

What's In a Diagram That a Computer Should Understand?

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This paper reports on an experiment to test the feasibility of using a diagramming tool to access an architectural knowledge base. Our hypothesis is that designers only use a small set of conventional elements to make diagrams of architect concepts. If this true, then a scheme for retrieving information from computer knowledge bases using diagrams would work. Therefore we asked designers to make diagrams from texts, to interpret' diagrams into texts, to pair diagrams and texts, and to comment on existing pairs from the case base. We found from the experiment that common features are shared between different designers' diagrams and texts.

Keywords: architectural diagrams, graphic interface, knowledge bases

1 Motivation - why study diagrams?

1.1 Diagrams are important in architectural education and the design professions

All designers make diagrams. Diagrams express complex real world architectural problems and solutions concisely and abstractly [1,2] and therefore designers often draw diagrams when they are concerned with general architectural concepts and issues. Diagrams also play an important role in the education of architects. Many instructors use diagrams to critique students and to show principles of circulation, adjacency, lighting, and visual field. Perhaps reflecting their important roles in design, diagrams are also employed in books to illustrate architectural concepts. For example, "The Image of the City" [3] "Problem Seeking" [4] and "Design Thinking" [5] all depend on diagrams to communicate basic concepts of architectural design'. In addition to common use of diagrams in architectural education, diagrams are also used in professional practice. Designers in architecture firms often work by making or copying diagrams from their design team colleagues for further development. We also find diagrams throughout the sketch books of famous designers such as Louis I. Kahn [6], Le Corbusier [7, 8], and Peter Eisenman [9].

1.2 Diagram-based indexing for architectural knowledge bases

To support design decision making, various architectural knowledge bases have been built, such as Archie, a case based design aid [10-12]. Archie's case base contains stories, problems and responses from post occupancy evaluation data collected in field studies that covers about ten courthouses and libraries. All related items are cross-linked. However, to access Archie's design information, one must use specific keywords assigned by the system developer. For visually oriented, graphic thinking designers [13,14] this textbased interface may be an obstacle to effective use. To ease accessing information from the Archie database, we built a prototype of a diagramming tool that helps users find cases by making hand drawn sketchy diagrams [15, 16] . For example, Figure 1 shows a case story about the arrangement of adult and children's sections in a library that was retrieved by a diagram -- the shapes contain annotations to indicate spaces.

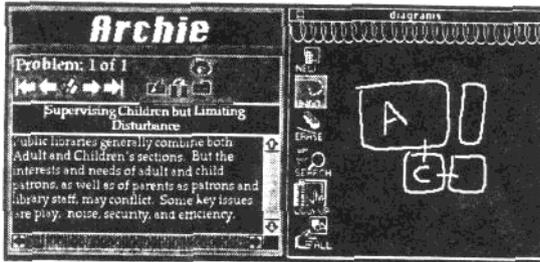


Figure 11 A case (jell) about the arrangement of adult and children's sections in a library, retrieved by a diagram (right). (A for adult and C for children).

1.3. *Diagrams, sketches, and their roles in design process*

Several recent books discuss the distinction between different kinds of architectural drawings and their uses in design. For example, Fraser and Henmi's "Envisioning Architecture" [18] looks at how techniques used to make different drawing types influence the making of architecture. Herbert's "Architectural Study Drawings" [17] examines the graphical media and design processes of six practicing architects. He argues that drawings are more than just a convenient strategy for solving design problems and that they are in fact "the designer's principal means of thinking." Robbin's "Why Architects Draw" [19], like Herbert's book, examines the work of well-known professional architects and includes architects' own descriptions of their personal design processes. Ervin's "The Structure and Function of Diagrams in Environmental Design" characterized diagrams as "abstract," "topological," and "propositional" that deal with organizing principles and relations between physical elements [20]

1.4 *In this study we focus on diagrams that explain design issues of environmental forces, building components, and human responses*

