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Abstract

This study examines the role of "conceptual diagrams" in architectural design, specifically how they facilitate conceptual elaboration in problem-solving processes. We single out a class of conceptual diagrams that we claim to be "double-referential," in that their structure corresponds to the generic structure of both the design conceptualization and solution. As such modifications of diagrams produce changes in the conceptualizations and their corresponding design schemes.

Keywords: Conceptual diagrams; diagrammatic reasoning; design cognition.

Studies in diagrammatic reasoning have investigated the role of diagrams in different domains in supporting reasoning, problem solving, and communication (Hegarty, Meyer, & Narayanan, 2002). These studies often are confined to domains that pose relatively well-defined problems, such as geometry (Koedinger & Anderson, 1990) and physics (Larkin & Simon, 1987), with fewer studies in domains where the problems are ill-defined, such as scientific discovery (Cheng, 1996), and architecture (Do & Gross, 2001).

Our study investigated the roles played by diagrams in concept generation and elaboration in complex, ill-defined problem solving situations as exemplified in architectural design. The paper discusses the characteristics of one particular class of diagrams, *conceptual diagrams* (Dogan, 2003). This class of diagrams was identified through cognitive-historical analyses (Nersessian, 1995) of several case studies in the history of architectural design (Dogan 2003). In the context of this paper we can only outline the salient points of one study, Daniel Libeskind's Jewish Museum in Berlin. We argue that conceptual diagrams differ from other types of representations used in design—in particular, sketches—in that they represent both the designer's conceptualizations and generic design solution schemes. This "double referential" nature allows them function as mediators between the problem space and the solution space in the design process.

Conceptual diagrams in design

By "conceptual diagram" we mean:
- *A visual/spatial configuration representative of the core of a design conceptualization.*

They differ from sketches in design in that:
- *They are not realistic representations of physical objects; they are, rather, representations of abstractions.*

They differ from other kinds of diagrams in design in that:

- *Conceptual diagrams are double-referential in the sense that they correspond to the design conceptualization and to potential generic spatial configurations, both of which are components of design conceptualizations.*

Studies in design representations have focused on sketches (Goel, 1995; Goldschmidt, 1991; Suwa & Tversky, 1997). These studies show that sketches are significant in generating ideas through their ambiguous and dense structure. However, research in the area of diagrammatic reasoning provides evidence for how diagrams can differ from sketches. The results of these studies have shown that diagrammatic representations directly represent the structure of their target domain (Shimojima, 2001; Stenning & Lemon, 2001), and thus simplify the complexity of conceptual domains (Bauer & Johnson-Laird, 1993).

Shimojima (2001) argues that the main determining factor of diagrammatic representations is the existence of nomic constraints. These constraints establish correspondences between the representation and what is represented through keeping at least one characteristic of the target domain present. Stenning and Lemon (2001) describe diagrammatic representations as "…plane structure[s] in which representing tokens are objects whose mutual spatial and graphical relations are interpreted directly as relations in the target structure" (p. 36). Johnson-Laird (2002) characterizes diagrammatic representations and their target domains in terms of a correspondence to a target domain, wherein the structure of the two domains remains the same. The correspondence between diagrams and their target domains, according to Johnson-Laird, is about structure and not any other arbitrary feature. Based on these characterizations of diagrams, the distinction we focus on here between sketches and diagrams is that diagrams highlight and represent structural relationships of their target domains, whereas sketches may represent these relationships but do not explicitly highlight them.

Johnson-Laird also points to an important similarity between mental models and diagrams in that they both maintain structural correspondences with their represented domains. We propose that some diagrams can provide external representations of structural correspondences of a mental model of a core design conceptualization. Manipulating such diagrams physically can create corresponding changes in the mental model, as has been proposed for simulative model-based reasoning with physical models (Nersessian, 2002). In this research we hypothesize that diagrammatic representations could potentially act as

physical models representative of mental representations and we conjecture that:

- *manipulations of the components of conceptual diagrams are likely to change the structure of their corresponding mental models.*

Why are diagrams well suited for design?

