degree of coherence, completeness, and consistency, serving as a test of design ideas. Finally, the public nature of sketches facilitates communicating ideas to others and collaborating with others (Heiser and Tversky, 2004; Heiser, Tversky, and Silverman, 2004). Sketches serve as an easy referent for words and gestures, so deictic expressions like *here* and *there* and *this part* and *that way* simultaneously make communication easier and more precise. In collaborations, they represent the ideas of the group, not of any individual, so all are committed to it. When we've barely begun to formulate a concept, sketches are useful because they externalize ideas, encourage coherence and completeness, allow expression of the vague as well as the

specific, map large space to small, extract the crucial, enrich by annotation, make the abstract concrete, relieve limited working memory, facilitate information processing, encourage inference and discovery, and promote collaboration—and more (Tversky, 1999, 2001, 2005).

WHAT IS THE NATURE OF SKETCHES?

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Design sketches are imprecise, at least at the beginning. They are tentative; they do not commit the designer to exact shapes or exact spatial relations. They use a limited vocabulary of abstract shapes whose meanings are suggested by their geometric or gestalt properties. In early design in architecture, for example, blobs can stand for structures, buildings or rooms, and lines for the paths or corridors that connect them. Blobs are used to represent concepts we think of as three-dimensional (turned two-dimensional on paper) and lines to represent concepts we think of as two-dimensional (turned one-dimensional on paper).

Diagrams also use a limited vocabulary of shapes, but they contrast with sketches in being exact and definitive. In sketches, the tentative nature of shapes and spatial relations is directly suggested by irregularities, by imperfections, by inexact tracings and retracings. By contrast, in diagrams such as circuit and molecular diagrams, for instance, shapes and lines tend to be symmetric or regular or straight. Whereas sketches are often meant to be suggestive, tentative, ambiguous, and open to reinterpretation, diagrams, especially explanatory ones, are meant to be clear and unambiguous, in order to avoid ambiguities and misinterpretations.

An example of a type of diagram that has become conventionalized through use is the route map. Route maps are meant for clear, unambiguous communication, not for creative design. Although route maps could be analog, they are not. In fact, they seem to schematize environments exactly the way human memory does, by straightening roads, making turns into right angles and roads parallel, by distorting distances (e.g., Tversky, 1981, 2005). An analysis of a corpus of route maps students spontaneously produced to guide a traveller revealed a small number of elements with quite specific meanings. These elements can be concatenated in specific ways to convey a multitude of routes. That is, route maps have a semantics and a syntax (Tversky and Lee, 1998, 1999). The semantics consisted of what might be called *graphemes*: for turns, L's, T's, and +'s; for straight paths, lines; for curved paths, arcs of circles; for landmarks, street names or blobs.

Significantly, the semantics for verbal route descriptions revealed parallel elements, “make a,” “take a,” or “turn” for turns; “go down” for straight paths; “follow around” for curved paths; names for landmarks. Each set of semantic elements, descriptive or depictive, forms an essentially complete semantics of routes. In one study, groups of participants were assigned either the visual or the verbal vocabulary and asked to use the vocabulary to construct a wide range of routes, short or long, simple or complex (Tversky and Lee, 1998). Participants were told they could add elements if needed, but very few did; in other words, the sets of elements were virtually sufficient. The semantics of gestures used in describing routes include the same elements (Tversky, Heiser, Lee, and Daniel, in press). The parallels between the semantics and syntax of depictions, descriptions, and gestures of routes suggest that they derive from same underlying mental model.

At an even more abstract level, the primary elements in route maps indicate concepts that are thought of as points, as lines, as areas, and as volumes. Design sketches also use these elements. Interestingly, a similar tripartite distinction is one that Talmy (1984) has proposed to characterize the language of space and time: one-dimensional points, two-dimensional areas, and three-dimensional volumes. We say the group will meet “at the corner at 1:45,” point-like spatial and temporal concepts. The hike will go “from the Capitol to the Barton Pond from 2 to 4,” both like lines or areas. It will take place “in two days’ time in Austin,” both volume-like concepts. These conceptual distinctions have metaphorical extensions: someone can be *at* a crisis but *on* top of things, so not *in* a panic.