By "diagram" we mean 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 differs from a sketch in that it contains symbols. For example, a diagram might have an arrow indicating directional "force", which is unlikely to appear in a sketch. A diagram also represents abstractly without giving detailed descriptions of scale or realistic pictorial representations. It can be spatial, for example, showing relative positions and approximate sizes of rooms, or it can be non-spatial, for example, showing the sequence of building construction. A diagram indicates spatial relationships only approximately with indefinite shapes. For example, a bubble diagram represents functional spaces in a floor plan with rough sizes, adjacencies, containment, and connections. In contrast, a sketch does not use symbols or abstractions and it is mainly about spatial form. For example, a perspective sketch provides three dimensional information about a scene, indicating physical elements and their spatial relationships. A plan or elevation sketch may be concerned with the proportions of a building or its components. A schematic drawing has features of both a diagram and a sketch. It uses conventional symbols to represent building components and it has the spatial feel of a sketch. It is more complex, and more precise than a diagram, and is drawn to scale. However, there are no clear cut distinctions between diagrams, sketches and schematic drawings.

The rest of the paper is organized as follows: Section 2 describes experiments we conducted using material from a case based design aid Archie. Section 3 presents the four major findings of the experiments. Finally, in Section 4, we discuss the results and their implications.

2 The experiment -- how do diagrams convey ideas?

The goal of the experiment was to find out what in diagrams can be read, what symbols, designers use most, and how they use them. The aim is to find whether different designers draw diagrams similarly. If so, in what ways? If not, can they at least interpret

other designers diagrams? Therefore, we performed experiments with task variations to explore= there are common features among diagrams drawn by different designers. The test materials included four tasks, each consisting of six questions. In each task, the first three questions were concerned with architecturally problematic situations, and the second three questions with possible design responses to repair an architectural problem. Participants were asked to spend no more than ten minutes on each task, but this timing restriction was not enforced. The time spent by participants ranged from thirty minutes to one hour. Sixty-two undergraduate design students participated in the actual test. There were nineteen (31%) female students and forty-three (69%) male students ages from twenty to thirty-three. Participants for the experiments were students enrolled in Design Theory and Method core course offered by Environmental Design Department of the University of Colorado at Boulder.

The first Task (1) asked participants to illustrate given text describing either architectural problems or responses. For example, here is the text from Question 1.

MAPS IN POSSIBLE SPECIAL COLLECTION

A separated special map room allows control over access to valuable material but if out of sight of normal staff areas may require an additional staff member to supervise.

The second Task (2) asked participants to write a brief text description for a given architectural diagram. They were given brief guidelines for writing text descriptions with examples. Figure 2 below shows the diagram from the first question in this task with its title.

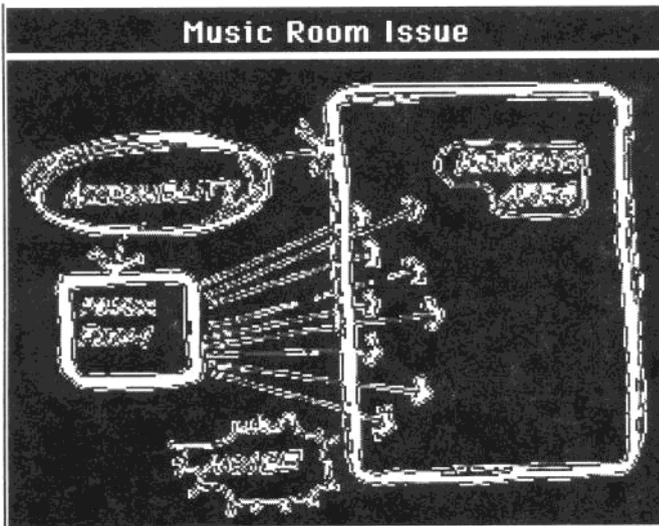


Figure 2 Material for Task 2, Questions 1, a diagram with title.