In the literature on design cognition and problem solving, design problems are held to be ill-defined (Reitman, 1964). Search in well-defined problems is confined to identifying the operators, whereas in ill-defined problems search includes both an alternative structuring of the problem statement and determining operators. In problem-solving literature, the former is known as problem structuring, whereas the latter as problem solution (Newell & Simon, 1972). We are not convinced that thinking of design problem solving in terms of the traditional notions of search through problem and solution spaces provides the best means of understanding the role of conceptual diagrams. However, since much of the literature in design cognition we want to respond to is couched in these terms, our analysis here will be as well.

The distinction between problem structuring and problem solution has often been cited as a distinguishing factor of design problems (Goel & Pirolli, 1992) and design problem solving is considered to progress in two search spaces, problem structuring and problem solution, as opposed to a single search from an initial state to a goal state. Problem structuring is the process through which information transferred from our knowledge is used to better define an ill-defined design problem (Goel & Pirolli, 1992), whereas problem solution is the process through which specific design schemes are formulated. For instance, to design a house of worship, among others, a designer needs to know for which denomination and for how many people this structure is going to be built. Any piece of information used to further specify the house of worship is an element of problem structuring. In contrast, when the designer starts thinking about the form, shape, and spaces of the house of worship, e.g., a triangular instead of a circular building, a specific design scheme is formulated in the solution space.

The main controversy in design studies about the dual search has been about the nature of the interaction between the two searches. Some have argued that there is a linear progression from problem structuring to problem solution (Goel & Pirolli, 1992); others have suggested a reverse linear progression (Lloyd & Scott, 1994), yet others have claimed that the interaction between the two is co-evolutionary rather than linear (Maher & Tang, 2003). The results from this research, however, are inconclusive about the relationship between problem structuring and problem solution in design and about their temporal order. Architectural design is replete with instances when designers start with problem structuring (Goel & Pirolli, 1992) and with those where the design starts with a solution (Lloyd & Scott, 1994). The main issue, therefore, is not about the temporal order between problem structuring and problem solution in design, it is rather about the nature of the coordination of the dual search in the design

process. Furthermore, different from those views which define problem structuring only in terms of information transfer, we claim that problem structuring could occur through formulation of a coherent conceptual framework responding to the main requirements of a design situation.

We contend that the dual search in design is facilitated through the double-referential aspect of conceptual diagrams. Conceptual diagrams represent both the generic structure of a design conceptualization, corresponding to problem structuring, and potential generic spatial configurations, corresponding to problem solutions. They align the structure of problem space with the structure of solution space. On our hypothesis, manipulations of the diagram are propagated to both spaces whenever there is a structural change, suggesting that if there is a structural change in the conceptual diagram it has the potential of changing the structure of the corresponding conceptualizations. Thus, when conceptual diagrams are constructed and manipulated in the design process, problem structuring and problem solution are brought into alignment. Conceptual diagrams can be thought of as:

- *mediating representations between abstract concepts and specific spatial configurations, i.e., between problem structuring and problem solution.*

Given the potential significance of conceptual diagrams, an inquiry into their role in actual design processes with successful outcomes might provide some answers to the question of how search in the problem space and search in the solution space are coordinated with each other and what role conceptual diagrams play in this coordination. In the remainder of this paper we will outline a cognitive-historical analysis of such a design process. Rather than constructing an historical narrative, cognitive-historical analysis examines problem solving practices exhibited in historical data with the objective of enhancing understanding of cognition.

The Design Process of the Jewish Museum of Berlin

With the case study of the Jewish Museum we highlight the significance of a series of conceptual diagrams through which Daniel Libeskind coordinated his evolving conceptualization with the formulation of a design scheme. The initial conceptualization centered on a representation of the Star of David (highlighting Jewish identity and history in the search of the problem space, i.e., problem structuring) and a zigzag line as a potential building form (constraining search of the solution space, i.e., problem solution). During the design process, the efforts of Libeskind and his assistants were directed towards improving the zigzag design while Libeskind simultaneously tried to reach a conceptually sound base for the specific design. In this process, constructing a series of diagrams helped Libeskind correlate the search in the solution space with the search in the problem space and end with a satisfying conceptual basis for the solution that entwined the structure of the building with Jewish identity and history in Berlin and in Germany, as it zigzagged through space and time.

