Discussion Paper: Architecture

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Thinking with Diagrams in Architectural Design

1. Introduction

Diagrams are essential representations for thinking, problem solving, and communication in the design disciplines, in particular disciplines concerned with making physical form: mechanical and civil engineering, graphic design, and architecture and physical planning. We focus here on architectural design, though diagrams are used in similar ways in these other design disciplines.

Diagrams are the primary form of representation in design. Traditionally the designer's job is to produce a "working drawings", a set of blueprints handed to the builder or fabricator that specifies what is to be made[*] . The representations the designer makes during design to explore and evaluate alternatives are more abstract and less precise than the working drawing, but, with the exception of physical models (which, one might argue are really a kind of three-dimensional drawing), all external representations made take the form of drawings. The earliest representations in this process are diagrams.

Unlike in the other disciplines such as mathematics or chemistry, designers think almost exclusively with diagrams. All design is done with drawings and drawings are done in every design. So we cannot compare design done with drawings versus design done without them. We can, however distinguish between diagrams and other forms of drawing - the sketch, the more formal schematic drawing - and study the relations between drawing forms and various design activities.

In the early design process, designers draw diagrams and sketches to explore ideas and solutions. Designers are trained to use paper and pencil to develop conceptual designs. They draw to develop ideas and communicate their thinking through the act of drawing. Design drawing is an iterative and interactive act involving recording ideas, recognizing functions and meaning in the drawings, and finding new forms and adapting them into the design. Drawing educator Betty Edwards argues that drawing is important not only as a vehicle for communication with others; the act of drawing actually helps designers see and understand the forms they work with (Edwards 1979). This theme - the act of drawing is intimately bound with thinking - echoes throughout the studies we review here.

Design diagrams convey topology, shape, size, position, and direction. In this they differ from the diagrams in other domains, which typically employ only one or two of these characteristics to convey meaning. For example, analog circuit diagrams convey only the identity of components and their connections position, direction, and size are unimportant. The design of physical artifacts is ultimately about the configurations, connections, shape, and orientations of elements. Even the most abstract design diagrams are early efforts to explore and resolve spatial layout concerns. Design diagrams do not necessarily only represent physical elements, but also forces and flows that the designer must consider (e.g., forces of sun, wind, and flows of people and materials). Thus one often finds arrows, lines, and other symbolic representations of forces and flows. The symbols typically convey spatial characteristics such as magnitude and direction.

In the remainder of the paper, following a brief discussion of the types of drawings in design, we focus on freehand design diagrams. We examine the roles of diagrams in design as discussed in several different sources:. First, we look at pedagogical books that aim to teach students the skills of architectural design through drawing. Second, we review several recent studies on drawing in design, which employ interviews and surveys of architect's drawings. Third, we look at several designers' introspective accounts of diagrams and design. Fourth, we look at several

empirical studies of the use of drawing and design, including our own work on the connection between graphic symbols and specific design concerns. We conclude with a brief discussion of computational approaches to support the use of diagrams in design.

2. What's a diagram?

Let us begin with a few definitional remarks, to distinguish diagrams from two other forms of drawing commonly used in design: sketches and schematic drawings. Certainly some drawings blur these boundaries: sketchy schematics and diagrammatic sketches; the categories are useful nonetheless. We mean by an architectural "diagram" a drawing that uses geometric elements to abstractly represent natural and artificial phenomena such as sound, light, wind, and rain; building components such as walls, windows, doors and furniture; and human behavior such as sight lines, perception of privacy and circulation, as well as territorial boundaries of space or rooms. A diagram may indicate visual phenomena such as wind, rain and sunshine, sight views and lighting, but it also can illustrate human perceptions of the environment such as noise and heat, as well as functional aspects of the environment.

