

Functional and Formal Reasoning in Architectural Sketches

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Abstract

Architects use different symbols and configurations in their drawings to explore alternatives and to communicate with each other. They use sketches to perform functional and formal reasoning in their design process. For example, when thinking about spatial arrangements, they draw bubble diagrams; when thinking about natural lighting, they draw a sun symbol and light rays. This paper reports the findings from empirical studies of drawings and reports the software systems that were implemented to support intention inference and automated activation of knowledge-based design tools to support design.

Why Study Design Drawing

In the early design process, designers draw diagrams and sketches to explore ideas and solutions. Drawings are mental tools. Architects sketch to help themselves to see and understand the form they work with, and to communicate with others. Despite the fact that these drawings may seem crude, they are valuable in understanding how designers work because each of them serves its purpose in a work of importance. Each line in a drawing plays a role. It could represent an outline of a form or a path of force (e.g., wind, rain, or light ray). Architectural design deals with both form and function.

The activity of drawing includes both seeing and thinking about the subject being represented. 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 (Goldschmidt 1991; Schön and Wiggins 1992; Suwa and Tversky 1996). It serves as external symbol systems to facilitate thinking and support emergent ideas (Goel 1995; Fish 1996; Mezughhi 1996).

Recently we have seen research work and computational systems to support sketching in various domains (Hearst, Gross et al. 1996; Stahovich 1996; Landay and Myers 2001). For example, a user can sketch widget symbols for interface design (Landay 1996) or military course of action planning (Forbus, Ferguson et al. 2001). They argued that electronic sketching tools provide designers focus on the task at hand, on spatial relations and structure of the design instead of specific detailed look and feel of the drawing (Ferguson 1992; Landay and Myers 2001). These

arguments hold true especially in the domain of architecture where the tool of the trade is drawing (Do and Gross 2001).

We are interested in building computational tools to support design reasoning through the interface of freehand sketching. In this paper, we first report our research on empirical studies of design drawings in both the functional and formal aspects. We then describe some computational tools built to support designing. Finally, we conclude with discussions and possible future research directions.

Studies of Design Sketches

We have conducted several empirical studies on design and drawing 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 drawing she has made. We are interested in how drawings get made, and what specific knowledge and reasoning process they represent. Specifically, we are concerned with the thought processes that underlie the operations comprising a drawing. Therefore, these empirical studies were conducted focusing on design problem solving with form or function, separately.

The studies include 1) data analysis of 62 architecture students' concept diagramming, 2) video transcripts and protocol analysis of four architects conducting design of an architect's office, and 3) a retrospective analysis of a pavilion house design that was carried over the period of 15 years by an architect.

Functional Reasoning

The first study used design stories and diagrams from a case-based design aid called Archie (Kolodner 1991; Domeshek and Kolodner 1992; Zimring, Do et al. 1995). The database library of Archie contains stories, problems and responses from post-occupancy evaluation data collected in field studies of ten courthouses and libraries. All related items are cross-linked. Each participant were given the tasks of making diagrams from stories, writing stories from given diagrams, pairing diagrams and stories, and commenting on existing Archie diagram-story pairs.

The second study involved protocol analysis of four designers in action. The designers were first given a

program brief of an architect's office space design. After reading the design program, designers were asked to start with a new sheet of paper (or tracing paper) for each task and to focus on four different concerns in conceptual, schematic design. The tasks include 1) spatial arrangement, 2) lighting, 3) visibility and privacy, and 4) fitting a special piece of furniture into the design.

From the diagramming experiment (Do 1995) and design protocol analysis (Do 1997) we found that designers use graphic symbols to represent certain physical objects and design tasks and concerns. For example, when thinking about spatial arrangements of functional spaces, designer would draw bubble diagrams to represent the rooms and their connections. They also drew graphic symbols for furniture objects to put themselves in the context of the design problems. When thinking about lighting concerns, a designer would draw a configuration consisting of an arrow penetrating a vertical rectangle, representing a light ray in a sectional view. Figure 1 shows examples of the diagrams drawn by the participants.

