Design Thinking Support: Information Systems Versus Reasoning

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Introduction

Numerous attempts have been made to conceive and implement appropriate information systems to support architectural designers in their creative design thinking processes. These information systems aim at providing support in varying ways: enabling designers to make diverse kinds of visual representations of a design, enabling them to make complex calculations and simulations that take into account various relevant parameters in the design context, providing them with relevant information and knowledge from all over the world, and so forth. Despite the continuing efforts to develop these information systems, they still fail at this point to provide essential support in the core creative activities of architectural designers. Seeking to understand why an appropriately effective support from information systems is so hard to realize, we began to look into the nature of design thinking and on how reasoning processes are at play in this design thinking. Our investigation suggests that creative designing rests on a cyclic combination of abductive, deductive, and inductive reasoning processes. However, traditional information systems typically target only one of these reasoning processes at a time, which might explain their limited applicability and usefulness. As research in information technology increasingly targets the combination of these reasoning modes, improvements in design thinking support by information systems might be within reach.

Information System Support for Design

Understanding how an information system can provide support in the design process requires sufficient understanding of how design thinking occurs in this process. Constructing such an understanding has been the goal of many research initiatives during previous decades. Several appropriate overviews are available that describe the historical evolutions in these research initiatives and their outcomes.[1] We elaborate here on some of the key points in this domain of research, focusing on the theories outlined by Nigel Cross, Bryan Lawson, Donald Schön, and Herbert Simon. Central elements in these theories are (1) the intensive interaction

1 See Nigan Bayazit, "Investigating Design: A Review of Forty Years of Design Research," *Design Issues* 20, no. 1 (2004): 16-29; Nigel Cross, "Forty Years of Design Research," *Design Research Quarterly* 1, no. 2 (2007): 3-5.

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between designer and design context, and (2) the reflective, "learning-while-doing" character of the design thinking process. In learning-while-doing, designers build up knowledge in direct reference to concrete experiences. This knowledge is often referred to as "a designerly way of knowing."[2] Designers make design decisions in newly encountered design contexts on the basis of this kind of knowledge. Through their ongoing interaction with new design contexts, designers continuously modify or adjust their designerly way of knowing. These adjustments obviously have a significant effect on future design decisions.

Over the years, the design research community has recognized how reasoning based on a set of previous experiences is crucial for creative thinking and for mental activity in general. Several theories refer to this kind of reasoning as "abductive reasoning."[3] These and comparable theories typically refer to the work of Charles Sanders Peirce, and more specifically to his work that combines abductive reasoning with deductive and inductive reasoning. Peirce argues that the combination of these three reasoning modes underlies any process of scientific inquiry.[4] Many researchers have tried to simulate these reasoning modes in a computer environment. Whether or not these attempts were successful, or could possibly and eventually be successful, is not of central concern for this article. Instead, we hope to evaluate to what extent and in which way(s) information systems might support these reasoning modes of the designer.

A digital repository of architectural information can be considered an example of a support system because it makes a limited version of other people's architectural experiences available to any reasoning process all over the world. One such repository is that which resulted from the initiative Metadata for Architectural Contents in Europe (MACE). This repository relies on metadata to interconnect and disseminate digital information about architecture.[5] However, examples of how such repositories are usefully deployed in existing architectural design practices are lacking, which might indicate that they are not fully suited to support the reasoning processes of a designer. Similar limitations exist for other types of support by information systems, essentially indicating a mismatch between design thinking and the support provided by information systems.

To understand the basic causes of such an apparent mismatch, we compare in this article how design thinking appears to occur in the human mind and how information systems aim to provide support to an architectural designer. We first give a brief overview of the most significant theories in design thinking. Second, we discuss natural human reasoning processes and how they relate to theories of design thinking. Third, we outline the supposed mismatch between the theories of design thinking and

2 See Nigel Cross, "Styles of Learning, Designing and Computing," *Design Studies* 6, no. 3 (1985): 157-62; Nigel Cross, *Designerly Ways of Knowing* (London: Springer-Verlag, 2006), 5-9.

3 See Nigel Cross, "The Nature and Nurture of Design Ability," *Design Studies* 11, no. 3 (1990): 132.

4 Charles S. Peirce, *Collected Papers of Charles Sanders Peirce,* vols. 1-6, ed. C. Hartshorne and P. Weiss (Cambridge: Harvard University Press, 1931-1935), vols. 7-8, ed. A.W. Burks (Cambridge: Harvard University Press, 1958).

5 Moritz Stefaner et al., "MACE – Enriching Architectural Learning Objects for Experience Multiplication," in *Lecture Notes in Computer Science 4753: Second European Conference on Technology Enhanced Learning,* ed. Erik Duval, Ralf Klamma, and Martin Wolpers (Berlin: Springer-Verlag, 2007), 322-36.

information system support, thereby considering three application development approaches. Based on this analysis, we offer suggestions for addressing the mismatch.