The third Task (3) asked participants to match six diagrams with six textual descriptions. Two sets of three diagrams and three text paragraphs were arranged in rows and the participants were asked to pair them (Figure 3)

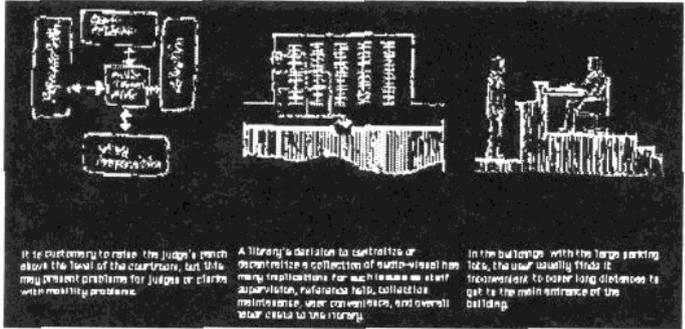


Figure . Example page for pairing test, Task 3, diagrams on top row, and texts on bottom row with different sequence.

The fourth and final Task (4) asked participants to comment on six given diagramtext pairs, taken from the Archie case base. For example, Figure 4 shows the actual Question 6 from this task.

3 Experiment results -- what's in a diagram that can be read?

In this section we describe our findings, with emphasis on Task 1, because it is a diagram-making experiment. Task 2 - 4 were all designed as supplementary tasks. The results of tasks 2 - 4 supported the findings of Task 1 and confirmed that designers can read others' diagrams.

We found the experiment results support our hypotheses about diagram making. First, participants used only a small set of basic geometric shapes such as ovals and rectangles, lines and hatch marks. Second, a small set of symbols is used in conventional ways to represent sun, lighting, sight lines, noise, furniture, walls and windows, doors, and people. Third, participants interpret other designers' diagrams or texts about architectural concepts in a similar way. Fourth, participants revealed a preference for drawing either a sectional or a plan view to illustrate different concepts. These observations suggest that a computer based diagramming tool would only need to provide limited pattern recognition facilities.

3.1 Task 1 reveals drawing elements and viewing preferences in diagram-making.

The six questions in Task 1 asked participants to draw a diagram from a given text description. There was wide variation in the level of completeness, detail, and drawing competence among the sixty-two sets of diagrams made for Task 1. For example, as shown in Figure 5, when asked to illustrate a text about using thick walls to reduce sound transmission between courtrooms and public areas, several participants simply drew a rectangle to indicate a thick wall. At the other end of the spectrum, some participants interpreted the task as a design task, and produced highly detailed configurations to solve the problem. Some even introduced concepts that were not given explicitly, such as putting restrooms beside the courtroom.