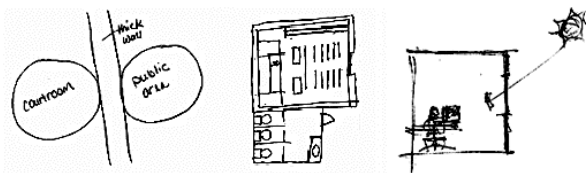


Figure 1. Drawing conventions: (a) bubble diagram for spatial arrangement, (b) graphic symbols for furniture layout, and (c) lighting concerns in sectional view.

Designers also wrote text to label the functions or names of the space. When thinking about fitting a piece of furniture in a conference room, designer would not only draw graphic symbols for furniture but also dimensional markers and numbers to reason about dimensions.

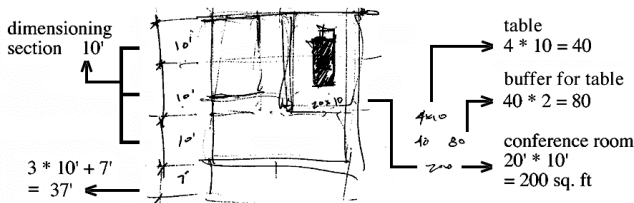


Figure 2. Dimensional reasoning for spatial arrangement according to program square footage requirements (numbers, markers and calculations)

For example, a participating designer drew dimensional marks with 10' intervals along the length of the site (three 10's and a 7'). Then he checked to see if the table could fit into the conference room (20*10). First he wrote down the dimension of the table (4*10), calculated and wrote down the answer 40, and doubled it (80) for buffer space. Figure 2 shows the drawing and annotations of the reasoning process derived from the verbal protocol.

Formal Reasoning

The third study is a retrospective analysis of the pavilion house design drawing. Over the course of 15 years, the architect had been engaged in formal manipulations of the design for a residence and archived all the drawing into six CD-ROMs. We looked at 110 drawings selected by the architect and developed a coding scheme to classify these drawings into different categories. This study resulted a conceptual framework to account for connections among the drawings (Neiman, Do et al. 1999). Our study attempts to identify relationships between drawings in order to understand the role of formal reasoning in a design process. What began as a thought experiment resulted in a range 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.

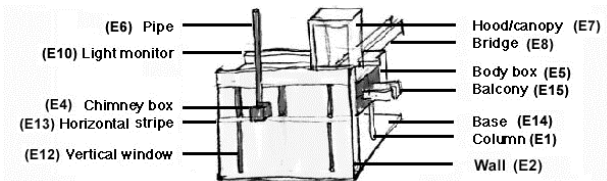


Figure 3. Principal architectural elements for the Pavilion House (with coding for element types).

Many of the drawings are composed of more than one drawing and consist a composition of plan, sectional, or isometric views of the floor plan, or study variations of a façade. We divided the composite drawings into individual drawings and coded them with unique identifiers and drawing properties. The scheme codes properties of the drawings such as the elements depicted as well as projection types and view angles of the building. Figure 3 shows the common architectural elements and their codes (in parenthesis, e.g., E1 represents a column, and E2 represent a wall). Figure 4 shows a drawing coded of element types, location and medium used.

ID #	Drawing	Elements	Location /scale	Medium
P1-30 (P1-9a)		E1, E2, E3,		pencil (M1)
P2-16		E4, E5, E6,		yellow, blue, red markers (M4)
(P2-15)		E7, E8, E9, E10, E12, E12, E12, E12, E12, E13, E14, E15		

Figure 4. A drawing in coded table of different classifications.

