Intentions in and relations among design drawings

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Designers use drawings to explore alternatives and to test ideas. We report here on two studies on design and drawing. The first study of design drawing symbols aims to determine whether and to what extent it is possible to infer, interpret, or even guess what a designer was thinking about by looking at the drawings she has made. In the second study we examined a collection of drawings for the design of a house to investigate the systems of design transformations. Drawings are characterized by drawing style, projection type, and key elements. We analyzed the relationships among the drawings and developed a notation system for documenting these relationships.

Keywords: drawing(s), architectural design, case study/studies, design activity, design research

We wish to understand the roles that diagrams and sketches play in designing, with the goal of building computational environments that better support designing than those in current use. By diagram we mean a drawing that uses geometric elements to abstractly represent natural and artificial phenomena such as sound and light; building components such as walls and windows; and human behavior such as sight and circulation, as well as territorial boundaries of spaces. In contrast, a sketch is mainly about spatial arrangements of physical elements. Despite these general differences, we do not draw clear-cut distinctions between diagrams and sketches, as a particular drawing may combine the two representations. We describe here two distinct studies of architectural design

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0142-694X/00 $ - see front matter *Design Studies* **21** (2000) 483–503
PII: S0142-694X(00)00020-X

practice that we have performed in order to understand these roles. The first study analyzes the graphic symbols architects draw as they engage with different concerns in a design problem. The second study examines the types of graphic representation made by an architect in the conceptual exploration of a design, and illustrates a scheme we developed for coding relationships among the sketches and diagrams made in the course of this exploration.

Studies of diagrammatic reasoning and design drawings have become of increasing interest to cognitive scientists, artificial intelligence workers, and researchers in design studies. Researchers in these fields have argued that drawing is important to design as an external representation that helps in solving problems and generating ideas. The roles that researchers ascribe to diagrams and drawing in design include:

- generating concepts;
- externalizing and visualizing problems;
- organizing cognitive activity;
- facilitating problem solving and creative effort;
- facilitating perception and translation of ideas;
- representing real world artifacts that can be manipulated and reasoned with;
- revising and refining ideas.

Studies of thinking with diagrams often take one of two stances. The first is that diagrams are external evidence of an internal thinking process and serve as valuable clues to reveal its functioning. The second stance is that diagrams and diagram-making are an inherent part of the thinking process, thus a 'medium of thought'. Researchers also differ on whether design drawing is essentially a symbolic process—each drawing mark corresponds to design elements or concepts—or if non-symbolic modes of thinking come into play.

Larkin and Simon argue that a diagram is a representation created to externalize and visualize problems[1], and that certain observations about a problem are more easily available in a diagram. Chandrasekaran, Narayanan, and Iwasaki[2] note an emerging consensus that diagrams function as an aid in organizing cognitive activity. Blackwell's 'Diagrams about thoughts about thoughts about diagrams'[3] reviews work in experimental psychology (e.g., [4–6]) that understands a diagram as a notation that provides information and clues about intention in a visual form. Fish, in 'How sketches work' argues that sketches are representations of 'visual thought' that help facilitate perception and translation of ideas[7].

1 Larkin, J L and Simon, H A 'Why a diagram is (sometimes) worth ten thousand words' *Cognitive Science Journal* Vol 11 (1987) pp 65–99
2 Candrasekaran, N, Narayanan, H and Iwasaki, Y 'Reasoning with diagrammatic representations' *AI Magazine* Vol 14 No 2 (1993) pp 49–56
3 Blackwell, A F 'Diagrams about thoughts about thoughts about diagrams', in **M Anderson** (ed.) *Reasoning with diagrammatic representations II: AAAI 1997 Fall Symposium*, AAAI Press, Menlo Park, CA (1997) pp 77–84
4 Goodman, N *Languages of Art: An Approach to a Theory of Symbols*, Oxford University Press, London (1969)
5 Bertin, J *Graphics and Graphic Information Processing*, Walter de Gruyter, Berlin (1981)
6 Ittelson, W H 'Visual perception of markings' *Psychonomic Bulletin and Review* Vol 3 (1996) pp 171–187
7 Fish, J C *How Sketches Work—A Cognitive Theory for Improved System Design* (PhD dissertation), Loughborough University of Technology (1996)

Suwa and Tversky report that architectural drawing reveals a designer's thinking graphically and facilitates problem solving and creative effort[8]. They argue that drawings provide the designer with visual cues for revision and refinement of ideas. They classify the information in verbal design protocols into different categories such as spaces, things, shapes, views, light and circulation. In 'Drawing and Cognition' Van Sommers[9] uses empirical studies of graphic production to argue that the act of drawing is a 'graphic engine or a production system' (p. 245) that helps people generate concepts. Goel's 'Sketches of Thought' argues that drawings are 'external symbol systems' to represent real world artifacts that can be manipulated and reasoned with[10], and that graphical representations have certain capacities that non-graphical symbol systems lack—for example, the ability to gracefully represent vagueness and ambiguity.

Schön argues that design reasoning is a thinking pattern that uses design rules[11] and a process of 'reflection-in-action'[12]. He argues that designers first 'see', then 'move' design objects[13]. Goldschmidt sharpens this notion, postulating that design reasoning consists of 'seeing as' and 'seeing that' modalities[14]. She views sketching as an operation of design moves and arguments, an 'oscillation of arguments' that brings about a gradual transformation of images[15]. Ullman, Wood, and Craig argue that in a design each marking action is an external representation of a chunk of information[16]. They note that the 'marks-on-paper contain different types of information'.

Architectural historians echo this understanding of the relationships between design and its drawing. For example, Hewitt argues that historians and theorists should look at the architectural drawing 'as a medium of thought'[17]. He argues that an 'idea sketch' may be 'personal and intuitive, or it may be based on clearly defined methodologies or programs of instruction'. This conception of design is 'a triad of interrelated operations—thinking, seeing, and drawing'. Along these lines, in a recent study, Akin and Lin[18] observed that novel design decisions usually occurred when the designer was simultaneously drawing, thinking, and examining.

Methods used in studying the role of drawing in design include analysis of think-aloud protocols, retrospective analysis of design behavior, introspection, and even analysis of design products and speculation about the processes that may have led to them.