A diagram, unlike a sketch, contains symbols. For example, a diagram might include an arrow indicating directional "force"; a symbol like this is unlikely to appear in a sketch. A diagram represents abstractly without giving detailed descriptions of scale or realistic pictorial representations. A diagram indicates spatial relationships only approximately, using indefinite shapes. For example, a 'bubble diagram' represents functional spaces in a floor plan with rough sizes, adjacencies, containment, and connections. A design diagram can be spatial, showing (for example) the relative positions and approximate sizes of rooms, or it can be non-spatial, showing a sequence of building construction.

A sketch, in contrast, is mainly about spatial form. For example, a perspective sketch provides three dimensional information about a scene, specifying the shape of physical elements and their spatial relationships. A plan or elevation sketch may be concerned with the proportions of a building or its components. Although a sketch falls short of precisely specifying dimensions and shapes, it provides more shape and dimension information than a diagram. A schematic drawing also differs from a diagram, having features of both a diagram and a sketch. It uses conventional symbols to represent building components and, typically drawn freehand (that is, not drafted with parallel rule and triangle), the schematic drawing retains the spatial feel of a sketch. Drawn to scale, it is more complex and precise than a diagram, yet it does not attempt the accuracy and precision of a working drawing.

3. Drawing in architectural design education

Diagrams play an important role in the education of architects. Several architectural books aimed at educating novice designers focus on specific drawing methods and techniques. In "Design Drawing Experiences," architect Kirby Lockard proposes that the ability to "diagram" a context depends on designers' knowledge of related issues in a setting, such as sun, wind, vegetation, traffic and surroundings. He argues that diagramming can be used to explore variations of design problems and that it allows our mind to "see, comprehend and respond" to more visual information than we can remember from verbal notes (Lockard 1973).

Diagrams transform verbal notation to an abstract graphic representation. Architectural educator Paul Laseau's "Graphic Thinking" (Laseau 1980) is a guide to making drawings for working out problems, and communicating with others. Laseau describes drawing as a means for design development, a "diagram" as an abstract graphic language, like verbal language, consisting of grammatical rules and vocabulary. He argues that a verbal language is sequential while a graphic language is simultaneous: "all symbols and their relationships are considered at the same time." Laseau calls a "diagram" an abstraction of architectural program. Diagrams are a means to express functions, the relationships between functions, and the hierarchy of those functions. They are drawn to present points of concern where shapes have no specific position implications.

Likewise, in "Art and Visual Perception," psychologist Rudolph Arnheim proposes that to diagram is to represent an object with its properties by "greatly deviating from its photographic appearance" (Arnheim 1974). He uses a subway map to show how a diagram can use simple elements to give needed information with clarity. The map diagram displays only topological properties accurately, it reduces and distorts factual geographic information by representing roads with straight lines, and it reduces angles to simplistic ninety and forty-five degrees.

4. Diagrams in professional practice

Diagrams are also used in professional architectural practice. In most firms, designing begins with a diagrammatic depiction of the architectural program. Gradually, the diagrams are transformed to more complex graphic representations by adding detail. One designer explained designing as a process of transforming and merging diagrams, "trying to take a structural diagram, a functional diagram, and a circulation diagram" and "combine[ing] them" (Rowe 1987). Designers often work by making diagrams or transcribing diagrams from their design team colleagues for further development (Graves 1977; Lockard 1977) .

Several recent design studies focus on the connection between design practice and drawing. They use case studies of well known architects through interviews, observations and works from portfolios. In "Design in Mind" (Lawson 1994) design theorist Bryan Lawson interviewed ten famous designers to study their design approaches, concluding that the act of drawing plays an important role: the designers "find it hard to think without a pencil in their hand" (p 141).

Diagrams are drawn to focus design knowledge and concerns. Peter Rowe's "Design Thinking" (Rowe 1987) examines how architects and planners use drawings to explore shapes for buildings and public spaces. Rowe explains that diagrams are used to establish guidelines or rules that help the designer plan and prepare for subsequent exploration, for example, placing vertical elements to define the street plaza . Fraser and Henmi's "Envisioning Architecture" (Fraser and Henmi 1994) looks at how techniques used to make different drawing types influence the making of architecture. They defined "diagrams" as "drawings" which engage in a "self-conscious reductive process," attempting to make clear a specific interpretation by excluding information the authors deem "irrelevant." They note that architects "symbolize...intangible factors such as movement, access, sound, view, function, and time.." (p 110) in diagrammatic form to represent the abstraction and reduction of information.