The comparison of the semantics and syntax used to convey routes in descriptions, depictions, and gestures, then, have revealed the underlying mental models people use for routes. A route consists of landmarks and paths, nodes and edges, turns and progressions. Exact distances and directions are not important, as they can be inferred from context, and neither are the regions not along the route. The underlying mental model and the graphic devices used to convey it can serve as cognitive design principles for creating sketches or diagrams that are useful and effective. This program of eliciting mental models from depictions and descriptions, extracting from cognitive design principles from them, and incorporating the cognitive design principles into algorithms to generate diagrams on demand has been successfully applied to both route maps and assembly instructions (Tversky et al., 2007). The program can be adopted for other domains. The productions of depictions and descriptions (and also gestures; see Tversky, Heiser, Lee, and Daniel, in press) simultaneously reveal the underlying mental models and suggest effective depictive and descriptive semantic elements and syntactic rules.

As design progresses, vocabularies and nuances grow and expand; sketches are typically enriched and articulated so that shapes of paths and regions, parts and wholes, are more specific, and can be recognized as such. Do and Gross (summarized in Do, 2005) have studied the visual vocabularies of architects as they expand. Even expanded and articulated, elements remain sketchy and schematic. For example, people may be represented as stick figures and rooms as rectangles with openings for doors.

HOW ARE DESIGN SKETCHES USED?

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Early design sketches are even more inexact than route maps. One reason is that the designer hasn't yet committed to specifics. Another reason, intended or unintended, is that sketches, because they are ambiguous, support many interpretations. The ambiguity of design sketches, rather than promoting confusion, promotes innovation. Because they support many interpretations, early sketches can be used for discovery and reinterpretation to further the design. Schon (1983) has described this as a conversation designers have with their own sketches. The designer creates the sketch to represent one set of constraints, elements, and relations, but on re-examining the sketch, sees other elements, relations, and patterns (e.g. Goldschmidt, 1994; Suwa, Gero, and Purcell, 2000; Suwa and Tversky, 1997). These unintended discoveries advance the design. In one study, novice and experienced architects were asked to design a museum on a particular site (Suwa and Tversky, 1997). Their design sessions were filmed, and afterwards, the designers viewed their sessions and explained what they were thinking at each stroke of the pencil. Both novice and expert architects got new ideas from examining their own sketches. However, the expert architects were more likely to get functional ideas from their sketches. The novices discovered structural features and relations in their own sketches; arguably, these require little interpretation as the structural features and relations are "there" in the sketch, ready to be perceived. Experts, by contrast, could "see" functional features and relations in their sketches, for example, changes of light or flow of traffic. These functional features and relations are not directly visible in the sketch, but require complex inferences entailing expertise. Seeing function in structure in fact seems to be a hallmark of expertise: for example, in chess (Chase and Simon, 1973; de Groot, 1965) and in engineering diagrams (Heiser and Tversky, submitted). Expertise, then, promotes seeing function in form.

HOW CAN SKETCHES BE EFFECTIVELY REINTERPRETED?

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What leads to these reinterpretations, so crucial to advancing design? A detailed study of one expert architect revealed that most of his new ideas came when he perceived the elements of the sketch differently; that is, when he reconfigured them into a different pattern (Suwa, Gero, and Purcell, 2000). A new idea, in turn, allowed him to reconfigure the sketch yet again, so that a positive cycle ensued: perceptual reorganization generating new conceptions and new conceptions generating perceptual reorganizations.

Is this strategy of searching for new perceptual relations a general one? The next step was to turn from designers to undergraduates (Suwa, Tversky, Gero, and Purcell, 2001). We showed undergraduates a series of ambiguous but suggestive sketches, those in Figure 4–1. Their task, adapted from a procedure used by Howard-Jones (1998), was to generate as many new interpretations as they could think of for each, taking four minutes for each sketch in turn. Approximately two-thirds of them used a strategy of attending to the parts of each sketch, either focussing successively on different parts or attempting to rearrange the parts mentally, for the purpose of coming up with new interpretations. Those who adopted an attention-to-parts strategy were more successful than those who didn't. Those who attended to different parts came up with 45 interpretations, and those who rearranged parts produced 50 interpretations, both in contrast to the participants who did not perceptually reconfigure the sketch and who produced only an average of 27 interpretations.