The task for Design Competition for the Jewish Museum in Berlin was to propose an extension to the Berlin Museum that would house its Jewish Collection. Our analysis of the design process is based primarily on an investigation of archival materials at the Getty Research Institute, which houses sketchbooks, final competition drawings and other drawings, letters, and additional textual materials from Libeskind's office. Other investigated materials include published writings of Libeskind and of others on the Jewish Museum and on Libeskind's architecture. In addition, a member of the design team was contacted to provide information about the design process. In the space of this paper we can only highlight salient aspects of the design process.

The design process of the Jewish Museum progressed in two search spaces. On one hand, the design team focused on a design scheme in the form of a zigzag, on the other hand the principal architect (Libeskind) worked on sorting out important features of the design conceptualization through the use of Star of David. Libeskind used the Star repeatedly to establish connections among different issues relevant for the design concept while at a later stage he managed to combine the search in the solution space, i.e., the zigzag form of the building, with the search in the problem space.

For Libeskind, the Star represented Jewish history and culture throughout the history of Berlin and its absence in the present-day city. He drew many variations of the Star throughout the process, leading to the version drafted for the competition entry (Figure 1). We will refer to this specific drawing as the conceptual diagram of the Jewish Museum project, because the drawing is:
- A visual/spatial configuration representing the core of the design conceptualization: with this diagram Libeskind emphasized the pervasiveness, yet, invisibility of the Jewish presence in Berlin and the intertwined histories of Jews and Germans.
- Double-referential: the spatial configuration both represents a generic spatial configuration and highlights the main features of the design conceptualization.
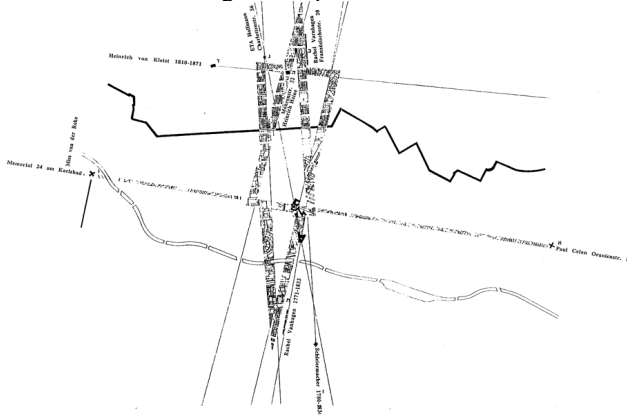

Figure 1: Star Matrix: a distorted version of Star of David.
(© Research Library, The Getty Research Institute, Los Angeles, 920061)

Over the course of the design process Libeskind used various drawings of the Star to establish a network of connections among different points of the city designating a network of historical social interactions among Berliners that is invisible in nature, yet resident in the physical urban fabric of the city. The imagined network emerged, e.g., from such explorations as superimposing addresses of historical Jewish figures in Berlin on a map of contemporary Berlin. Libeskind saw this network as an invisible aspect of Berlin because although the history of social and cultural interaction runs through the fabric of Berlin it remains largely unseen – the holocaust had the effect of eliminating the Jewish culture from the post-war city. Libeskind's Star represents both this presence and absence, this history and its distortion.

Libeskind started the design process by drawing six distorted and eight partial Stars on the back of the Berlin Museum pamphlet, attached to the competition invitation letter he received from the competition organizers. On the second page of the same document, Libeskind had about 15 more stars and on the back of the page he drew a zigzag (Figure 2), which became the final form of his building. On the site plan, he sketched a preliminary layout for his building and its relation to a close-by public circle.
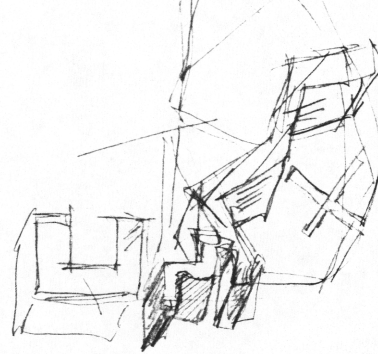

Figure 2: The zigzag building with the Berlin Museum.
(© Research Library, The Getty Research Institute, Los Angeles, 920061)

In the initial competition representation the distorted star on the site plan and the zigzag lines, one of which shows a zigzag building adjacent to the Berlin Museum in an axonometric drawing, were conceived as generic spatial configurations for the Jewish Museum. In the subsequent design process, the team changed the width of the zigzag and explored ways of making the zigzag more vertical, while Libeskind merged the zigzag plan with the distorted star layout. In the final design, the spatial configuration of the building was represented by two intertwining-lines, one straight line defining the voids and one zigzag line housing the exhibition spaces.