Diagrams are also used to explore, analyze and synthesize ideas. Dan Herbert's "Architectural Study Drawings" (Herbert 1993) examines the graphical media and design processes used by six practicing architects. He describes a diagram as an analytic statement that may be a "composite of graphic marks and written notes." A diagram thus governs and transforms the meanings of verbal statement into a graphic context to solve design problems. He also argues that drawings are more than just a convenient strategy for solving design problems and that they are

"the designer's principal means of thinking" (p 1). He argues that designer "must interact with the drawing" (p 121).

Ervin in "The Structure and Function of Diagrams in Environmental Design" characterized diagrams not only as "abstract," "topological," but are also "prepositional" with low resolution compared with pictorial maps. A diagram deals with organizing principles and relations between physical elements (Ervin 1989). He argued that the use of diagram in designing is a sequence of refinement. For example, the urban design beginning with a diagram of elements of urban forms such as plaza, building blocks and streets and with their topological relations, then adds details: such as size, shape and tone and using design "rules" to develop the design. Finally, the symbols are replaced by physical elements.

Diagrams played an important role in Christopher Alexander's early descriptions of design process. His "Notes on the Synthesis of Form" described the diagram as the "starting point of synthesis," and the end product is "a tree of diagrams." He describes design as matching program requirements with corresponding diagrams (Alexander 1966b) arguing that "any pattern which, by being abstracted from a real situation, conveys the physical influence of certain demands or forces is a diagram...." (p 85). Alexander and Mannheim in "The Use of Diagrams in Highway Location" (Alexander and Manheim 1962) outlined a graphical technique for siting a road in a landscape. Their diagrams, (crude maps), indicated the feasible region for siting the road, each with respect to a different criterion, with more favorable locations shaded darker. Then they overlaid the maps to obtain their spatial intersection, which synthesized the feasible region considering all the criteria. (Alexander 1966a)

5. What architects say about diagrams

We find diagrams in the sketch books of famous designers such as Louis I. Kahn (Brownlee and Long 1991), Le Corbusier (Guiton 1987; Sekler and Curtis 1978), and Peter Eisenman (Eisenman 1987). For example, Kahn's diagrams of Unitarian Church in Rochester, (Figure 1) use geometric shapes such as circles, squares, arrows and lines with text annotations to explore spatial arrangement of functional spaces.

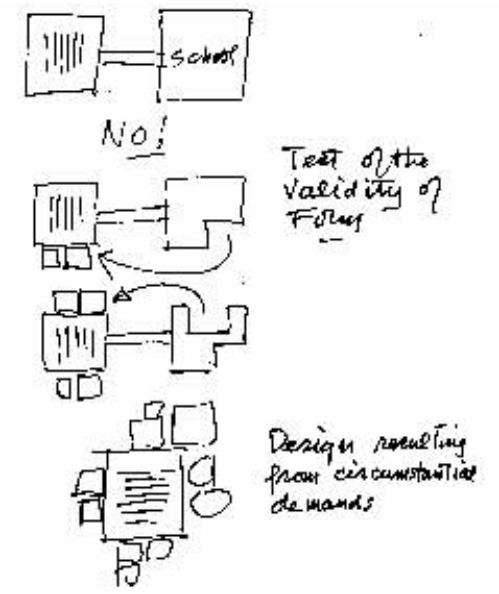

Figure 1. Diagrams with simple geometric shapes, Unitarian Church

in Rochester by Louis I. Kahn (Brownlee and Long 1991).