For any two drawings, the coding scheme also accounts for the transformations of the design elements such as geometric translations of shapes, locations and color. The letter codes E, L, T, and C correspond respectively to element identifiers, 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 ->(T4+T1+T17) ->@L9

indicates that the design element #16 (staircase) at location #4 (middle left) moves down (transformation #4), moves right (transformation #1) and rotates 180° (transformation #17) to location #9 (lower right). If there is no transformation (transformation #17) of the location (L9: lower right) of element #16 between two drawings, it would be coded as

E16@L9 ->(T16) ->@L9

Figure 5 shows three design drawings, the 3x3 location grid, and the expressions of transformations of the staircase between them.

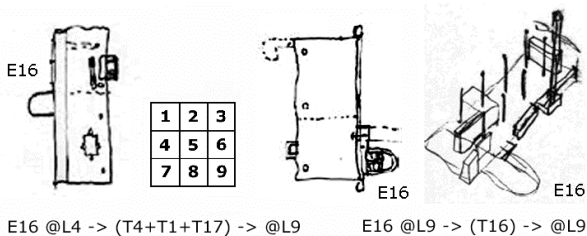


Figure 5. Staircase (E16) in drawing I (left) is moved (T4: down, T1: right, and T17: rotate 180) to a different location (from L4 to L9) in drawing II (middle). The location of the staircase is identical between drawing II (middle) and drawing III (right) and coded as transformation T16 (no transformation).

Drawing Evolution in Design Process

The notion of design being the fusion of form and function is widely accepted and followed in the field of architecture and industrial design (Meikle 1979). The dictum 'Form follows Function' was first introduced by the architect Louis Sullivan (Twombly 1986) in 1896 to explain that his building design follows natural law. Later Mies van der Rohe further argued that 'Form IS Function', and many modernist architects and designers share this notion. There are often debates about whether form precedes function or vice versa (Janson 1982; Anderson 1987). However, it's in the common training and education of architects that successful building should incorporate form and function together.

The East Building of National Gallery of Art designed by I. M. Pei is a good example of how conceptual drawing evolves to account for the form and functional arrangements of the building. Figure 5 shows the final drawing of the building on site. The original National Gallery of Art, or the West Building is a symmetrical, rectangular, neoclassical building with a rotunda in the middle.

The East Building was designed to extend space for programming and to act as complement to the West Building. It was a design task to provide not only organization and functional needs, but also to fit in a none-regular (trapezoidal) site with strict restrictions of setback lines from the surrounding streets and aesthetic principles (symmetry, axis, etc).

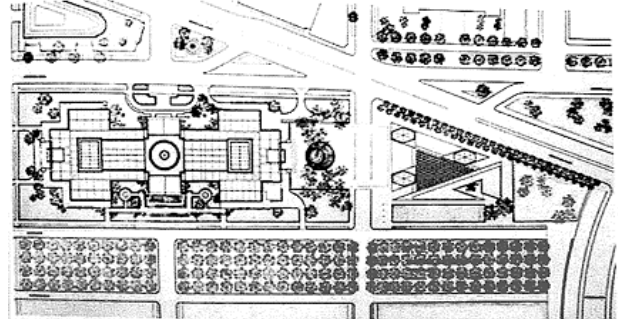


Figure 6. Site plan for the East Building, National Gallery of Art (drawn after (Galleries 1978))

The early design concepts kept in Pei's notebook or diary shows concerns about the axis of the West Building (Figure 6, left), and extending it to divide the trapezoidal lot into several triangles, as shown in Figure 7 (right).

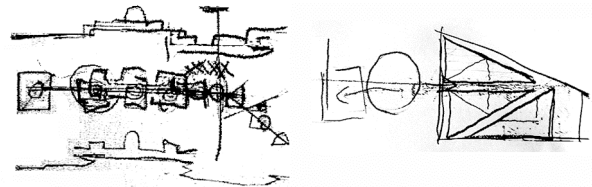


Figure 7. Concept sketch, site analysis, and spatial arrangement (drawn after (Galleries 1978))

Examining Pei's design drawings from a formal perspective reveals that the shapes or the form are tightly connected to the function of the spaces. At first glance, the drawings in Figure 8 share similar shapes and structure. They all have triangle components. The three drawings on the right are actually from facing pages of the notebook.

