Abstract. Creative thought is invisible. Sketches of thought not only make it visible to others, so they can study creativity, and to self, to foster creativity. Sketches reveal thought, promote communication, and foster inference and discovery. A range of quantitative and qualitative data from coding sketches, interactions with sketches, and inferences from sketches uphold these conclusions.

1. Solving Impossible Problems

Creativity seems impossible to study. First, we don’t know what it means. And second, whatever it means, it goes on in the mind, invisibly. Whatever it is, creativity is not just wild ideas, unusual associations, weird combinations. Any dumb machine can do that, probably more effectively than people. Although it may sound paradoxical, creativity is constrained. Creative solutions may indeed appear wild, unusual, and weird, but they suit needs, fit goals, satisfy constraints. Thus, creativity has two components: divergence and convergence.

Divergent thinking expands, each connection leading outwards to many more. Convergent thinking reduces, requiring connections across the divergent ones. Either of these processes quickly exhaust the mental workspace. There is an ancient solution: make the mental workspace physical, put it in front of the eyes instead of behind them. One of the most flexible cognitive tools is a sketch or diagram. Just as a stick lengthens the arm, a sketch lengthens and broadens the mind.

Sketches externalize thought, expand the mind, force abstraction, provide a playground for exploration of new ideas, make ideas visible to self and others. They are a natural tool for designers as they map space onto space. They are often augmented, especially in social situations, with talk and gesture, primarily iconic and deictic gestures. And, a boon for researchers, sketches provide data for those who wish to study design.

Externalizing ideas onto paper has benefits beyond extending the mind. Paper provides a space, a space that can be organized, just as we organize physical spaces to suit our needs and just as the natural physical organization of space suberves memory and behavior. Thus, a diagram invites structuring a set of ideas using a variety of devices (position, indentation, size, etc.). Diagrams make abstract problems concrete, hence easier to conceptualize. They promote inferences based on spatial reasoning, proximity, direction, distance. For designers of any kind, diagrams invite not just organization but also reorganization, easy trial and error.

But, as for many tools, cognitive or physical, diagrams have disadvantages as well, many of them their very advantages. They make the abstract concrete. They promote concrete spatial thinking. They structure and organize. Thus, diagrams can constrain thought in ways that have nothing to do with the problem at hand. Working effectively with diagrams requires expertise, to make the concrete abstract again, to see abstract implications in concrete spatial relations, to reconfigure configurations. These processes will be documented by several ongoing research projects examining inferences from diagrams for science, engineering, and design.
2. Sketches Reveal Thought

Sketches are exactly that, schematic. They give an idea of what a designer has in mind, but they are inexact and incomplete, blobs for entities, like buildings, rough lines for relationships, like paths. They omit detail that hasn’t been worked through or that is not relevant. In emphasizing the essential aspects of the design they may exaggerate and distort others. They simplify. In so doing, they can reveal the underlying representation or model the designer has in mind. The schematic nature of diagrams also invites inferences and enables revisions, tools for thought.

2.1 MAPS

Maps are one of the commonest uses of sketches, by everyone. People’s sketch maps of regions or routes typically straighten curved roads and make streets more parallel and perpendicular. Just as they don’t pay much attention to angle, they don’t pay much attention to distance, often compressing large empty distances and enlarging small ones that contain much information. They reduce large complex environments not just in size but in detail, including only detail of relevance (e.g., Fontaine, et al., Lynch, 1968; Taylor and Tversky, 1992; Tversky, 1981). Route maps get further simplified; they typically include only the relevant from-to path (Tversky and Lee, 1998, 1999). People’s mental representations of urban environments, then, consist of links and nodes, where the links are typically roads, and the nodes are typically intersections or landmarks, usually accompanied by names. Significantly, this same structure, and the same elements, underlies people’s descriptions of environments (e.g., Taylor and Tversky, 1992; Tversky and Lee, 1998, 1999). This suggests a phenomenon that we have found across many domains: the same mental model drives descriptions and depictions.