Design Conceptualization

In the process of constructing and elaborating a meaningful conceptualization of the design situation, Libeskind focused on two major themes: the relationship between Jews and Germany in the history of Berlin and the invisibility of Jewish culture in present day Berlin.

The conceptual dilemma for Libeskind was acknowledging the oneness of Jewish and German culture without diminishing the significance of the historical facts of the thirties and forties. Libeskind articulated a conception of the historical evolution of the relationship through a series of

drawings in which the Jewish and German histories are depicted by two converging/diverging lines representative of their close interaction. In some of these drawings (Figure 3), Libeskind draws numerous numbers of trajectories between two points (AB), representing the individual biographical trajectories of citizens of Berlin, which Libeskind refers to as histories.

Figure 3: Trajectories between points AB.

None of these trajectories, however, is linear. They are all convoluted lines that crisscross each other and their sum is a complex network of lines rather than a single resultant of all different lines. The conception of history in these drawings dictates a double helix-like historical progression of two intertwined lines, suggestive of the zigzag layout of the design, which refers to the merging as well as parting of the two histories and which represents the complex and convoluted historical relationship between Jews and Germans.

In one particular drawing (Figure 4) the analogy between the history of the interaction of Jews and Germans and the Jewish Museum Building becomes clearer. Libeskind labels the straight linear block cutting through the building as the Jewish history line whereas the zigzag block as the Berlin history. He also adds dates to the zigzag substantiating the idea that the lines represent trajectories in history. In his final scheme, the straight line would become the series of voided spaces that cut across the exhibition spaces. At this stage, the conceptualization of the historical relationships between Jews and Germans is not yet linked to the Star of David imagery.
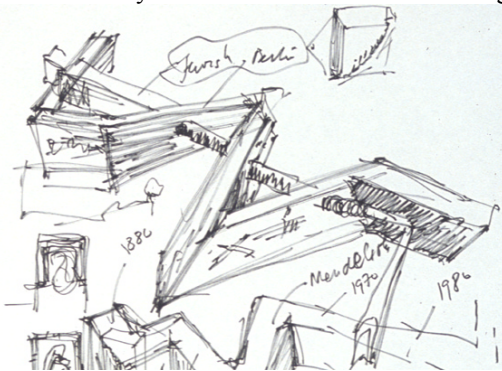

Figure 4: Crisscrossing Jewish and German history lines.

The German-Jewish history, however, remains obscure when one walks in the streets of contemporary Berlin not only because Jews no more live in Berlin but also because their mutual artifacts were destroyed. The contemporary plan of Berlin, therefore, is an "obstructionist form" which renders invisible the Jewish material presence in Berlin.

Conceptually Libeskind makes the invisible visible by trying to trace the Jewish presence in Berlin's sky (Figure 5). The sky invokes the Jewish presence in the air of Berlin while the Star of David materializes that on the map of contemporary Berlin.
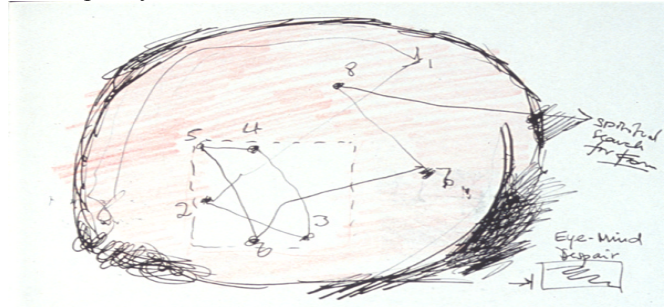

Figure 5: The Berliner Luft—the air across Berlin.