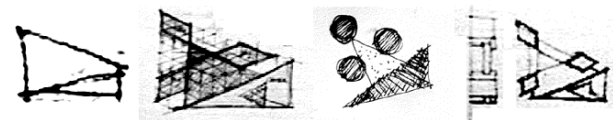


Figure 8. Design drawings from the design notebook. (after (Galleries 1978))

The first sketch on the left is a very simple diagram showing two triangles, one isosceles and one right triangle. The second sketch is much more elaborate. The motif of triangles has become patterns covering several areas. The final building uses the triangle pattern for the space frame above the concourse that connects exhibition space and the Center for Advanced Study. The form of triangle serves the purpose of functional support for the frame. The third

sketch is diagrammatic. Each circle represents an independent museum as noted in the notebook (Galleries 1978), and connected to the bottom right triangle with another triangle. The last sketch shows the symmetric feature of the West Building, and each gallery has a prism shape and is connected by bars.

Figure 9 contains a series of diagrams explaining the development of the East Building from preliminary concept stage to the final conception realized in the building. Besides obeying the setback guidelines and specific stipulations from the urban agencies, Pei projected the longitudinal axis of the West Building to bisect the building lot. Using the axis as a guide, a symmetrical line that is diagonal on the site is drawn and divides the lot into two essential spaces. One is the isosceles triangle, facing the West Building and echoing the symmetrical geometry. The other space is a right triangle. This formal arrangement solves the problem of the site; at the same time it provides functional space for two programming requirements. The isosceles triangle is used for exhibition galleries, and the right triangle is the Center for Advanced Study and other scholarly and administrative functions. These two functional spaces are connected by a triangle concourse, an atrium with skylights. The three corners of the isosceles triangle became gallery towers connected by bridges.

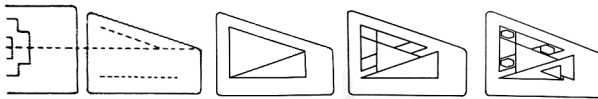


Figure 9. Design evolution: (1) axis extended from West Building, and setback lines, (2) diagonal divides 2 spaces, an isosceles triangle and a right triangle, (3) corners of isosceles triangle became exhibition towers, and (4) the right triangle became the Center for Advanced Study. (after (Galleries 1978))

Stories of how these drawings account for the design, and the solving of aesthetic and engineering decisions are abundant (Wiseman 1990) (Art; Galleries 1978). The descriptions of form and function in design development are usually inter-connected. Besides the evolution of architectural drawings in the design process, some other drawings also shed light on what actions designer take when thinking about design.

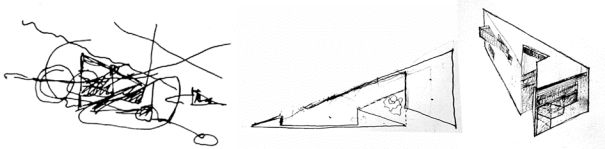


Figure 10. (1) Concept sketch of the building with right triangle circled and called out. (2) Design of the Center for Advanced Study with courtyard. (3) Isometric drawing of the volume for the Center for Advanced Study.(after (Galleries 1978))

The first example is the move or projection from two-dimensional floor plan drawing to three-dimensional isometric drawing. Figure 9 shows a 3D isometric drawing

(right) derived from the 2D plan (middle). Note also the concept sketch on the left of Figure 10: though crude, several shapes and lines are identifiable. The bottom right angle is circled and connected with bubbles for more development of the courtyard scheme for the Center of Advanced Study. Figure 11 shows a pair of the East Building design with similar shapes but different details. This is similar to the findings from the Pavilion House study. Designers move, rotate, and transform design elements in their drawing to make formal arrangements. It is worth noting that in this case, the transformation of the drawing elements involves functional arrangements as well. (We may be able to further verify this if we can capture design rationale and verbal protocols of the whole design process.)