Think-aloud protocols are often used to study problem-solving activity[19]. In examining designing, think-aloud studies typically record the designer's mark making activity (using, for example, video recording) as well as the

8 **Suwa, M and Tversky, B** 'What architects and students see in architectural design sketches: a protocol analysis', in *1st International Symposium on Descriptive Models of Design* Istanbul, Turkey (1996)
9 **Van Sommers, P** *Drawing and Cognition—Descriptive and Experimental Studies of Graphic Production Processes*, Cambridge University Press, Cambridge, UK (1984)
10 **Goel, V** *Sketches of Thought*, MIT Press, Cambridge, MA (1995)
11 **Schon, D A** 'Designing: rules, types and worlds' *Design Studies* Vol 9 No 3 (1988) pp 181–219
12 **Schön, D A** *The Design Studio*, RIBA Publications, London (1985)
13 **Schön, D A and Wiggins, G** 'Kinds of seeing and their functions in designing' *Design Studies* Vol 13 No 2 (1992) pp 135–156
14 **Goldschmidt, G** 'Problem representation versus domain of solution in architectural design teaching' *Journal of Architectural and Planning Research* Vol 6 No 3 (1989) pp 204–215
15 **Goldschmidt, G** 'The dialectics of sketching' *Creativity Research Journal* Vol 4 No 2 (1991) pp 123–143
16 **Ullman, D G, Wood, S and Craig, D** 'The importance of drawing in the mechanical design process' *Computer Graphics* Vol 14 No 2 (1990) pp 263–274
17 **Hewitt, M** 'Representational forms and modes of conception: an approach to the history of architectural drawing' *JAE* Vol 39 No 2 (1985) pp 2–9
18 **Akin, O and Lin, C** 'Design protocol data and novel design decisions' *Design Studies* Vol 16 No 2 (1995) pp 211–236
19 **Ericsson, K A and Simon, H A** *Protocol Analysis*, MIT Press, Cambridge, MA (1984)

spoken think-aloud protocol that accompanies it. Numerous design researchers have used think-aloud protocols to investigate drawing and design. In each of these efforts, subsequent analysis of the verbal and graphic protocol attempts to account for connections, correlation, and relationships between drawing and design thinking, and to identify patterns in design behavior.

Cross and Dorst suggested that although protocol analysis is a useful research technique for analyzing design activity[20,21], it has the disadvantage that concurrent verbalization and behavior could cause side effects or account for incomplete activities. Schooler and Engstler-Schooler's experiments indeed demonstrate that verbal reasoning interferes with visual reasoning in visual memory tests[22]. Wilson shows that people often misstate what they are thinking about in think-aloud protocol studies[23]. Thus, the procedure involved in verbal protocols can obstruct reasoning and may result in inaccurate accounts of the design process. In addition, prorotcol analysis usually also imposes the artificial time and place constraints of a laboratory setting.

To avoid some of these problems of protocol analysis, Suwa and Tversky instead used *retrospective* reports of design sessions[8] to study designers' perceptual processes. First, they videotaped designers designing an art museum. Later as the designers watched their own design activity on videotape, they were asked to report what they had been thinking as they sketched.

Other studies use introspective or speculative approaches instead of 'think-aloud' protocols to investigate the relationship between design thinking and drawing. For example, Galle and Kovács[24] present a record of design sketches and the 'train of thought' for a housing layout design by Galle. They argue that an introspective record allows a designer ample time for reflection and avoids reliance on an information processing model or other assumptions. They note that introspection may be a useful supplement to other kinds of studies conducted over a short period of time.

Porter and Schön carried out a *speculative* account of a design process as a 'thought-experiment'[25] to account for the underlying logic of designing. Porter claims that although 'replication' is a fictional design process that does not necessarily match the actual design experience it is a form of inquiry appropriate to teaching design and considering the potential of computer tools. He presents two examples of applying this process—to an urban design and a building, showing a plausible chain of reasoning about how the design might have been developed.

20 **Cross, N, Christiaans, H and Dorst, K** (eds) *Analyzing Design Activity*, John Wiley & Sons, New York (1996)
21 **Dorst, K and Cross, N** 'Protocol analysis as a research technique for analysing design activity', in *Design Engineering Technical Conferences*, Vol 2 No DE-83 (1995) pp 563–570
22 **Schooler, J W and Engstler-Schooler, T Y** 'Verbal overshadowing of visual memories: some things are better left unsaid' *Cognitive Psychology* Vol 22 (1990) pp 36–71
23 **Wilson, T D** 'The proper protocol: validity and completeness of verbal reports' *Psychological Science: a journal of the American Psychological Societ* Vol APS. 5 No 5 (1994) pp 249–252
24 **Galle, P and Kovács, L B** 'Introspective observations of sketch design' *Design Studies* Vol 13 No 3 (1992) pp 229–272
25 **Porter, W** 'Notes on the inner logic of designing: two thought-experiments' *Design Studies* Vol 9 No 3 (1988) pp 169–180

The two studies presented in the following sections are methodologically quite different to each other; they attempt to elucidate different aspects of design drawing. The first study, an examination of symbols through videotaped design protocols, takes the view that architectural diagram making is (at least in part) a process of external symbol manipulation, and that symbols used in a diagram can reveal the designer's intention in making it. The second study, which looks at the relationships among drawings and other graphic representations made in a design process, does not depend on a purely symbolic view of design drawing, although parts of the study do identify symbols in the graphic representations.

1 *Intentions: examination of graphic symbols in designing*

This study (carried out by Do, as part of her doctoral work, in collaboration with and under the supervision of Zimring and Gross) aimed to determine whether the graphic marks an architect makes during design correlate with the type of task that he or she is engaged in. It may seem obvious that architectural design drawings are conventional. Yet, when we proposed to architects that a computer might be programmed to read their drawings and guess what task they were engaged in, many designers doubted that this would be possible because they thought design drawing was highly idiosyncratic.

We wanted to demonstrate that the production of drawings in design is conventional—not only in that certain graphical symbols represent certain physical objects—but also with respect to design tasks and concerns. A pilot study with 62 architecture students[26] showed that designers share and can understand one another's conventions in diagramming architectural concepts. In the study summarized here we found that these results apply not only to the artificial diagramming task, but that architects employ similar conventions when designing.

We gave participants an architectural program and we asked them to carry out a sequence of four tasks, each focusing on a particular architectural concern. The four concerns were (1) spatial arrangement, (2) lighting, (3) visibility and privacy, and (4) fitting a special piece of furniture into the design. Each task in the sequence was given and carried out separately. We videotaped the designers at work, and asked them to explain what they were doing as they worked. Then we transcribed and analyzed the videotapes.

Two undergraduate architecture students and two instructors participated in the experiment. Roger, the 'functional designer', was a graduating senior

26 **Do, E Y-L** 'What's in a diagram that a computer should understand', in **M Tan and R The** (eds) *CAAD Futures '95: The Global Design Studio, Sixth International Conference on Computer Aided Architectural Design Futures*, National University of Singapore, Singapore (1995) pp 469–482 who spent all his summers working in architectural design firms. He believed that he produced good designs by making sure his design work fulfilled functional aspects. '3D sketcher' Noi was also a graduating senior who enjoyed using freehand drawing for 'everything' and was proud of his ability to draw 3D sketches from any drawing. Samuel, the 'philosopher', was an instructor. A philosophy major prior to studying architecture, he believed that everything in a design should be justified. Mario, the 'research architect', was a visiting scholar who had professional experience in architectural offices and consulting firms.