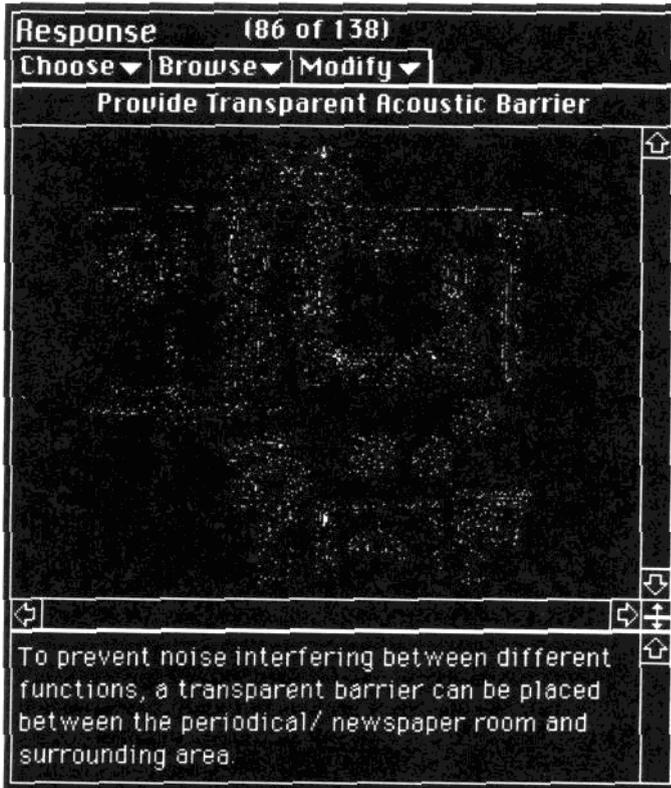


Figure 4. Material for Task 4, Question 6, diagram-text set from Archie.

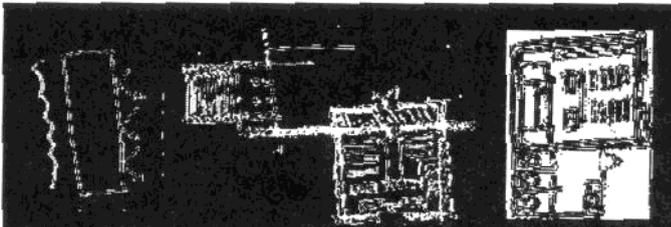


Figure 5. Diagrams to illustrate using thick walls to reduce sound transmission included 1) a simple rectangle to represent a thick wall, 2) detailed floor plan configuration, and 3) concepts not from text (restrooms).

Study of Task 1 data revealed four significant features of diagram making. First, concepts suggest sectional or plan preferences. Second, participants used only a limited set of symbols to represent design concepts. Third, plan diagrams have more text labels than sections. Fourth, diagrams included labels and symbols not mentioned in the text.

(1) Concepts suggest sectional or plan preferences. The first finding of Task us that participants seem to share a preference for using plan or sections to illustrate certain architectural concepts. For example, most participants chose a plan view to illustrate relationships between different functional spaces and acoustics; however they chose a sectional view to illustrate lighting conditions and sight

lines. Figure 6 below shows that (except for Question 5) each of the six questions in Task 1 resulted in a strong preference for either plan or section diagrams.

#	Summary of text	Plan	(%)	Section	(%)	Other	(%)
1	map room location	58	94	0	0	4	6%
2	natural lighting creates glare	3	5	52	84	7	11
3	fun children's section	45	73	14	23	3	5
4	thick walls to reduce noise	40	65	8	8	14	23
5	visual contact to children's area	25	40	31	50	6	10
6	glass windows for lighting	7	11	52	84	3	5

total participants = 62 (100%)

Figure 6. A table showing drawing preference on plan and section diagrams Task 1.

For example, as shown in Figure 7 below, most diagrams illustrating Question 1, a functional arrangement issue about placing a map room in a library, were plan representations. In contrast, the issue in Question 2 (natural lighting and glare) seemed to suggest sectional diagrams with symbols for light and sectional walls. In Question 3, about fun spaces for children, mostly plan views were employed to illustrate the functional arrangement issue. Interestingly, the smaller number of sectional diagrams made for Question 3 all represent attempts to solve the design problem using a change in level. In summary, the pattern of preference for plan or section diagrams was found from the experiment results. A functional arrangement concept suggests a plan preference. In addition, a concept of lighting or sight lines suggests a sectional preference.



Figure 7. Diagram examples showing view preference for descriptions, Question 1-- plan representations, Question 2 -- sectional diagrams and Question 3 -- both plan and section diagrams.

(2) Participants used a limited set of symbols to represent design concepts.