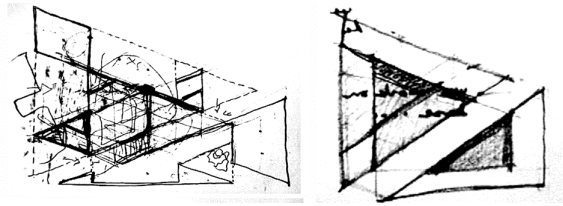


Figure 11. The location of the opening or courtyard for the Center of Advanced Study (occupying the right triangle at the bottom) are different in these two design sketches. The opening on the left scheme is on the south side, while the drawing on the right has the opening from the slope of the triangle. (after (Galleries 1978))

Computational Tools for Sketching

Recognizing that it is possible to associate symbols and spatial arrangements in a drawing with the designer's intention, or task context, we have implemented computational tools to use freehand sketching as an interface to intelligent systems for design. These design tools include using diagrams for knowledge and image retrieval, building performance simulation, and three-dimensional model making for early stages of design (Do 1998; Gross and Do 2000).

At the most basic level of symbolic processing, our systems capture stroke data from the tablet and use the pen path and stroke features (speed, corner, aspect ratio, etc) to identify symbols drawn by the designers. A symbol could be a single-stroke glyph, or consisted of multi-strokes glyphs. A low-level recognizer starts the processing and display recognition upon a pen-up action. Designers can also turn off the recognition display, or ask the background processor not to resolve ambiguous symbol until further information is given that helps the program identify the context. Resolving ambiguous intentions is necessary because the same drawing symbol could mean different things in different context (Gross and Do 1996). For example, a circle on a floor plan could mean a column while a circle outside and above a building section with a line penetrating the building envelope would be the sun and light ray. Similarly, a circle with alphabet neighbors is

likely to be an alphabet O while a circle next to a number is likely to be the number zero. A higher-level recognizer deals with analysis of spatial relations among drawing symbols and the combination thereof. For example, a big circle surrounded by small squares on a floor plan could mean a dining table set. Figure 12 shows that the wiggly-line placed directly below an horizontal line can be recognized as a symbol for the "ground," thus set the context into 'section.'

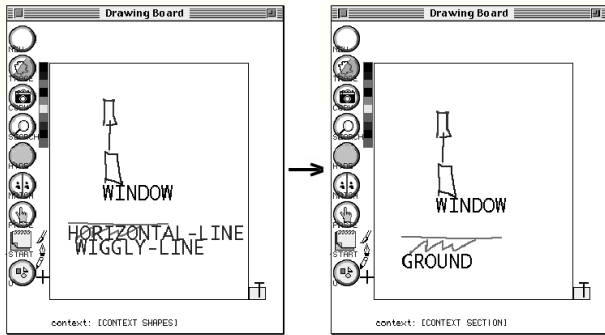


Figure 12. A "ground" symbol is composed of a horizontal line and a wiggly-line (left). The names of the elements are replaced by the new name of the configuration (and sets the context to 'section')

The Right-Tool-Right-Time manager identifies context based on existence of special symbol or configuration to trigger an intention recognizer. Once design intention is recognized in the drawing, the system would automatically activate the appropriate tools for the task at hand. For example, Figure 13 shows a visual analysis program called Isovist (Do and Gross 1997) can be activated once the Right-Tool-Right-Time program recognizes the intention of 'view'. The viewpoint and lines are translated into the program for simulation.

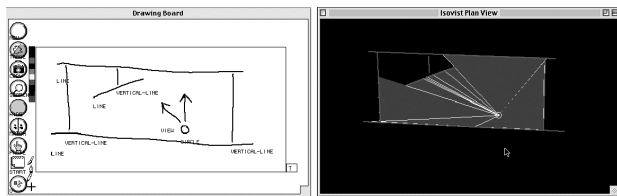


Figure 13. A 'view' intention is recognized in a 'plan' context (top) and the drawing is translated into wall lines (from lines) and a viewpoint (arrows and circle) and sent to the Isovist visual simulation program (bottom).