Many architects express the importance of diagrams and drawing in their design process. For example, Graves explains that the "referential sketch" serves as the architect's "diary" or record of discovery (Graves 1977). It is a "shorthand" notation, a "reference" of an architectural theme recorded to be "used, transformed, .. engaged," elaborated and combined with other sketches in a later composition.

Gunnar Birkerts in "Process and Expression in Architectural Form" shows examples of his own projects with drawings from various stages to illustrate the development of design (Birkerts 1994).

The margins of Kevin Lynch's "Image of the City" (Lynch 1960) contains a fascinating sequence of tiny diagrams that illustrate symbolically the ideas about the built environment and cognitive maps described in the test. Each diagram is composed of only a few lines or symbols, yet together the hundred or so together demonstrate the diversity of meaning that can be conveyed -- or at least illustrate -- using a small set of symbols and spatial relations.

6. Empirical studies

Protocol analysis studies have been used to study problem solving in design. All these research involved the collection of both verbal and visual data. In one of the first protocol studies of design process, Charles Eastman showed that the representations designers use - words and drawings - correlate with the problems they find and solve(Eastman 1968). He argues that design is a problem solving activity performed through sketching. In his study, six subjects performed a simple task of improving a bathroom layout through drawing. Eastman documented the design operations they used, the objects they manipulated and the "control mechanisms" they employed.

Akin's "Psychology of Design" (Akin 1986) followed Newell and Simon's information processing model of human problem solving (Newell

and Simon 1972). Akin's protocol studies of architects sketching analyzed the chunking of design actions and their shifts in attention. His experiment on recall looked at the time interval between the drawing of lines to identify the grouping of architectural elements in memory. His study revealed several chunks: the wall and window segments, steps, furniture of similar size that have close spatial relations. However, he did not identify the symbols and their configurations these architects used when they performed the recall tasks through drawing.

A more recent chunking study was done by Suwa and Tversky (Suwa and Tversky 1996); they video taped architects sketching to design an art museum. While watching the tape, the participants then reported what they had been thinking about. Suwa and Tversky looked at the relation between concepts (as identified by chunks in verbal post-design review protocols) and graphical acts of sketching, arguing that seeing different types of information in sketches drives the refinement of design ideas. Suwa and Tversky classified the information in the protocols into different categories such as spaces, things, shapes, views, lights and circulation. Based on this study, they proposed a computational tool that responds to sketches to stimulate design thinking.

In a recent paper (Akin and Lin 1995), Akin and Lin observed that previous protocol research mostly emphasized recorded verbalizations and that little has been written about the role of drawings produced in the protocols. They discussed symbolic encoding of different modes such as drawing, thinking, examining and speaking. In their two-part experiment subjects were asked (1) to reproduce a drawing from a printed transcript, and (2) to predict verbal data from a video of the design drawing process with the sound track suppressed. They conclude that the verbal transcripts and drawings are complementary, and echo each other. They point out that novel design decisions often occurred when the designer was in what they call a "triple mode period": drawing, thinking, and examining.

Donald Schön analyzed protocols of architects' sketches in an attempt to infer their design reasoning. He argues that design reasoning employs (among other things) the use of design rules (Schön 1988). He asked architects to make guidelines for entrance locations for a library, given a diagrammatic building 'footprint' (outline). Schön says that his protocols show that rules derive from previously known types, and may be "subjected to test and criticism" by reference to these types. Designers frame a design problem, "set its boundaries, select particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves." In "The Design Studio" (Schön 1985) Schön uses design sketching protocols to illustrate the idea of "reflection-in-action." He argues that designers first "see" then "move" the design objects. He categorizes the kinds of seeing and their functions as (1) literal visual apprehension of marks on a page, (2) appreciative judgments of quality, and (3) apprehension of spatial gestalts (Schön and Wiggins 1992). Schön uses examples from protocols to portray designing is a "reflective conversation with materials". The structure of design, he proposes, is a structure of "seeing-moving-seeing," an interaction of designing and discovering.