How do we know all this? That is, how do we study the sketches? We collect a large number from individuals under standard conditions and code them. The coding is both a priori—we have some ideas of what we expect to find and look for them—and a posteriori—in looking through the maps people produce, we see phenomena that seem interesting and code those as well. The coding takes into account what isn’t there as well as what is there. For what is there, it takes into account how it is visually represented. Roads, for example, are usually there, as single or double lines; some landmarks are there, usually as blobs. In the distortion of angle and distance, we compare the real angles of streets and distances to what participants produce. Similarly for omissions, we compare what people put in their maps to what they could have put in. We count all those cases and compute statistics on the counts. Then we generalize, making small leaps from the data: to the notion of links and nodes; to the distortions of angle and distance; to the essentials, from what is and isn’t.

2.2 BUILDINGS

As many writers on the topic have noted, architectural sketches, buildings are similarly represented (some of the many: Goel, 1996; Goldschmidt, 1991, 1994; Gross, 1996; Laseau, 1989; Robbins, 1994; Schon, 1983; Suwa and Tversky, 1997): blobs of varying shapes, some suggestive, some neutral, for structures and single or double lines for paths among them.

2.3. Systems design

A current project is examining how master’s students in a course in design of information systems create and use sketches in the service of design (Nickerson, Corter, Tversky, Zahner, and Rho, submitted). The design of information systems is elusive because systems consist of concrete objects like computers and servers which have a real configuration in real space.
However, what is critical is not the real configuration but a functional conceptual one; how the objects are networked. What is particularly hard for students to grasp is a bus, a module or group of objects that are mutually interconnected, but may have unique links into and out of the group. As the course progressed, students were given a series of design tasks. They were typically given a description of a system to be designed and asked to make a sketch of the system, and also to make inferences from the system, typically, the set of shortest paths through the system. Reasoning about paths of information flow is crucial to system design. Both their diagrams and their inferences showed that especially early on, they had problems with the bus structure, indicated by faulty sketches as well as errors of commission, specifically, listing paths that were not shortest paths. This is a sequential bias, to treat all connections as linear and ordered. Systems diagrams bear some resemblance to route maps, which are appropriately regarded sequentially. The inference errors of omission indicated a second bias, a reading order bias. Students tended to list shortest paths from upper left to lower right, and to miss the later paths. Importantly, students who did master the bus in their sketches made more correct inferences from them. The data supporting these conclusions depended on characterizing the diagrams as well as the inferences and comparing the two.

Other work on diagrams corroborates these finding. One striking example is a resistance to diagramming cycles as circles. When students are asked to make a representation on paper to show the seasons or to show the water cycle, most students make linear arrays rather than cyclical ones (Kessell and Tversky, 2007). That is, they see the processes as having a beginning, middle, and end rather than endless repetition. Research on describing environments represented as sketch maps revealed a reading order bias (Taylor and Tversky, 1992). When the environments had a natural beginning, like an entrance, people tended to start their descriptions at the entrance. But when environments did not have a natural beginning, people began their descriptions at the upper left. Put together, the findings suggest that students bring habits from everyday spatial reasoning and interactions with text and with simpler diagrams, such as maps, to the creation and understanding of sketches of more complex and subtle ideas. The implication is that creation and interpretation of sketches should be carefully taught.

2.4 IDEAS

It has become clear that the basic structure of a broad range of sketches is nodes and links, where nodes are typically visible entities and links are spatial relations among them. Another, more abstract, way of putting it is that the nodes are nouns and the links are predicates; nouns and predicates of course are the basic elements of language. In fact, the node-link structure is also commonly used for abstract ideas, where the nodes are virtual entities, concepts, and the links are relations among them. The applications are too many to list, from concept maps to encourage order in ideas in school children to flow charts to decision trees to visualizations of the web. The ubiquity of node-link diagrams suggests that they reflect core qualities of human thought.