Another example uses the intention and context information derived from the drawing to activate keyword search on a web search engine or a database. Figure 14 shows that an intention of "monitor_glare" is recognized by seeing the configuration of a computer (monitor and hard drive) and a sun ray (sun symbol with arrow indicates light direction). This intention activates the browser to launch a keyword search using a web site. The same interaction can be applied to other knowledge-based systems, a slide library, or a case library like Archie.

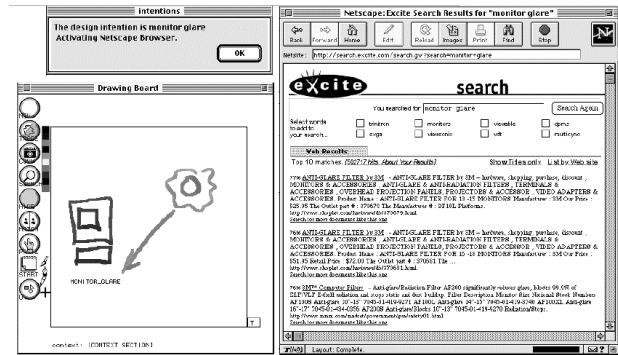


Figure 14. When a 'monitor_glare' intention is recognized, (bottom left) a message prompts the user (top left) and it activates a Web Browser (right), requests a keyword search and the search returns a list of relevant information

A common task in design is dimensional reasoning and calculation of area footage. Drawing symbols of dimensional markers and numeric operators can be recognized as a context of 'calculation' and thus activate a calculator for designer. Figure 15 shows such interaction.

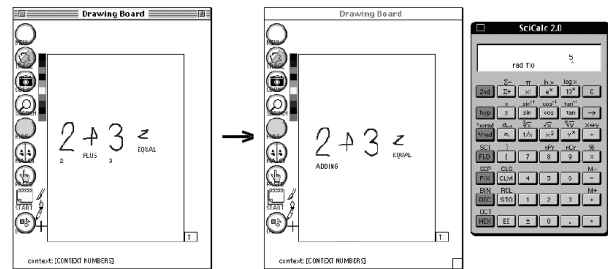


Figure 15. A configuration of numbers and arithmetic marks (left) is recognized as an "adding" intention (middle) and RTRT activates a calculator (right).

The Back of an Envelope project and the Right-Tool-Right-Time manager demonstrate that a pen-based, or calligraphic interface can be used in a variety of domains in design process. Designers can use freehand sketches and diagrams to index and retrieve databases or to activate knowledge-based information systems and simulation programs. It is a framework of knowledge capture. One can use the graphic recognition of the system and add to the framework more modules and functionality to support design. Below we describe two new sketching interfaces for supporting formal and functional reasoning in architectural design: 1) GIDA – Graphics Interpreter of Design Actions, and 2) VR Sketchpad – an interface for creating instant 3D worlds by sketching.

Graphics Interpreter of Design Actions

With the coding scheme developed for the Pavilion House analysis, we are currently working on a Graphics Interpreter of Design Action - GIDA to manage drawing

comparison and sorting of the diagrams. The GIDA system allows a user to diagram over a picture underlay of design drawing and to generate an analysis of the drawing itself and its relationships with other drawings. For example, a diagram's topological and geometric relations among parts of the drawing can be recorded and used in comparison to another diagram traced from a different design drawing to reveal the spatial transformations among the elements. Figure 16 shows a pair of design drawings traced from the Pavilion House façade study. The GIDA system lays out a 3x3 grid over the drawing and generates a list of occupied cell numbers for each object.