Gabriela Goldschmidt's design protocol studies, like Akin, examine drawing as well as verbalization. In "Dialectics of Sketching" (Goldschmidt 1991), Goldschmidt proposes that sketching is a mode of visual thinking and imagery is a conceptual framework for investigation. She views sketching as an operation of design moves and arguments, an "oscillation of arguments" that results in the gradual transformation of images. Sketching, she argues, is a systematic dialectic between the "seeing as" and "seeing that" reasoning modalities. Goldschmidt uses protocols to support her oscillation theory of "seeing as and seeing that." Her studies showed that design sketches are not merely representations of images designer already have in mind, but that the act of sketching is a vehicle for design thinking.

All the above studies describe the association of thinking, verbal protocols with design drawing. However, none identified the graphic symbols designers use in design. They mainly looked at the verbal descriptions of design problems and solutions, the state shift or chunking of the thinking.

Do's study, however, focuses on identifying the association of the drawing marks with the design thinking. "What's in a diagram that a computer should understand" (Do 1995) reports empirical studies on design problem description and diagramming to explore the feasibility of diagram based interfaces for design. The experiment used diagrams and stories from a case based design aid Archie (Domeshek and Kolodner 1992; Kolodner 1991; Zimring and others 1995) as test material. Archie is a database library that consists of post occupancy evaluation cases. The experiment took place in an undergraduate design theory and method core course. Sixty two design students were divided into four groups with variations of task sequence and supplement of text titles. The whole experiment comprised four tasks: making diagrams from stories, writing stories from given diagrams, pairing diagrams and stories and commenting on the existing Archie diagram-story pairs. We found that 1) designers only use a small set of symbols in their drawings and arrange them in conventional and consistent ways (figure 2 shows the lexicon of symbols they used), 2) designers exhibit different view preference for different concepts (e.g., plans or sections) to illustrate different sorts of problems (e.g., spatial arrangement versus getting light into a building), 3) keywords from the stories are often used as labels in diagrams, and vice versa, and 4) designers mostly agree with each others' diagrams.

Figure 2. Designers used conventional symbols and configurations for architectural concepts in diagrams.

7. Computational Inquiry

Given these observations about design reasoning and the various ways that drawing seems to support it, we come to the question of whether artificially intelligent computational design media--'intelligent paper'--can support design better, and if so, how? We believe that sketching programs that take advantage of AI techniques can indeed provide an enhanced environment for design. We mention two complementary approaches to computational support for design diagrams: Stephen Ervin's "Constraint Based Diagrammer" (Ervin 1990), and our own freehand drawing program, "the Electronic Cocktail Napkin" (Gross 1996; Gross and Do 1996).

Ervin's Constraint Based Diagrammer (CBD) is a system for translating symbolic propositions into graphics. The program has a set of default rules for creating objects and representing class distinctions between them, a vocabulary of diagrammatic relations between objects, and a set of default rules for generating graphics from these objects and relations. Provide the system a set of propositions, and CBD generates default diagrams that with objects and relations between them derived from the given statements. In other words, CBD generates diagrams from propositionally stated relationships such as the containments, adjacencies, and connections among elements.

The Electronic Cocktail Napkin, conversely, recognizes and parses hand drawn diagrams into relational propositions. The Cocktail Napkin program (Gross 1994a; Gross 1995; Gross 1996), as the name suggests, aims to support the kind of activity of scribbling that happen on the back of an envelope or on a cocktail napkin. Designers employ a digitizing tablet and a cordless pen, or a mouse or a PDA (personal digital assistant, e.g. an Apple Newton) for their design drawing. The program supports recognizing drawing elements, records drawing pressure and pen paths, registers author information and drawing speed and creates time stamps. Designers can diagram and sketch freely on the drawing surface, and can customize the program to recognize personal defined symbols by combining drawing elements together.

Figure 3. The Electronic Cocktail Napkin -- [a] drawing area, [b] sketchbook for storing interesting sketches.