2.5. More Than Nodes and Links

Nodes and links do not exhaust what sketches do and can do. As noted, sketches add language, where depictions won’t do. Sketches add icons for objects, buildings, and the like. Sketches add a range of schematic graphical forms, lines are one, but that group also includes arrows, boxes, blobs, brackets, boxes, and more. These especially have meanings that are readily interpreted in context from their geometric or gestalt properties (Tversky, Zacks, Lee, and Heiser, 2000). Lines connect, indicating relations; arrows are asymmetric lines, indicating asymmetric relations. Boxes contain and separate. Blobs are vague shapes, indicating 2- or 3-D objects that make take more definite shape. Because these schematic forms readily take on meanings that vary with context, they are useful and used across a broad range of sketches and diagrams.
3. Sketches Foster Collaboration

Sketches, as we have seen, make ideas public, the invisible visible. The externalization of thought onto paper, where it can be inspected and reinspected, eases communication. Sketches are more permanent than speech, and ideas structured on paper are more interpretable than ideas conveyed in words. They provide a physical model that can be internalized to a mental one.

Sketches also allow easy embellishment with speech and gesture, to further enhance communication. Because much essential information is there in the sketch, that information doesn’t have to be conveyed in awkward, clumsy speech. It can be pointed to or gestured on, accompanied by deictic terms like “this,” or “that way,” or “from here.” In one project, pairs of participants were given a hypothetical map of a situation on campus after an earthquake, where some roads were closed, and injured gathered at special places. Participants were asked to draw a new map showing a route that would rescue the most injured as efficiently as possible. Some pairs worked over the same map, so they could gesture and see each other’s gestures. Others were separated by a curtain, so they could easily hear each other, but not see each other. The groups who could work together over the same map produced far better new maps in less time, and were much happier with the interaction (Heiser and Tversky, 2004; Heiser, Tversky, and Silverman, 2004). The main kinds of gestures were pointing at landmarks (0-D), tracing paths (1-D), and sweeping areas (2-D). These gestures served dual roles, a deictic role of pointing to or indicating particular places and an iconic role, showing the shape of something. The dependent measures here are the quality of the sketch maps, as rated by blind judges, the subjective reports of the participants, and the analyses and comparisons of the gestures and the accompanying speech for both groups of participants, co-present and remote.

In this case, the gestures on the sketches were in the service of the design of a route. There is every reason to believe that gestures and speech on sketches will facilitate communication and joint design of other things. In fact, using an externalization of thought in the form of a sketch would seem to be especially effective for more abstract ideas, which may be harder to grasp without a stable external representation that provides some structure to the ideas.

4. Sketches Promote Inferences And New Ideas

So far, we have examined how sketches represent thought and how they convey thought. Each is a step in creative thinking. But creativity also depends on going beyond what is in a sketch, in making inferences, seeing implications, altering and recombining elements, and more. There are numerous examples. The addition of arrows to diagrams of mechanical systems, such as a car brake or bicycle pump, turns interpretations from structural to functional. Without an arrow, people describe the spatial relations among the parts. With arrows, people describe the causal action of the system from start to finish (Heiser and Tversky, 2006). Data presented as bars induces inferences of discrete comparisons whereas data presented as lines induces inferences of trends (Zacks and Tversky, 1999). The students in the class in design of information systems who drew correct sketches also made correct inferences from their sketches (Nickerson, et al., submitted). Getting the sketch right gets the thinking right.

This especially holds in design, where designers use successive sketches to hold design conversations (e.g., Goldschmidt, 1991, 1994; Schon, 1983). Designers put skeletal ideas on paper, and then reflect on what they’ve drawn. Sometimes they see new things in their diagrams, things they might not have intended. Visual patterns repeated, or overall configuration; these are perceptual inferences. Designers also see, make inferences about, functional aspects of what they are designing. They may see the flow of traffic or the light changing throughout the day or seasons. They may see bottlenecks or unused open spaces. These processes can be studied using protocol analyses. As they design, designers report their thoughts out loud; their thoughts are categorized and coded, and the temporal progression and interlinking of thoughts are analyzed (e.
In our own work, we asked expert and novice architects to design a museum under certain constraints (Suwa and Tversky, 1997). They worked (with pleasure, for the most part) for about an hour, usually producing a series of sketches, gradually refining their designs. Afterwards, they were shown a videotape of their sessions and asked to report why they made every pencil stroke. This retrospective protocol analysis allows the designers to focus completely on the design task, without interrupting themselves, a more natural situation. However, it runs the risk of forgetting and reinterpretation on the part of the designers. Nevertheless, the protocols have indeed provided valuable data.