The second finding is that participants chose primitives from a limited universe of geometric shapes and symbols to draw their diagrams, and composed these in highly conventional ways. They used predominantly lines, ovals and blobs, rectangles, and hatching. Each of these shapes and symbols were used with some small variation. For example, lines were drawn either solid or dashed, with or without arrowheads, and occasionally wiggly or curved. Ovals and rectangles were drawn with varying size and aspect ratios. Hatching was drawn in two main variations, as one-directional closely spaced parallel lines, and a single continuously oscillating line made without lifting the pen from the paper; occasionally a second hatch pattern was overlaid on the first to make a cross hatch pattern. We call these drawing elements, primitives, for example, lines, arrows, and geometric shapes. (Figure 8). These primitives are also used in diagrams from different domains, and are not limited to architectural design.

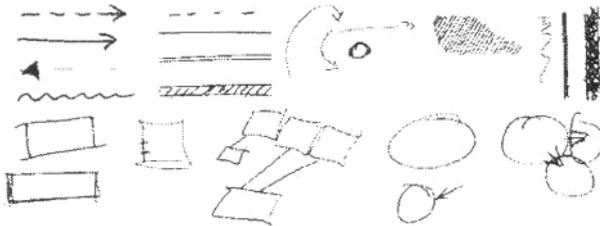


Figure 8. Primitives (drawing elements) used in diagram, included arrow,, me, hatches and simple geometric shapes

When primitives are combined, they form symbols to represent architectural objects such as walls and windows or to illustrate natural phenomena such as sun and human figures. For example, a circle was composed with radial lines to indicate the sun; lines were composed to indicate walls and windows; and a circle with lines or a blob was drawn to indicate a person (see Figure 9).

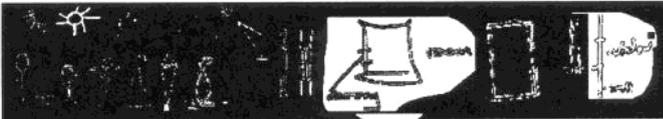


Figure 9. Primitives were composed to make more complex symbols.

For example, most diagrams for a lighting issue in Question 2 included a representation of light from a sun passing through the building envelope (Figure 10). These representations were made using conventional symbols for the sun, light rays, windows and walls; some diagrams also included symbols for persons and video screens. Each symbol was drawn in a small set of variations. Forty-one diagrams (66%) indicated light rays as lines with arrows. Another fifteen diagrams (24%) indicated light rays as simple lines (a total of 90% diagrams used lines). Only six diagrams did not use lines or arrows to indicate lighting.



Figure 10. Diagrams illustrating lighting use light lines penetrating the building envelope (windows and roofs).

(3) Plan diagrams have more text labels than sections.

The third finding is that participants were more likely to include keywords from the given text as labels in plan diagrams than sections. Of the fifteen plans drawn to illustrate Question 6, thirteen (87%) included labels. On the other hand, of the forty-two section diagrams, only seventeen (40%) included labels.

The use of labels varied significantly among the questions. Questions 3, 4, and 5, all stories involving noise and acoustic privacy, produced a higher percentage of diagrams with labels. Questions 2 and 6, involving lighting and sight lines, produced a higher percentage of diagrams without labels.

The Task 1 data also revealed that participants frequently included keywords from the text as labels in their diagrams. Functional space were mostly written inside a containing shape (oval, blob, or rectangle), and only occasionally beside the shape with an arrow or line pointing to the shape (see Figure 11). In contrast, concept labels such as 'supervise,' 'light,' and labels of sectional elements such as "atrium" and "corridor," and labels of material, such as "walls," "frosted glass" are usually placed beside the shapes with or without a pointer (line or arrows). For example, in Question 1, forty-seven (76%)

participants wrote the word "map" as a label in their diagram; twenty-two (35%) wrote staff', eighteen (29%) wrote "library" and six (10%) wrote 'supervise'. The given text is shown below, with these words that appeared in diagrams in uppercase:

In a community LIBRARY, a separated special MAP room allows control over access to valuable material but if out of sight of normal staff areas may require an additional STAFF member to SUPERVISE.



Figure 11. Diagrams use keyword map' given in the text to label a space (Question 1 of Task 1).