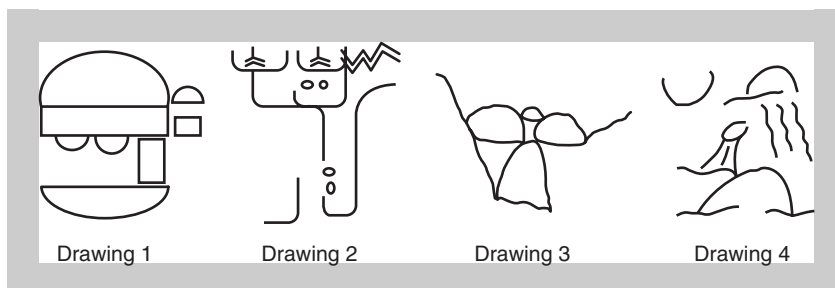


Figure 4–1 Four Ambiguous Drawings.

The parts-focus strategy was also effective against *fixation*, the plague of designers: getting stuck on a particular design and not being able to see alternatives. During the early phases of design, designers typically generate many ideas, but as they work and their designs become more constrained, they find it more and more difficult to see alternative solutions. The undergraduates who adopted the parts-focus strategy succeeded in producing more ideas in the second half of each session than those who did not.

Perhaps not surprisingly, practicing designers were more fluent at the task of generating new ideas and produced more of them than did the design students and laypeople (Suwa and Tversky, 2001, 2003). This suggests that experience promotes the required skills. The practicing designers reported a variety of ways to perceptually reconfigure the sketches, notably regrouping the parts and changing reference frames. In addition, they sometimes reversed figure and ground relations in the sketches. However, perceptual reorganization is only half of the process of coming up with new interpretations. Those interpretations must have meaning. To some extent, both the perceptual skill and the conceptual skill can be measured. The perceptual skill is measured by the embedded-figures test, in which participants' ability to see a simple geometric figure in a complex one is assessed. The conceptual skill is measured by an associative-fluency task in which participants' ability to find a meaningful association relating two unrelated words is assessed. The number of interpretations produced increased with each of these abilities independently. That is, those proficient in perceiving embedded figures and those high in associative fluency produced more interpretations, but the two abilities were not correlated.

Integrating these results suggests that actively reconfiguring sketches and finding meanings in them, termed *constructive perception*, promotes new design ideas and protects against fixation. The fact that designers are more proficient than laypersons suggests that the skill can be fostered. The fact that abstract ideas can be sketched suggests that constructive perception may have applications beyond the design of real objects and structures to the design of abstract objects and structures.

IMPLICATIONS

Design entails generating ideas and adapting them to users. This requires thinking broadly about possibilities and linking those possibilities to meaningful uses. This process is iterative, and facilitated by sketches. Sketches

allow designers to express ideas both vague and developed, and then see their ideas, contemplate them, alter them, and refine them. This iterative process of constructing, examining, and reconstructing has been called a kind of “conversation” (Schon, 1983). Successful conversation with sketches depends on finding new perceptual configurations as well as new meanings, and connecting the configurations to the meanings, seeing function in form.

Designers report, and research supports, that sketches, even rudimentary and ambiguous ones, are helpful to design early on. These early sketches typically capture very general aspects of a design, using a limited range of domain-specific visual elements. As design progresses, sketches become more articulated. CAD/CAM tools are often avoided in early phases of design because they require or impose a completeness that is premature (e.g., Do, 2005; Hearst et al., 1996). There are ongoing efforts to adapt these findings to create tools that can facilitate both early and late processes of design (e.g., Do, 2005; Hearst et al., 1996). These tools try to facilitate design first by aiding sketching: recognizing the primitive elements, often completing and remembering them, and allowing them to be manipulated and replicated. The tools can also enhance design in ways that go beyond sketching, by retrieving examples that use similar elements or have similar goals so that the designer can use these as examples or analogies. These other examples can be related artifacts, such as other spiral staircases or buildings, or natural objects with similar shapes or goals, such as snails. By retrieving examples that are functionally similar as well as examples that are perceptually similar, these tools can aid both perceptual and functional aspects of constructive perception. A rich and relevant source of examples can increase innovation by providing the designer with ideas the designer might not otherwise consider. A broad range of new examples can also break fixation, a persistent problem for designers. These new tools have the potential not only to facilitate innovative design but also to make it more fun.

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