In an early analysis, the information in the protocols was categorized by topic: emergent properties such as shape and size; spatial relations such as “connected” or “near” or “configuration;” functional properties such as views or circulation; and conceptual knowledge. Typically, there were longs strings of comments on one of these topics, and then a shift of focus. The architecture students were not consistent in what attributes drove the shifts of focus or the continuing strings. In contrast, for the architects more than the students, focus shifts were characterized by both spatial and functional relations. Similarly, for the architects, the connections between the continuing strings tended to be functional much more than for students. The dual implications are that students are not adept at inferring the functional information from the sketches, and that architects are adept at integrating the perceptual and the functional when focusing to a new aspect of the design, and to continue thinking about the new aspect in high-level functional ways.

Further analyses of the data provided a window on the origin and consequences of unintended discoveries, that is, things designers see in their own sketches that they had not intended. This phenomenon points to one of the key advantages of diagrams (Suwa, Tversky, Gero, and Purcell, 2001). Designers drew them with one thing in mind, but see new relations and properties and implications once the diagram is in front of their eyes.

Sketches are deliberately ambiguous early in the design process. Designers do not want to be locked into particular structures and shapes and spatial relations at first. The ambiguity fosters unintended discovery as well as flexibility of rearrangement. In fact, the protocol of one experienced designer showed clearly that after he perceived a new arrangement of parts, he was more likely to make an unintended discovery, and after an unintended discovery, he was more likely to regroup the parts.

This positive cycle, of unintended discoveries generating reinterpretations and reinterpretations generated new unintended discoveries seems general and productive. In a partner study, students were asked to generate as many interpretations as possible for a set of ambiguous, suggestive sketches. Those who spontaneously adopted a strategy of mentally reorganizing the parts of the sketch generated significantly more new interpretations than those who didn’t.

Generating new interpretations is an essential part of creativity, the divergent part. But especially in design, creativity needs also to be focused to an end or an outcome. That requires convergent thinking. Further research investigated that, again using the generate new interpretations paradigm (Suwa and Tversky, 2003). In that study, students, both designers and non-designers, were first given a remote associates test, requiring then to find a relationship between distant word concepts. This requires focusing on the often abstract detail or details that connect the concepts. Students who scored high on remote associates also produced more interpretations for the ambiguous figures. These two predictors of generating new ideas, reinterpretation and remote associations reveal two sides of creative thinking: reorganization and connection, divergence and convergence. In the service of design, this dual set of processes was termed Constructive Perception, the active reorganization of perception in the service of a design...
aim. Like other design processes, especially sketch-dependent ones, it is an iterative one: looking, seeing new arrangements, perceiving new relations, inducing new design roles. Constructive perception is a pair of abilities, but a pair of abilities that can be trained.

These related projects have integrated three methods in the study of design creativity: retrospective protocol analysis that reveals the hidden design deliberations and decisions; generation of new interpretations of ambiguous figures; individual differences; expertise. Two factors foster the creative use of sketches, expertise and ability, and these trade off, one can compensate for the other.

5. What Can Be Learned from Sketches?

Sketches are a cognitive tool, closely related to diagrams, visualizations, and graphics. Here, a variety of projects were reviewed, demonstrating a variety of roles for sketches in design: revealing thought, fostering collaboration, and promoting inference and discovery. Although the present focus is design, sketches, and even more, their tidied-up sister, diagrams, are effective in learning, teaching, thinking, and communication in many other domains of life, getting from one place to another, putting something together, operating equipment, understanding scientific phenomena, sharing and revising ideas (e.g., Tversky, 2001). What makes sketching in design special is ambiguity. In navigation, in construction, in instruction, in communication, clarity is essential, and diagrams are often even distorted in order to make essential information clear. In design, especially in creative design, ambiguity is essential, as ambiguity encourages many interpretations and reinterpretations.

Sketches are a natural tool used in design of the concrete and the abstract. They expand the mind, make thought visible, and allow inspection and reinspection, promoting inferences and fostering recombinations. These processes and more have been revealed from studying how sketches are produced and used by novices and experts.

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