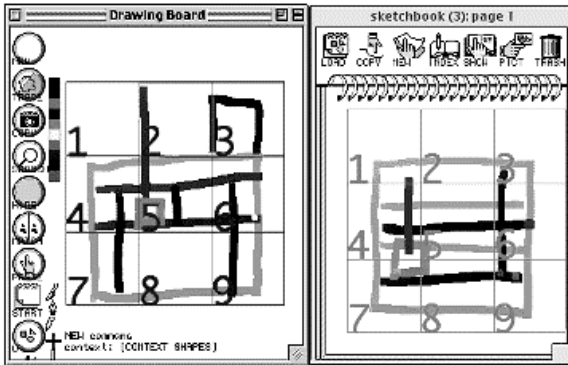


Figure 16. GIDA's location identifier (3x3 grid) over two design drawings

In the example of Figure 16, Drawing #1 (Figure 16 left) has nine elements and Drawing #2 has eight. Each element has a position in the global coordinate system and a list of the local grid cell sequence. Figure 17 is a table showing the list of elements for each drawing and their corresponding cell sequence.

Element	Drawing #1	Drawing #2
Thick Wall	(7 4 5 6 9 8 7)	(7 4 1 2 3 6 9 8 7)
Chimney Box	(4 5 4)	(7 4 5 8 7)
Chimney Pipe	(1 4)	(1 4)
V-window 1	(6 9)	(3 6 9)
V-window 2	(5 1)	
V-window 3	(4 7)	
Hood	(6 3 2)	
H-strip 1	(4 5 6)	(4 5 6)
H-strip 2	(4 5 6)	(4 5 6)
H-strip 3		(4 5 6)
H-strip 4		(7 8 9)

Figure 17. State of drawing elements represented as list of cell sequence.

Transformations between drawings can be inferred by comparing the lists of the same elements from different drawings. For example, the cell sequence list of V-window 1 was changed from (6 9) to (3 6 9). The bounding box sizes of the element in the two different drawings are very close. This describes the shifting-up transformation for this

element from first drawing to the second one (addition of grid cell 3). The table shows that the Hood element in Drawing #1 is removed from Drawing #2. Likewise, the transformation of the Chimney Box is a moving down from (4 5 4) to (7 4 5 8 7).

VR Sketchpad

In VR Sketchpad (Do 2001) we developed a simple sketch recognition system that inferred three-dimensional models from two-dimensional sketches. The idea is to use drawing to construct virtual built spaces. Our current prototype system enables a designer to draw a floor plan with walls, columns, and furniture elements and the program produces a 3D model in VRML (Virtual Reality Modeling Language). Figure 18 shows that any freehand sketch can be converted and extruded as columns and wall partitions.

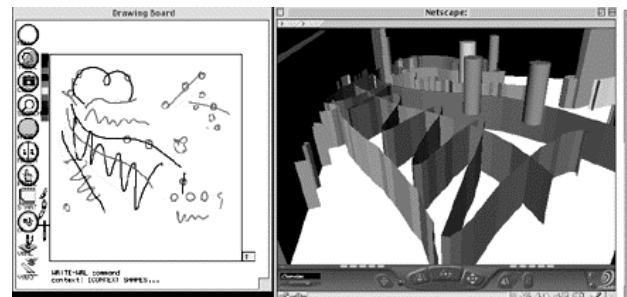


Figure 18. Curve shapes and lines (left) are extruded to make partitions in a VRML world (right).

The recognition engine of the system interprets drawing symbols (e.g., circles and lines) with designer intended object representations (columns, walls) and diagram configurations (e.g., dining table and chairs). A designer can also draw arrows to indicate locations of interests and therefore define a viewing path into the 3D world (encoded as viewpoints into a VRML world). A designer can also define a configuration of symbols to represent furniture objects as shown in Figure 19. By sketching the furniture layout in diagrammatic form with arrows indicating specific viewpoints and view angles, designer can produce a 3D scene in an instant and the visitors can follow the guided path to explore the virtual space as designed.