The experiment revealed several patterns of design drawing behavior: first, the four participating designers employed drawing conventions common among themselves and with the 62 architecture students who participated in the pilot diagramming study. Several drawing conventions corresponding to different design concerns were identified. For example, designers drew bubble diagrams and partitioning lines when working on spatial arrangements; they drew a sun symbol and light rays when addressing natural lighting concerns; and they wrote down numbers when reasoning about sizes and dimensions. Second, designers combine symbols in specific configurations to indicate design contexts. For example, they portray conference rooms as chairs surrounding a long table, and indicate the direction north by the letter N and an arrow. Third, designers have specific preferences for diagramming different design concerns. For example, visual access concerns are portrayed in plan view with arrows representing view lines, lighting issues are illustrated in sectional view using light rays that penetrate the building. Fourth, designers label design concepts and space names in their drawings. Finally, designers write down numbers to reason about size and scale and to calculate dimensions.

There were also individual differences among the designers. Roger, the functional designer, used a well-defined set of drawing elements to indicate different concerns. He drew bubble diagrams (Figure 1a) when thinking about conceptual, schematic design and he drew furniture such as tables and chairs in the room to test how the space would work (Figure 1b). He drew a sun symbol with a light ray penetrating the windows into the building when working on the lighting task (Figure 1c), lines and double arrow links to indicate relationships or movement for visibility and privacy issues. He used dimensional symbols and wrote down numbers when reasoning about dimensions (Figure 1d; see also [27] for a more complete account of the dimensional reasoning process).

Noi, the 3D sketcher, turned all his plan and sectional drawings into three-dimensional projections. He used lines as 'spatial partitions' to arrange

27 **Do, E Y-L and Gross, M D** 'Inferring design intention from sketches—an investigation of freehand drawing conventions in design', in **Y L Liu and J Y Tsou** (eds) *CAADRIA, Computer Aided Design Research in Asia 97*, Hu's Publishing, Taipei (1997) pp 211–221

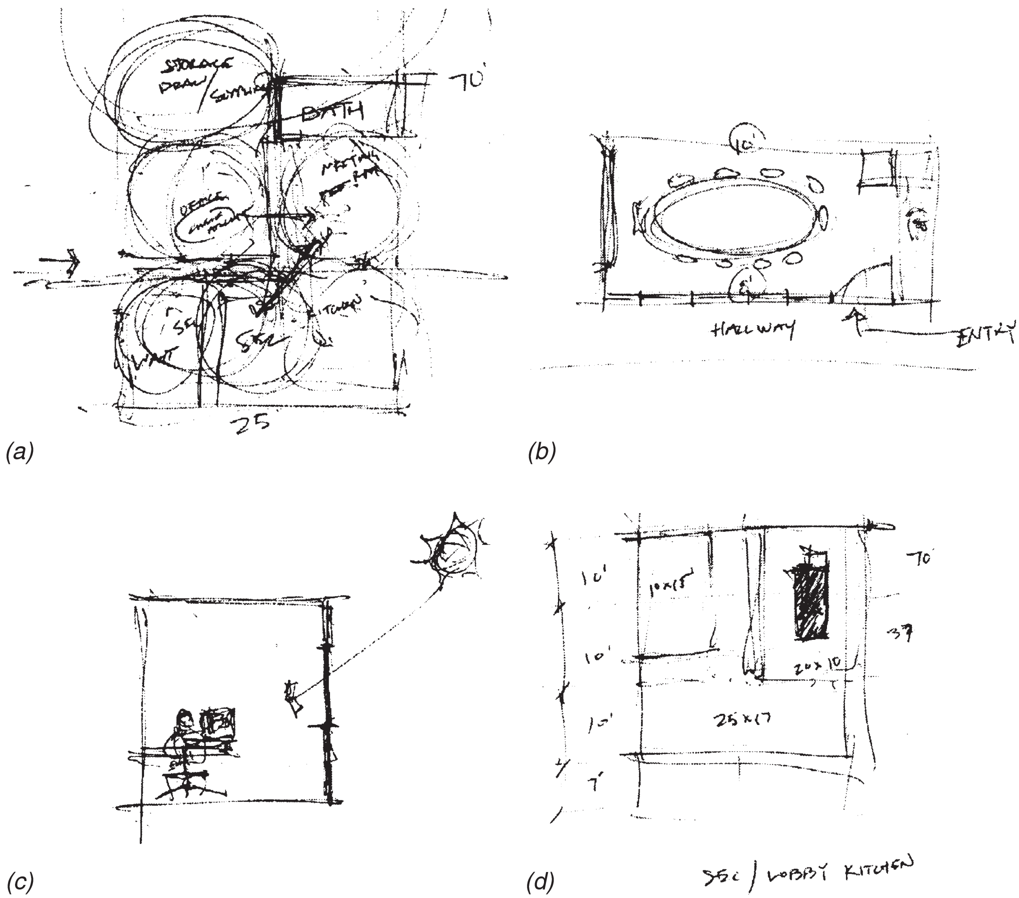


Figure 1 Roger's conventions: (a) bubble diagram, (b) furniture, (c) lighting section, (d) dimensional reasoning

space. He used a set of drawing conventions such as dimensions (70, 25) and directions (N, E, W, S). He used hatching and text labels to indicate space (Figure 2a) and drew simple furniture and human figures. Instead of bubble diagrams, Noi drew partition lines for the spatial layout task (Figure 2b) and he drew lines penetrating the building to illustrate lighting (Figure 2c).

Samuel, the philosopher, talked a lot about what he was doing and his verbal protocols were informative. However, his drawing symbols tended to be few and simple. His spatial layout plan was a hybrid of spatial partitioning and bubble diagram. He drew bubbles to represent different functional space (Figure 3a, left). He also drew many lines to define space—labeled 'chief' (architect's office), 'meeting' room, and 'kitchen'—and in

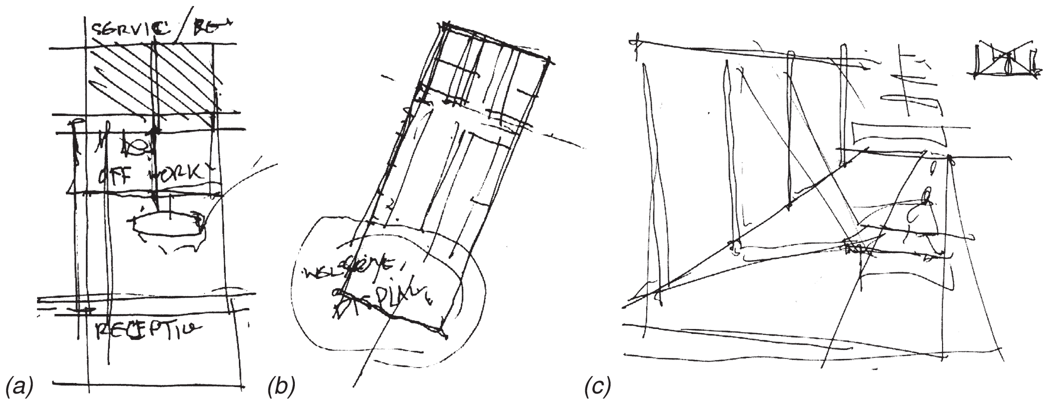


Figure 2 Noi's conventions: (a) label and hatching of space, (b) spatial partitioning lines, (c) lighting concern