Later in the design process, Libeskind managed to combine the two components of his design concepts, i.e., the oneness of German-Jewish history and the invisibility of Jewish presence, with a series of diagrams in which intertwined zigzag lines (Jewish-German history lines) transformed into a Star of David (invisibleness of Jewish presence) (Figure 6). In one of his set of drawings, he drew several incomplete or distorted stars in different form and nature. Here, Libeskind explodes the two completely enclosed lines of the original star becoming two intertwined lines suggestive of the final zigzag footprint of the Museum building and the double-helix like histories of Jews and Berlin. In certain cases, the two lines start as the two triangles of the Star of David, yet they suddenly break the geometry of the star and become a zigzag. In these instances, there is a combination of an incomplete star and a zigzag. In other instances, there are no stars. The intertwining lines start as a zigzag and remain like that. In the majority of these cases, both lines make acute turns. In one case, however, one of the lines remains straight all the way through and the other makes up-and-down turns very similar to the overall composition of Libeskind's competition entry. In few of them the lines become one zigzag line and a straight line cutting through the zigzag.

Through this set of diagrams, Libeskind managed to conceptually integrate different lines of thinking and aligned the search in the solution space with the search in the problem space. When Libeskind transformed the two intertwining lines of the Star into a zigzag line and a straight line cutting through the zigzag, he also changed the initial zigzag form which the design team had been working on since the beginning of the design process. In the subsequent phases, the form of the building became one of a zigzag and an interrupted line cutting through the zigzag which becomes visible only at times when it crosses the zigzag. At these crossing Libeskind placed void spaces—unoccupied spaces— which are representative of the contemporary invisibility of the Jewish presence in Berlin.
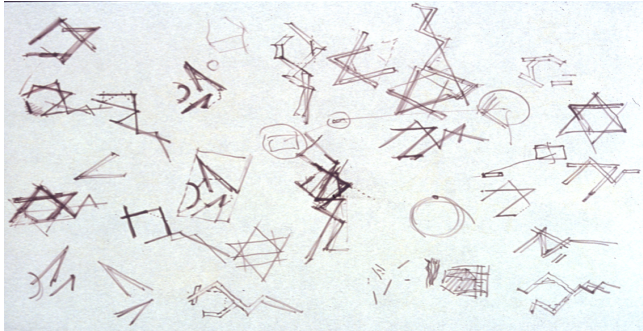
Figure 6: Star evolving into a zigzag.

Discussion

Libeskind's explorations within the problem space and solution space followed neither Goel and Pirolli's (1992) linear characterization of design nor the co-evolutionary characterization (Maher & Tang, 2003). Libeskind's exploration within the problem space continued throughout the design process, even though the spatial configuration was determined early in the design process, through borrowing from an earlier project of Libeskind, and that generic configuration remained the design solution throughout the process.

Libeskind's conception of the design remained relatively constant throughout the design process, even while various sources influenced his elaboration of the design concept. Throughout the process Libeskind established links to historical, philosophical, cultural, and material sources to various instantiations of the star diagram. Each instantiation of the diagram can be characterized as a move within the problem space through which new relationships to other domains were established. In the elaboration, new layers of meaning were added by connecting the generic representation of the Star (problem space) with the zigzag configuration (solution space). But throughout the core conceptualization and the core configuration solution remained constant.

With respect to explorations within the solution space, Libeskind and the design team remained within the same space throughout. The design team only considered closely related schemes, all of which retained the generic spatial configuration. As with his Star conceptualization, Libeskind elaborated the meaning of the spatial configuration of the zigzag. Although the design team took the generic zigzag form from an earlier project, in the subsequent design process, Libeskind linked the zigzag to the elaborated conceptualization by transforming it into two crisscrossing lines: a straight line representative of the Jewish history and a zigzag line representative of the German history. The crisscrossing lines of the zigzag originated in the crisscrossing lines of the Star of David. The emergent configuration was representative of both the Star and the zigzag. Therefore, the solution space acquired two specific conceptual source domains: the visibility of the Jewish presence, embodied in the Star imagery, and the intertwined histories of Jews and Germans, in the intersecting lines.