(4) Diagrams included labels and symbols not mentioned in the text.

The fourth finding is that diagrams included elements -- both text labels and symbols - that were not explicitly referred to in the text of the problem or response. For example, in Question 2, about natural lighting and glare, a significant number of diagrams included representations of people, desks, chairs, and the building envelope, even though these elements were not mentioned in the text. Similarly, text labels in many of the diagrams also identify additional or extraneous elements. For example, in Question 6, (frosted glass on corridor windows) text labels included "hall," "public," and "space." Although these labels are plausibly related to words in the given text, participants also included such diverse annotations as "President's office" "Prz Bath," and 'small trees."

Responses to Question 3 used keywords "read", "children" and "library" from the text as labels for spaces in the diagram. However, other words not mentioned in the text such as "play" and "kid" also annotated the participants' diagrams. In Question 4, "Court," and "Public," (some used C and P) occurred frequently in the diagrams, while three participants (5%) included the unmentioned word "private". In Question 5, while "atrium," "corridor" and "frosted glass" were included in the diagrams, the terms "space" "hall" and "public" were also used.

3.2. Task 2 reveals consistent interpretation of diagrams among designers.

The six questions in Task 2 asked participants to write a story from a given diagram. Participants were provided guidelines to help them understand the text writing style. Though the wording and writing style varies, the sixty-two sets of stories were quite similar. One or two participants interpreted the diagrams very differently than the others, but most answers are consistent. For example, participants were given diagrams consisting of bubbles with labels and arrow lines (about the relation of noise and accessibility to a music room and reading area). Fifty-five participants (89%) introduced the concept of separation, writing that accessibility leads to adjacency of the two areas, while the concerns of noise transmission should be addressed by a soundproof buffer.

The Task 2 data revealed two interesting features of reading diagrams. First, conventions of symbols in diagrams enabled participants to recognize and make stories. For example, in Question 2, they interpreted the parallel filled lines as floors and the arc lines on top of the structure as an atrium with glass (thirty-eight participants, 61%). They saw the diagonal lines that cut through the buildings as sun light (fifty participants, 81%), and dotted hatching as spaces in shadow (forty-two participants, 68%). Second, participants used labels from the diagrams as keywords in the text description they wrote and included words and concepts that were not explicitly given in the diagram. For example, in Question 1, all participants included the words "music' or "noise" in their written text.

3.3. Task 3 reveals that designers can easily associate a diagram with its pairing text.

Task 3 included two sets of diagram and text pairing exercises. Each set had three diagrams on the top row, and three texts on the bottom row. Participants were asked to draw lines connecting the fittest pair of a diagram and a given text description.

This task appeared to be the easiest to perform. Only two persons (out of the 62 participants) failed to answer this task correctly and their comments yield clues to why they failed. As the diagram provides no indication of scale or labeling, the division lines of the parking lot (see Figure 12 and Figure 3) look like bookshelves in a library floor plan. Also, the text about the library (Figure 3, second column text) appears prior in the test sequence to the parking text (Figure 3, third column text).



Figure 12. One participant failed to associate this diagram with its text *because* parking lot division lines look like bookshelves.

The participants made interesting comments. For example, some suggested removing diagram labels to make the task more difficult. Some suggested that using symbols to illustrate a concept makes a diagram easier to read. For example, "no handicap access" could be illustrated with a restricted traffic sign showing a person and wheelchair inside the circle. Two persons commented that three-dimensional views or sections would be helpful for the Question 5 diagram (Figure 13) about "vary form and layout." A few Participants circled a part of the diagram that could have potential problems, and drew a line to write down the problem, while others underlined or circled words in the text and drew arrows out to comment further. And, some participants interpreted the task as a design task and made suggestions to solve the problem.