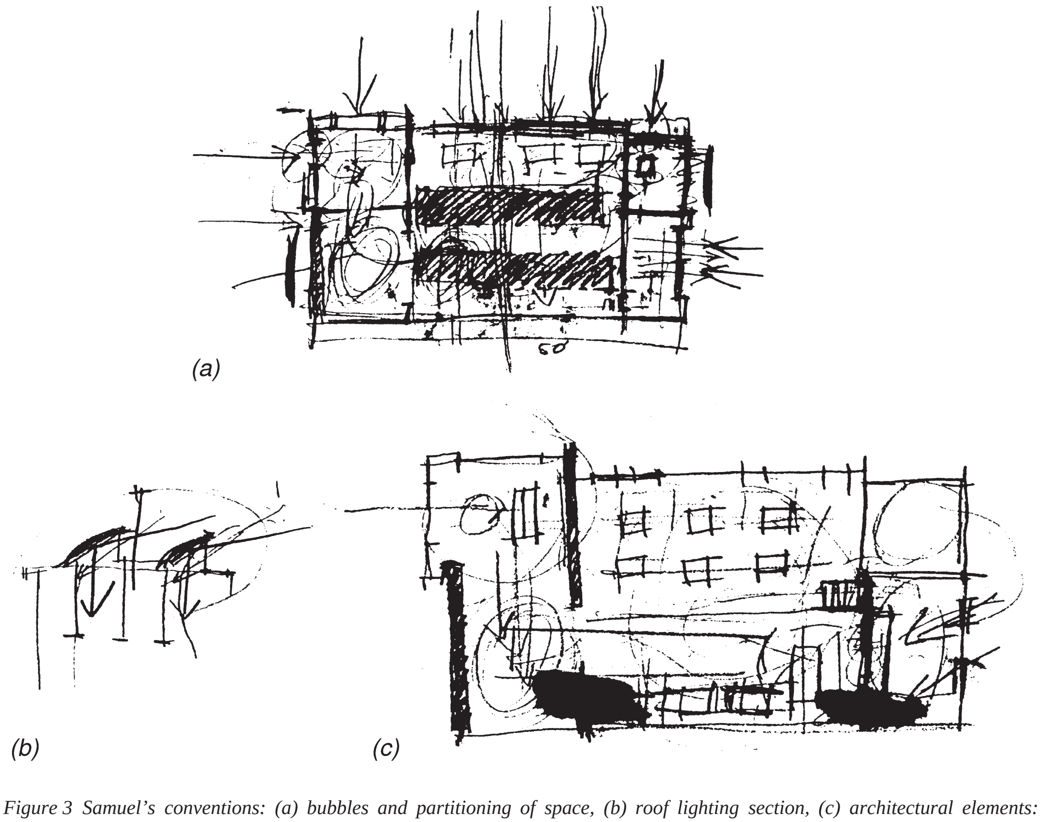


Figure 3 Samuel's conventions: (a) bubbles and partitioning of space, (b) roof lighting section, (c) architectural elements: stair, tables, windows and walls

the verbal protocol called these lines walls, windows, or screens. He drew sections with light rays to illustrate lighting (Figure 3b) and used arrows to indicate entrance, lighting and visual access (Figure 3a). Samuel also drew lines, hatching and shapes to represent windows, walls, and furniture (Figure 3c).

Mario, the research architect, mostly ignored the instruction to consider the lighting, visibility, and special furniture tasks. Instead, he used the entire design session as a testing task by drawing furniture elements to test the dimensions of the space against the program. Mario started by thinking about the site and program. Unlike other designers who underlined program requirements or drew shapes to visualize the space requirements, he copied them on the tracing paper. He proceeded to understand the dimensions and orientation, writing down numbers, using scale measurements, and indicating site orientation by the letters N, E, W, S. Next he partitioned the site to correspond to the program (Figure 4a), arranging space by drawing partition lines for walls, windows and doors (Figure 4b). Finally, he checked the partitioned space against the program functions by drawing in furniture such as tables and chairs, human figures, plants and dogs. He drew the same kinds of objects in sequence (Figure 4c, three monitors, three tables and three chairs). He used symbols to label dimensions (Figure 4d) and wrote numbers to calculate area and to convert between metric and English dimensions (Figures 1 and 4e).

1.1 Implications for computational design environments

The four design sessions showed that different concerns and contexts can be identified through drawing conventions. The graphical marks that architectural designers make are conventional and correspond to specific tasks that they engage in as they work. For example, when thinking about natural lighting, a designer might draw a configuration consisting of a symbol for

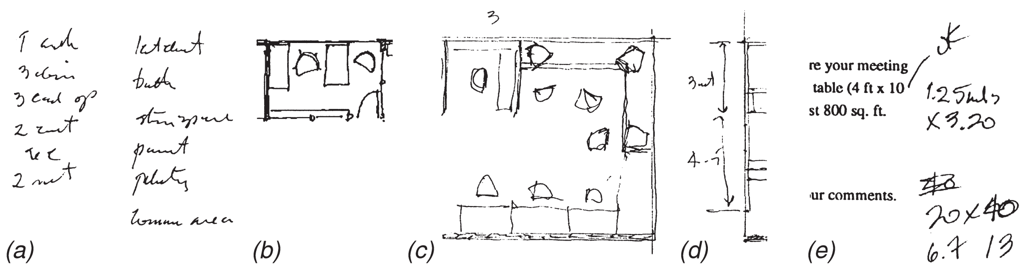


Figure 4 Mario's conventions: (a) design program as copied in writing on the trace, (b) architectural elements: door, wall and window, (c) objects drawn in sequence: three monitors, three tables and three chairs, (d) labeling dimensions on side, (e) dimensional reasoning, conversion of numeric calculations

the sun and an arrow representing a light ray in section. The presence of these symbol configurations indicates the designer's concern with natural lighting.

A computer can be programmed to recognize these symbols and configurations and infer the designer's intentions, and trigger appropriate design tools targeting the task at hand. That is, the results suggest that a computer system could infer design intentions from the drawing symbols that designers use and provide the designer with the 'right tool at the right time'. A prototype of this Right-Tool-Right-Time computer program has been implemented[28].

2 *Relations: a retrospective analysis of a pavilion house*

During conceptual design an architect engages in diverse tasks: concept formation, form-making, testing functional capacity, and exploring structural and construction possibilities. The architect moves among these activities, producing various representations: sketches, drawings, and models. From the collection of drawings for an architectural project we can trace the designer's intention through different concerns. Our second study (carried out by Do, Neiman, and Gross at the University of Colorado) examined sketches and drawings made by architect Bennett Neiman for the design of a residence. We tried retrospectively to understand the purpose of each drawing, and we constructed a conceptual framework to account for connections among the drawings.