We have built several prototype systems for querying databases of design information using hand drawn diagrams, employing the Cocktail Napkin's graphical search routines. (Gross, Zimring and Do 1994). This diagram index scheme linked specific diagrams with visual database items in a one-to-one mapping. Our more general present scheme enables several databases to be used simultaneously by virtue of a sketchbook that links diagrams with database items. The designer can paste drawings into a sketchbook, leaf through its pages, copy and modify drawings, and use the sketchbook to query the image collections. Figure 4 shows a schematic diagram of the query process.

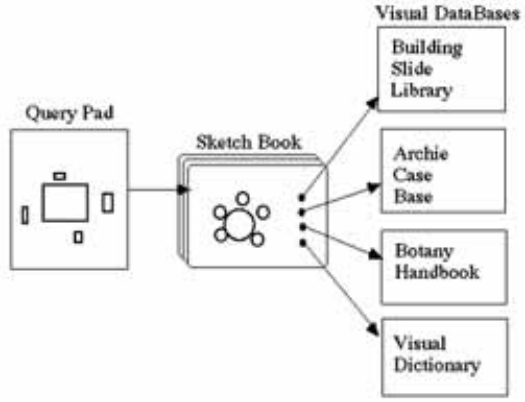

Figure 4. The sketchbook indexes several databases simultaneously, relating items in different databases that have similar shapes.

When the designer draws a diagram or a sketch on the query pad, the program's graphical similarity routines first identify the most similar sketch(es) in the sketchbook. Then the program sends database lookup calls to each of the various databases identified on that page to display their items.

A drawback of paper is that the designer must maintain the spatial relations and constraints to reflect desired or required design behavior. We have also implemented a scheme whereby the drawing program first recognizes, then maintains spatial relations in the sketch. The Stretch-A-Sketch prototype shows how `intelligent paper' might automatically keep track of these relations and ensure that the drawing reflects them (Gross 1994b).

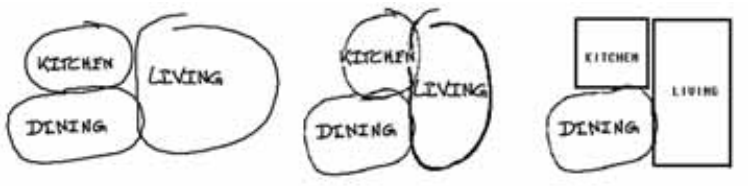

Figure 5. Stretch-A-Sketch maintains relations in the diagram. (a) diagram as first drawn; (b) after resizing a room; (c) partially rectified drawing.

We have built several prototypes in which the drawing environment is linked to an interactive simulation. In each of these programs, the designer sketches an initial design; the design is then carried over into a simulation environment, and the designer can test and evaluate its performance. For example, figure 6 shows the integration of sketching into a viewshed analysis program. In future work we would like to integrate the simulation components more tightly with the sketching (Gross and Do 1996).

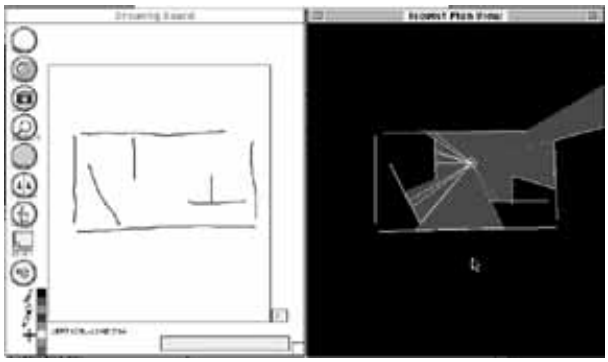

Figure 6. A drawing of floorplan activates a viewshed analysis program (IsoVist).

We have suggested that design activities involve drawing and interpreting of the drawing. These activities are closely interlinked and inseparable. We have attempted to show how we might support some cognitive processes in design such as recognition, finding references and evaluation with our freehand sketching environment.

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