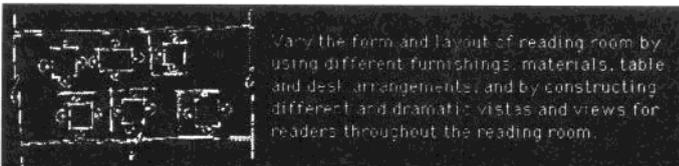


Figure 13. Participants suggested changing this diagram to a three dimensional view (Question 5 of Task 3)

3.4. *Task 4 reveals that designers agree with Archie diagram-text pairs*

The six questions in Task 4 asked participants to comment on diagram-text pairs from the Archie case base. They were asked to draw diagrams or comment on given pairings of diagram and text description sets. The overall result is that participants found the text and diagrams well paired, which suggests that people can understand and agree on other people's illustrations of text stories. For example, in Question 4, fifty-nine (95%) of participants simply wrote "good fit," "OK," or "fit" to comment on the given pairing of text and diagram (Figure 14).

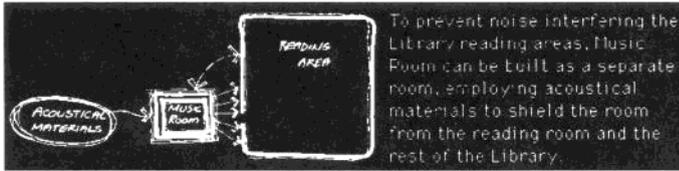


Figure 14. Diagram showing music room issues, given for Question 4 of Task 4.

Study of Task 4 data revealed four features of diagram making. First, most participants read the diagrams clearly without much labeling, although several participants noted that labels help reading. Second, some participants suggested a sectional rather than a plan view to illustrate sight line relationships in Question 5 of "sheltered waiting area remains visible." Third, participants had a tendency to read diagrams from left to right, and to interpret diagram elements as real physical objects. For example, a shape representing a space can be moved to a different location and can hold symbols of sound inside its content. For example, participants commented that the Question 4 diagram (Figure 14) looks like a mathematical formula $A + B = C$ and suggested moving the far left bubble labeled "acoustic material" between "music rooms" and the "reading area". Some suggested keeping arrow lines that represent noise within the "music room. Fourth, similar to the Task 1 finding, concepts were illustrated in a conventional way such as using concentric arcs or lines with arrows to represent the symbol for "noise," and using lines with arrows to indicate either circulation path, visual access, and occasionally even noise.

In summary, the results from Tasks 1-4 support our initial hypotheses about diagram features. We found that participants used only a small set of basic geometric shapes such as ovals and rectangles, lines and hatch marks. They used these primitives to make symbols in conventional ways to represent architectural concepts. Moreover, participants interpreted other designers' architectural diagrams or texts in a similar way.

4 Discussion and future work -- implications for diagrams and computing

4.1 Designers' shared understanding of diagrams

Designers seem to share an understanding of the definition of diagram, though it is unclear in their own minds. Some participants commented that they made sketches instead of diagrams, and some asked for a definition of "diagram." Some participants suggested that we include definitions in the test material to ensure that they make the "right kind" of diagrams. However, most participants described the elements of diagrams they use most, with text or by drawing simple geometric shapes such as lines, rectangles, circles and hatches.

4.2 Future experiments

The participants were students with at least three semesters of design studio experience from the environmental design department of the University of Colorado. Perhaps reflecting the range of participants' design studio experience, the task data show a wide range of response. However, perhaps due to these students' design education, the diagrams and texts had significant common features. A pre-test with two Georgia Tech Ph.D. students, who both did their undergraduate studies outside the United States, found similar results. If the common features are due to design education, then at least it is fairly universal. A future expanded study would use a broader range of subject material and a more diverse population of participants, or different design professionals to explore the universality of diagram making and diagram reading. For example, a similar test using material from different sources might reveal a different symbol universe. Moreover, one might also automate the experiment, using a computer-based diagrammer to collect and analyze data (though some of the analysis process may be hard to automate). To more accurately and efficiently analyze the results, the next experiment might also be conducted with fewer participants, and fewer questions.