Our study attempts to identify relationships between drawings as a way of understanding a design process. What began as a thought experiment resulted in a repertoire of plausible interpretations to account for what might have actually happened in the design process. The interpretations were made through several iterations of sorting, classification and coding. The results were later compared with the designer's retrospective examination of the drawings.

We selected for examination drawings from Neiman's personal archive of scanned images stored on six CD-ROMs. These drawings have no date or time stamps and, therefore, we could not examine the work as a sequential process. Rather, we were forced to consider all the drawings at once. We found this unorthodox approach plausible for several reasons: first, these drawings came from a real design project carried out over a period of years, rather than a controlled experiment done over the course of an hour or so. Second, Neiman's design project deals more with form manipulation than with functional problem solving that is often the subject of empirical

28 **Do, E Y-L** *The Right Tool at the Right Time—Investigation of Freehand Drawing as an Interface to Knowledge Based Design Tools* (PhD dissertation), Georgia Institute of Technology (1998) studies of design drawing. Third, dealing with the drawings as artifacts freed us from analyzing specific 'low-level' events (e.g., the order of strokes in making the drawing). Instead, we investigated patterns of design operations, manipulations, and relationships that emerge from the drawings. Finally, Neiman insisted that his method of design production did not depend on the sequence of drawings.

Neiman's design for the pavilion house is a personal design journey carried out continuously over 15 years. It was inspired by Le Corbusier's thematic elements, by an exercise offered by John Hejduk (Neiman's teacher at Yale) and by 'speculative sketches' Neiman made in his sketchbook. Here is the architect's description of the project:

> …This project begins with Le Corbusier's five points of architecture: piloti, free-plan, free-facade, ribbon window, and rooftop garden. It also investigates the idea of place within a place. The design is seen as a singular volume suspended somewhere between the sky and ground (House in a Box). A thickened wall serves as both lateral structure and threshold plane (House on a Wall). Entry to the structure is via a bridge from the north. The entry facade presents a mysterious masked plane of projections and voids that partially hide the view beyond. The verticality of the house offers numerous indoor and outdoor framed views beyond to the south. The sequence culminates with a rooftop garden. The entry level has the living, dining, and kitchen activities. The single volume is sub-divided in one primary double height volume (as living) and two secondary volumes; one as dining/kitchen, the second as sleeping quarters (upper portion of the singular volume).

We first approached the data—Neiman's collected drawings—as a puzzle solving activity in which the pieces put together would reveal the whole picture. However, in analyzing the drawings we found our original goal of 'putting everything together' unfeasible. As we looked at all the drawings at the same time, and found links between different drawings by either spatial or visual relationships, we found the design project more a puzzle making process[29].

We selected four single drawings—a 3D isometric sketch, a plan collage, a concept isometric sketch, and a section—that we thought best represented the essence of the design. We also identified key design elements that recur throughout the collection of drawings. Figure 5 shows these drawings annotated with their elements.

2.1 Analysis of the project drawings

We briefly describe our analysis and the coding schemes we used. Wang[30] presented a similar coding scheme that focused on spatial relationships between elements within a design. Our notation system, by contrast,

29 **Archea, J** 'Puzzle making: what architects do when no one is looking', in **Y Kalay** (ed.) *Computability of Design*, Wiley Interscience, New York (1987)
30 **Wang M** *Ways of Arrangement: The Basic Operations of Form-making* (PhD dissertation) Massachusetts Institute of Technology (1987)

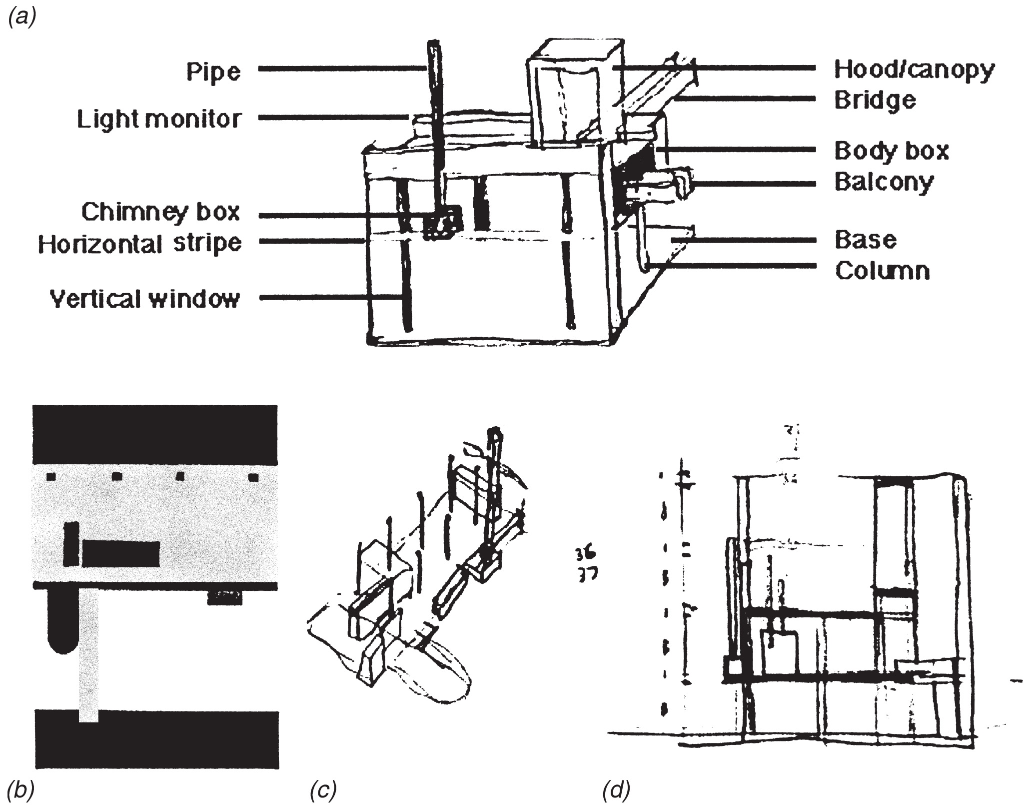


Figure 5 (a) Principal architectural elements, (b) plan collage, (c) 3D sketch, (d) section

focuses on state transformations of design elements from one drawing to another (e.g., stair moved from east to west, wall height reduced) as well as changes of view and projection type.