Initially, the process of the Jewish Museum did start with a focus on problem structuring, as Goel and Pirolli (1992) suggested, but exploration in the problem space continued throughout the design process. Second, the zigzag provided a generic design solution scheme right from the beginning of design. Different from Goel and Pirolli's characterization, the initial phases of design were not only dedicated to problem structuring but also to problem solution. Contrary to the linear characterization, Libeskind thought and elaborated on a conceptualization while developing a satisfactory design scheme. This last point seems to support co-evolutionary views of design (Maher & Tang, 2003) and solution-oriented views of design (Lloyd & Scott, 1994). In contrast to co-evolutionary views of design, however, the explorations in the problem space and the solution space remained isolated during most of the design process and there was no need for constant interaction between the two exploration spaces. Most often the implications of moves in one space did not get propagated into the other, as is predicted by co-evolutionary views of design. Rather, only significant changes in the problem space, e.g., the linkage between the intertwined histories of Jews and Germans and the invisibility of Jews in contemporary Berlin, were propagated into the solution space, e.g., the addition of the voided spaces into the zigzag building form. Furthermore, search in the solution space provided meaning to an independently conceived design scheme and its elaboration. It enabled the scheme to be interpreted as a satisfactory solution to the design problem of creating a *Jewish Museum in Berlin*.

Libeskind's conceptual elaboration provides a fascinating example of how manipulation of the components of diagrams can mediate changes in the corresponding conceptual and spatial configuration domains. One example of a significant and traceable conceptual elaboration in this design process occurred when the idea of the intertwined histories of Jews and Germans was integrated with the idea of the significance of Jewish culture for the German culture. In this instance, Libeskind modified the Star of David through a series of diagrams and literally unfolded it into two zigzagging lines with which the two conceptual ideas were combined into a single representation. Figure 7 is our schematic representation of this process some of which is evidenced in Libeskind's Figure 6.

The combination of the two conceptualizations could have been triggered by the perceptual similarities between the two diagrammatic representations, the zigzag and the star (Figure 7). The matching perceptual features were: crisscrossing lines, intersections, and corners. Once the two diagrammatic representations were combined the meanings of these perceptual features were superimposed. In the final configuration each element acquired a double meaning, at once representing the invisible nature of Jewish culture in contemporary Berlin and the integrated history of Jews and Germans. Furthermore, Libeskind finally managed to relate the two explorations in the problem space and in the solution space through mutating the star into two crisscrossing lines. In the final spatial configuration, Libeskind left a void where

the lines crossed, symbolic of the invisibility of the Jewish presence in present Berlin.
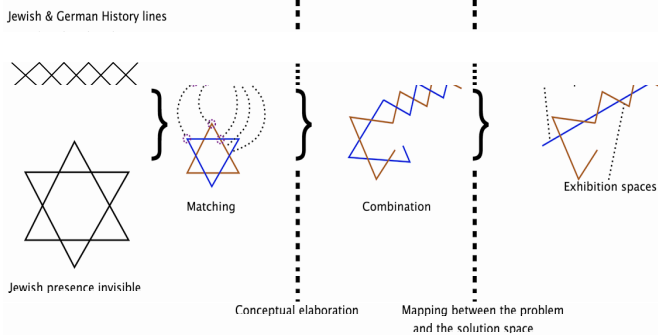

Figure 7: Combination of the invisibility of the Jews and the history lines of Jews and Germans [drawn by the author].

This manipulation of the components of the two diagrammatic representations and their coalescence is an example of how changes in a physical representational system can create corresponding changes in a conceptualization. The change in the conceptualization, in turn, triggered a change in the spatial configuration of the building, i.e., in empty spaces at the points where the lines cross. This superimposition of meanings was achieved through manipulating diagrammatic representations, and changes in the conceptualization and in the spatial configuration were mediated by the structure of emergent the diagrammatic representations. The emerging representation retained its structural correspondence to both of its corresponding conceptual domains and thus acquired double meaning.

Conclusion

This study presents a case in which a series of diagrams facilitated conceptual elaboration in the design process while aligning the search in the solution space with search in the problem space. The study shows that modifications and elaborations in design conceptualizations can be fostered through the manipulation of components of conceptual diagrams, which are here considered physical representations corresponding to mental models. The study shows also that design can start either in the solution space or in the problem space, but that search in both spaces needs to be aligned. Conceptual diagrams, because of their double-referential nature are potentially significant in facilitating search in dual space.

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