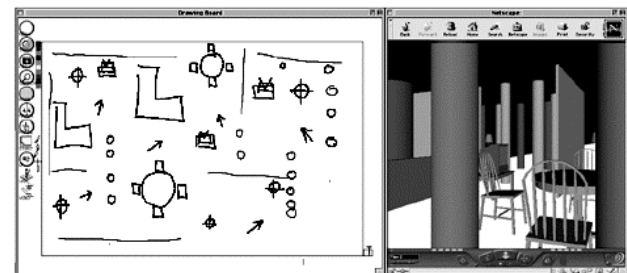


Figure 19. Furniture layout sketch (TV, couch, dining table set, columns, and walls) creates 3D VRML scene (right) with objects.

Discussion

Sketching is important in the early, conceptual stages of architectural design. Therefore, computational tools should support sketching activities. The empirical studies examined intentions in and relations among design drawings. Our prototype systems demonstrate how freehand drawing interfaces can support analysis and design. These are all part of a larger research agenda on the role of drawing for design support. Many issues are worth exploring further.

The act of drawing is a form of design reasoning. An architectural design involves both functional and formal reasoning. Design drawings use lines and geometric shapes to represent natural or man made artifact such as building components and plants, phenomena such as sound and light, human behavior such as sight and circulation, as well as boundaries of spaces. The studies of design students on the concept diagramming exercise and the protocol analysis of architecture design reveals promising results for computational tools to support sketching. We found the designers draw different symbols and configurations when thinking about different functional design concerns.

On the other hand, our exploratory study of the Pavilion House broadened our understanding of the formal role that drawings play in design. Design sketches are made of geometric shapes. Not surprisingly, aesthetic principles and formal expressions also influence how a designer works. From the study we found that a designer manipulates design objects through transforming shapes and locations, changing viewpoints, drawing types, and media to explore design alternatives. When functional concerns are easy to solve, these form manipulations involve the search of implicit graphical law or convention. For example, the balance of the configuration, its symmetrical or axial considerations, aspect ratio of the object and proportion, all serve as criteria for design manipulation, or or moves.

Transformations are applied to previous designs to generate alternatives and to predict the outcomes of new proposal. The designer manipulates the visualized representations to evaluate the consequences of design moves. These manipulations are simply geometric transformations but in combination the process becomes complex. We found that designers play mental games with themselves. They play by defining rules, selecting strategies, making design moves from the rules, and evaluating and discovering the outcome. These design moves change the shape, dimensions, orientations, and placements of the design elements.

If a design process always involves fusion and interchanging activities of both functional and formal aspects, then how might we find the appropriate interpretations of the design intentions expressed in drawing? Are there specific symbols that can be identified to indicate the right context? The series of design drawings of the East Building reveal that designer move back and forth from functional to formal concerns fluently. The

geometric shapes are manipulated first for formal arrangements such as symmetry and establishing axial lines. Then these shapes are read as symbol arrangements for functional spaces. The ingenious part of the design is that all problems, be they functional or formal, are all solved and evolved through these architectural sketches.

In summary, we conclude that we can view the act of drawing as manipulations of symbols that represent internal functional and formal knowledge. Understanding architectural sketches are not an easy test. Laboratory studies can isolate formal or functional problems separately. However, in a real life setting, these issues mingle and are dealt with at the same time. To make computational tools really support sketching activities in design, we would need to study more how designers move between different modes in a real design task. Observing and analyzing design protocols could probably help identifying how designer operates. Maybe the transitions among various states, the sequence of drawing, are the external controls of the environment representing the mental image. It is clear that the activity of drawing can not be detached from seeing, and thinking about the subject being represented. We can not draw an object or a scene unless we see it before us whether in real physical world, or in mind's eye. Many times, the drawings are created from adopting and adapting objects from memory or imagination. Therefore, using drawing to accessing databases or knowledge repository is definitely an important issue. Analyzing and understanding what sketches represent is important. However, there is still a broad area to explore in order to understand how sketches are made, and why are they made, to support what activities.

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