We performed several iterations of analysis. In an initial presentation (P1, Figure 6, left) Neiman first showed the project images with brief explanations. We questioned Neiman about the relationships between the drawings; for example, which drawings represent the conceptual ideas and references and which drawings he developed later. Neiman organized this first presentation of 44 images into six categories: (1) multiple viewpoints/ideas, (2) plan variations, (3) sections, (4) frontal projection/obliques, (5) isometric, and (6) related projects and ideas. A few weeks later, he presented the pavilion house a second time (P2, Figure 6, right) with a different organization in which one category, ‘design itinerary’, accounted for 33 images. In this category, Neiman grouped the drawings and sequenced them by drawing type: (1) reference sketch, (2) variations of object

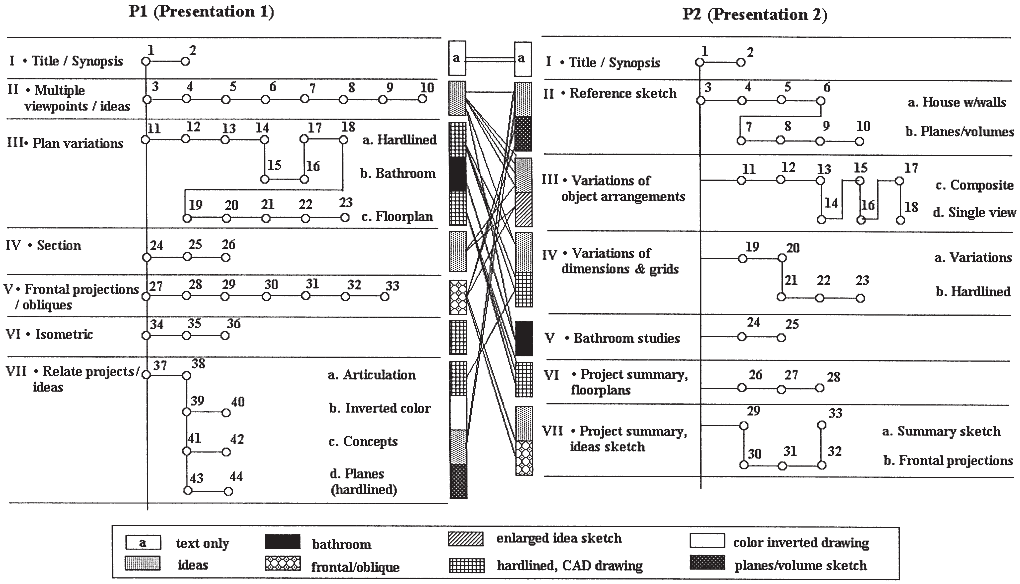


Figure 6 Graphs showing images in different categories, and relations between the location in sequence in the two different presentations

arrangements, (3) variations of dimensions and grids, (4) bathroom studies, (5) floor plans, (6) project summary.

Both presentations included concept sketches in the beginning and the end, but each was organized with a different emphasis. Presentation P1 was organized by projection types (e.g., plan, section, isometric), whereas presentation P2 rearranged the sequence according to design intentions (variations of object arrangement, dimension studies, etc.). The second presentation had fewer images (33 instead of 44) and formed a clearer sequence. Links in Figure 6 show the relationships between the positions of the 22 drawings that both presentations included.

It became apparent that two drawings may share various properties: they may employ the same projection (plan, section, isometric), the same medium (crayon, pencil and pen), or exhibit the same design intentions. They may describe the same elements (bridge, columns, stripe windows) in different configurations. They may be constructed from the same view angle. Or, one drawing may be a blow-up singled out from a composition of multiple drawings. The graphs in Figure 6 show the presentation sequence coded by different categories. For example, P1 images in the category of 'related projects and ideas' (37–44) are sorted into four subcategories: articulation study, color inverted 3D drawing, concept sketch, and planes. Likewise, images in the P2 category of 'object arrangements' are sorted into two subcategories: images that contain a single drawing and composite images of several drawings. The sequences show how Neiman restructured the presentation, regrouping slides according to the changed classification scheme. We later found that Neiman performs similar manipulations (i.e., move, rotate, view from different sides) in the design process.

After Neiman's two presentations, we arranged all the drawings on the table to make a map in which drawings are positioned by their similarity to one another (Figure 7). We identified and color-coded the main elements in the design. The elements are thick wall, bridge/entry, pipe/chimney, structure grid, light monitor, stair case/balcony, columns, infill units (fixed, e.g., bathroom and storage, and free, e.g., furniture). By color coding the elements we could easily track their presence, position, and properties in the drawings.

Making the collage map helped us recognize that many images were composed of several drawings made on the same sheet of tracing paper. Some represent alternatives, or variations on one theme, i.e., facade studies (Figure 8a). Some are different projections that explore the same idea (plan,

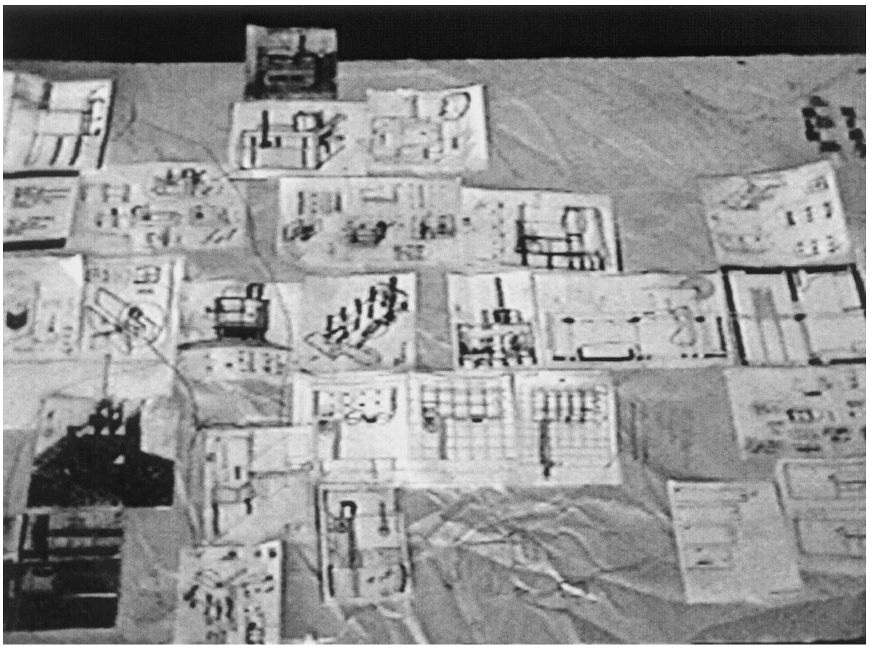


Figure 7 The collage of all drawings appearing on a relation map

section and 3D, Figure 8b). Some explore different concerns (structure grids, dimensions, functional capacity, Figure 8c).