Our experiments also raise questions that could be explored in further experimental studies. First, we suggest that a diagram is a simplified representation of a complex relationship. What purpose, then, do diagrams serve in a design process? Second, we suggest that architectural diagrams illustrate natural or artificial phenomena, building

components and human behavior. Are diagrams limited to these concepts? Third, what is the structure of a diagram? Is there a grammatical rule and syntax for diagrams? Fourth, does diagramming reflect specific theoretical positions in design? For instance, do diagrams reflect particular education, training, or style for arranging layouts and form? Fifth, to what extent is diagramming a matter of individual style and preference?

4.3 *Future work - diagrams as an index to design information systems.*

We began this study of designers' diagrams to explore the feasibility of using diagrams to access a design information system. We found that diagrams are used conventionally among designers, which supports the feasibility of computer support for visual note taking, and for indexing a database of design information. Our study shows that designers can read other designer's diagrams and that they often use symbols to illustrate their ideas. In our experiment many participants agreed that diagrams are useful and that existing Draw and CAD programs should provide the ability to diagram. This suggests that a computational environment that supports and recognizes hand drawn diagrams would be useful.

We have built Archie's Napkin, a prototype system linking a diagramming tool to Archie [15, 16]. It recognizes a small set of diagrams that serve as symbols indexing Archie's case base. For example, a designer concerned about connecting two functional spaces by a path might draw two circles or shapes connected by a line. Archie uses the diagram to find stories about how corridors connect two rooms in the background while designers remain in design drawing activities. Although we have illustrated the idea of diagram indexing with a case based system, we could also use diagrams to access other design information knowledge bases.

We currently have several items on our agenda to augment our prototype. First, to expand Archie's Napkin diagrammer with more diagramming abilities such as indexing, note-taking and cases-accessing, we need to further study the features of diagrams. We would examine how speed and the drawing pressure reflects the thinking involved during the design activities. The questions of how diagrams are transformed to sketches an schematic drawing and construction drafting still remains for exploration. To understand more about the role of drawing in design, we need to look also at sketches and other types of drawing, not only at diagrams. We would also explore automating the diagram indexing process.

Second, we would develop a more structured organization of diagram primitives. For example, the recognized features of diagrams could include spatial relationships such as adjacencies, proximity, relative size, and alignment constraints. A structural engineering diagram could include different symbols for material, joints and mounting; an urban design diagram could include symbols for landmarks, axis and edges. We would define more useful

primitive objects found in design folios and office tracing papers and build a larger symbol library.

Third, we would perform usability tests for our retrieval by diagram scheme. We would develop experiments to find how a diagramming interface can help designers find relevant issues from Archie. An architectural story can be accessed in different ways, each of which has different virtues. For example, a keyword search is powerful when the designers know exactly what the design problems are. A diagram might support different reading based on context and shape information. Designers might be reminded of a case story by recognizing simple geometric shapes and spatial relationships before they find the correct text specification.

To sum up, our goal is an "intelligent" user interface that recognizes design diagrams and provides selection of retrieval choices. We are currently exploring how to weigh similarity between different diagram primitives, and finding efficient ways to parse a diagram. We believe the diagramming tool should be integrated with the design information system. To further support designing, designers should be able to find relevant stories from the case base, copy diagrams into the sketch environment, and enhance and develop diagrams into more precise drawings. In the background, a design knowledge base would watch, find, and display examples of relevant design stories.

5 Acknowledgments

Discussions with Craig Zimring and Mark Gross provided help in developing the test set-up and analysis of the experiment. The paper also benefits from the remarks of Suguru Ishizaki and Ray McCall. Thanks to Archies principal investigators Janet Kolodner and Eric Domeshek. The data in Archie comes from previous P.O.E. studies done by the author with Ali Malkawi, Ameen Farooq, Husam Khalil and Osman Ataman.

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