We divided the composite images into individual drawings, assigned unique identifiers to each drawing, and pasted them up on a large sheet of paper to examine them simultaneously and in detail. We then developed a coding scheme to classify these 110 drawings. The scheme codes properties of the drawings such as the elements depicted as well as projection type and view angles. Table 1 illustrates the categories of classifications

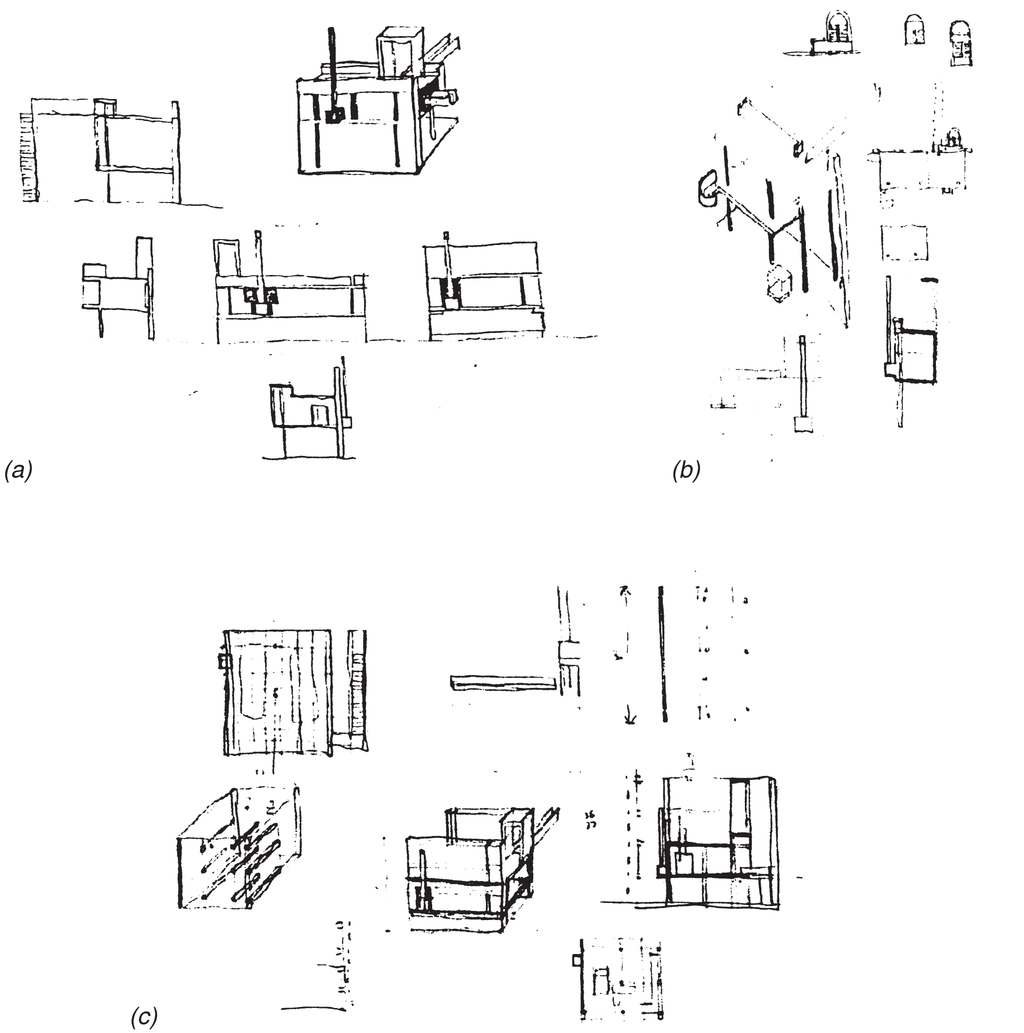
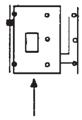
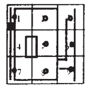
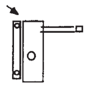
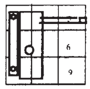
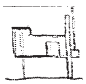
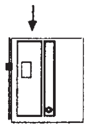
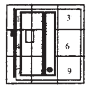
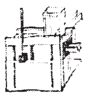
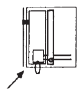
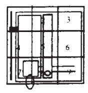


Figure 8 Compositions of multiple drawings: (a) facade variations (P1-9), (b) different drawing types: plan, section and 3D (P1-6), (c) different concerns, structure and dimension (P1-7)

Table 1 Drawings in coded table according to different classifications

ID #	*Drawing*	*Title*	*Intention annotation*	*Drawing type*	*View angle*	*Elements*	*Location/ scale*	*Medium*
P1-7g (P1-26), P2-13g (P2-14)		Section: vertical cadence	Dimension, object relations	Section (D2)		E1, E2, E3, E4, E5, E5, E5, E6, E7, E8, E9, E10		Pencil (M1)
P1-41a, P2-4a		House on a rail	Concept diagram	3D section (D4 + D2)		E1, E1, E1, E1, E3, E5, E7, E8, E9, E10, E11, E12		Pen (M2)
P1-9f, P2-15f		Thickened wall and projection	Variation of sectional space	Section (D2)		E1, E2, E3, E4, E5, E6, E9, E10, E14		Pencil (M1)
P1-30 (P1-9a), P2-16 (P2-15)		Wall and projected volumes (variations on the theme)	Isometric front; slots in wall; marking internal grid system on the facade	3D, frontal isometric (D3 + D4)		E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E12, E12, E12, E12, E12, E13, E14, E15		Pencil (M1), yellow, blue, red markers (M4)

with four drawings and their codes. Table 2 shows the coding scheme for elements and transformations.

2.2 Types of drawings

We identified several projection types (e.g., plan, section, isometric) and viewing angles (e.g., north, south, northwest) and the medium used for the drawings (pencil, pen, maker, CAD). We identified drawing intentions from the titles, texts and annotations that Neiman provided in the presentation slides. Table 3 shows our coding legends.

2.3 Coding relationships among drawings

The relationships between any two drawings can be coded as a list of transformations applied to each design element in the drawing. The letter codes E, L, T, and C correspond respectively to element identifiers,

Table 2 Codes for elements, transformations, locations, and color

Elements	*Transformation*	*Location (in plan)*	*Color*
E1: column	T1: move right	L1: top left	C1: yellow
E2: wall	T2: move left	L2: top center	C2: light blue
E3: thickened wall	T3: move up	L3: top right	C3: dark blue
E4: chimney box	T4: move down	L4: middle left	C4: red
E5: body box	T5: rotate 90 CW	L5: middle center	C5: black frame only
E6: pipe	T6: rotate 90 CCW	L6: middle right	C6: black
E7: hood/canopy	T7: enlarge length	L7: bottom left	C7: white
E8: bridge	T8: reduce length	L8: bottom center	C8: light gray
E9: small box	T9: enlarge width	L9: bottom right	C9: dark gray
E10: light monitor	T10: reduce width		C10: green
E11: horizontal window	T11: enlarge height		C11: orange
E12: vertical window	T12: reduce height		C12: other
E13: horizontal strip	T13: shape change		
E14: base	T14: removed		
E15: balcony	T15: added		
E16: stair case	T16: no transformation		
E17: other	T17: rotate 180		
	T18: other		

1	2	3
4	5	6
7	8	9

Table 3 Coding legends for a design drawing

Drawing type	*View direction*	*Medium*	*Intention*
D1: plan	V1: north	M1: pencil sketch	I1: variations
D2: section	V2: east	M2: pen sketch	I2: dimension
D3: elevation	V3: south	M3: crayon	I3: grid
D4: isometric	V4: west	M4: marker	I4: volume
D5: frontal projection	V5: NE	M5: hardline	I5: wall attachment
D6: perspective	V6: SE	M6: measured softline	I6: reference
D7: other	V7: SW	M7: CAD	I7: sequence
	V8: NW	M8: inverted color	I8: entry
		M9: hybrid	I9: service
		M10: other	I10: concept
			I11: other

location identifiers, and transformation types, and C specifies the use of a color. D indicates the projection type, V the view direction, M the drawing medium, and I the designer's self-described intention in making the drawing.

For example, the expression

$$E16@L4 \rightarrow (T4 + T17) \rightarrow @L9$$

indicates that design element #16 (staircase) at location #4 (middle left) moves down (transformation #4) and rotates 180° (transformation #17) to location #9 (lower right).

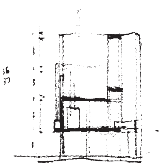
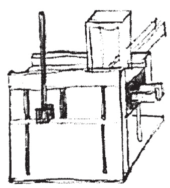
The examples that follow are selected from the pair of drawings illustrated in Table 4, P1-7g and P1-9a. We code relationships both between the drawings (for example, changes of viewpoint) as well as among design elements (for example, the different positions of an element from one drawing to the other).

The transformation between drawings (see Table 1) is a change of viewpoints from section (D2) to a frontal isometric projection (D3 + D4). We code it as:

D2→(D3 + D4).

The transformation of design elements such as chimney box and pipe, and horizontal stripe (E4, E6, E13) in the two drawings can likewise be coded. A chimney pipe (E6) that moves up from one drawing to the other is described as

Table 4 Operations and relationships among two design drawings

P1-7g (also appears as P2-15e)	*Transformations*	*P1-9a (also appears as P2-15a)*
	D2→(D3 + D4) V3→V7 M1→(M1 + M4) (I1 + I2)→(I1 + I5 + I10)	
Drawing type: section View direction: south Medium: pencil Intention: variation, dimension (vertical cadence) (also appears as P1-26, P2-14)	E1@L2-5-8→T16 E2@L3-6-9→T14 (bridge) E3@L1-4-7→T12 (front) E3 C5→T18→C1 E4@L1-T3 (chimney) E5@L1-2-4-5-7-8→T3 E6@L1→T3 (chimney) E7@L8→T2→L7 E8@L9-6-3→T5→L8-9 E9@L4-5→T14 (inside) E6@L4-5→T14 (inside) E6@L4-5→T14 (inside) E10@L2-5-8→T16 E12 C5→C2 E14→T16 E15→T15@L8	Drawing type: elevation, 3D View direction: SW Medium: pen, markers Intention: variation, concept wall attachment, elements in space (thickened wall and projections) (also appears as P1-30, P2-16)

(E6→T3)

and thickened wall (E3) with a reduced height is indicated

(E3→T12).

With these codes we can sort drawings according to the transformations between them as well as the transformation of the individual design elements they contain. For example, a bridge in drawing #1 (at the right side of the plan, at grid locations 9, 6, and 3) that rotates 90° clockwise and moves to the bottom right of drawing #2 is represented as

E8@L9-6-3→T5→@L8-9.

The codes facilitate easier comparison and sorting of the element types and operations. However, the amount of descriptive data—the number of types and fields associated with each drawing quickly becomes difficult to manage. Furthermore, it is hard to keep track of the sorted design elements and their source drawings.

2.4 What can we infer from this analysis of project drawings?

Neiman used drawings and fragments of drawings from previous designs as studies for the pavilion house. Thus, one kind of drawing that appears in the process is a 'memory sketch' (Graves' 'referential sketch'[31]) that recalls elements and organizations from previous work. Other 'functional arrangement' sketches, made in plan and section, explore layouts of building uses: a service core, access, and stairs. A 'structure sketch' examines layouts of a structural grid, and the spatial and dimensional implications of the locations of columns, beams, and walls. Isometric 'form making sketches' examine the three-dimensional geometry of the building, exploring alternative arrangements of the primary architectural elements, volumes, and voids.

Our coding scheme is low-level, dealing with the specific characteristics of, and relationships between, drawings. A higher-level coding built on top of our low-level scheme might account for operations that we believe can be found in Neiman's design process. For example:

- direct quoting—a piece of a previous design is used without modification;
- reference—a previous design is modified before inclusion;
- division—an area or volume is subdivided;

31 Graves, M 'The necessity for drawing: tangible speculation' *Architectural Design* Vol 6 No 77 (1977) pp 384–394

- addition—a pattern is allowed to extend an existing arrangement of material and space;
- geometric transformation—elements are reversed, rotated, or otherwise permuted;
- capacity testing—compares physical elements against space needs of specific functions.

Our exploratory study broadened our understanding of the role that drawings play in design. A designer manipulates design objects through transforming shapes and locations, and changing viewpoints, drawing types, and media to explore design alternatives. Previous designs are used to generate alternatives and to predict the outcomes of new proposals (by applying transformations to various design objects). The designer manipulates the visualized representations to evaluate the consequences of design moves. The manipulations are simple but in combination the process becomes complex. Once an object is positioned, the designer elaborates and reformulates both the object and its context (other objects). Recalling previous designs seems also to play an important role. Previous designs suggest possible solutions, frameworks and design strategies. The designer's preference for certain visual aesthetic properties, such as specific proportions and balance, imposes constraints. We found that the designer 'plays games' by defining rules, selecting strategies and design moves from these self-imposed rules, and discovering and evaluating the outcome. Each of the design elements was transformed throughout the design process, i.e., in changes of dimensions, orientation, and placement.

We assigned categories to the drawings, the tasks that they were made for, the operations that they reflect, and the resulting changes to the design. The subjective nature of retrospective analysis makes it impossible to argue for the truth of interpretation, plausible as it may be. Our analysis of Neiman's design does, however, illustrate a style of projection and exploration that we believe can be found in architectural design processes more generally, one in which specific tasks, operations, and results can be identified at each step in a design history.

In future work, we plan to ask different designers to sort the project drawings, so as to establish inter-rater reliability in identifying drawing types and operations. We would also study design projects that have a different focus than form manipulation, such as a site planning problem or the design of a highly functional building like a hospital. Our study also suggested computational tools that could help in sorting and analyzing drawings. For example, a 'diagram spreadsheet' could sort drawings according to the number of objects, the types of objects, or the drawing and projection types. A program could track drawing intentions and arguments along with sequence of moves with linked documents.

Acknowledgments

The participation of the four designers in the design experiment is greatly appreciated. A more complete description of the first study can be found in Do's PhD dissertation. This material is based upon work supported by the National Science Foundation under Grant No. IIS-96-19856 and IIS-00-96-138. The views and findings contained in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors also acknowledge support from the Chancellor's office at the University of Colorado at Denver.