Theories of Design Thinking

A lot of theories of design thinking exist. We focus in this section on (elements of) these theories that are related to the actual reasoning processes of the designer, and to design representations and guiding principles in design.

Reasoning in Design

Several researchers have made a case to identify design as a separate discipline in human thinking, apart from the disciplines of the arts and the sciences. With his theory of "a designerly way of knowing," Nigel Cross can be counted among these researchers.[6] His theory essentially distinguishes design knowledge from the kinds of knowledge typically at play in the disciplines of the arts and the sciences.[7] Throughout his publications, Cross strongly associates this kind of knowledge with the specific nature of design thinking. His reference to the research of Douglas and Isherwood illustrates his understanding of this kind of thinking:

> For too long a narrow idea of human reasoning has prevailed which only accepts simple induction and deduction as worthy of the name of thinking. But there is a prior and pervasive kind of reasoning that scans a scene and sizes it up, packing into one instant's survey a process of matching, classifying and comparing. [...] Metaphoric appreciation, as all the words we have used suggest, is a work of approximate measurement, scaling, and comparison between like and unlike elements in a pattern.[8]

Later on, Cross refers to several other research initiatives that distinguish a very similar kind of reasoning as fundamental for design thinking; here, he mentions the terms abductive reasoning, productive reasoning, and appositional reasoning, which are the terms assigned by their respective originators, Peirce, March, and Bogen.[9]

The "work of approximate measurement" or "metaphoric appreciation" is closely related to analogical reasoning and the reasoning involved in pattern recognition. Analogical reasoning is often explained as the cognitive ability to think about relational patterns.[10] It allows one to find a structural alignment or mapping between a base and a target pattern residing in (partially) different domains.[11] By making such an analogical mapping, familiar knowledge about the base pattern can be related to the target pattern, thereby filling in the gaps of the target pattern and creating new knowledge. In a context of architectural design,

6 Cross, *Designerly Ways of Knowing.*

7 Nigel Cross, "Designerly Ways of Knowing," *Design Studies* 3, no. 4 (1982): 221-27.

8 Mary Douglas and Baron Isherwood, *The World of Goods: Towards an Anthropology of Consumption* (New York: Basic Books, 1979), viii.

9 See Cross, *The Nature and Nurture of Design Ability,* 132; Peirce, *Collected Papers of Charles Sanders Peirce;* Lionel March, "The Logic of Design and the Question of Value," in *The Architecture of Form,* ed. Lionel March (Cambridge: Cambridge University Press, 1976), 1-40; Joseph E. Bogen, "The Other Side of the Brain II: an Appositional Mind," Bull Los Angeles Neurological Societies 34 no. 3 (1969): 135-62.

10 Keith J. Holyoak, Dedre Gentner, and Boicho N. Kokinov, "Introduction: The Place of Analogy in Cognition," in *The Analogical Mind: Perspectives from Cognitive Science,* ed. Dedre Gentner, Keith J. Holyoak, and Boicho K. Kokinov (Cambridge: MIT Press, 2001), 1-19.

11 Dedre Gentner et al., "Metaphor Is Like Analogy," in *The Analogical Mind,* 200.

analogical reasoning often occurs between a new design-related experience (e.g., a building, sketch, 3D model, conversation, etc.) and a previous design experience. But also in the very act of sketching, analogical reasoning is critical because it allows reinterpreting or "seeing as," as Goldschmidt puts it.[12] In "seeing as," the designer reinterprets the sketch and adds new and unique meaning to it, thereby generating new ideas.

Another argument for the recognition of design as a separate discipline, apart from the disciplines of the arts and the sciences, is formulated by Bryan Lawson in his theory of "how designers think."[13] An important basis for his argument stems from his experimental observations in which he saw differences between the thinking processes of architects (closer to "imagining") and of engineers (closer to "reasoning").[14] Reasoning in this case is considered more purposive and directed toward a particular conclusion, whereas imagining is said to draw from an individual's own experiences, combining material in a relatively unstructured and perhaps aimless way. Note that Lawson does not exclude the coexistence of imagining and reasoning in one mind. Instead, he considers the control of the delicate balance between rational and imaginative thought as one of the most important skills of a designer.[15] Note also that this definition of imagining is again closely tied to analogical reasoning. Because analogical reasoning is guided by encountered target patterns, which are out of the designer's grasp, the designer appears to proceed "in an unstructured and perhaps aimless way." A similar characterization is given by Boden's research on "the creative mind."[16] She stresses the importance of the incubation phase in creative thinking. In this phase, the conscious mind focuses on other domains, problems, or projects, thus enabling the creative mind to make diverse analogies with the (design) situation at hand.

A second characteristic of reasoning in design is given by Donald Schön. He characterizes design thinking as a sense-making process, in which the designer "must make sense of an uncertain situation that initially makes no sense."[17] This type of reasoning process can be distinguished from more "traditional" reasoning processes, in which problems are typically represented as well-confined and fixed givens, and one merely has to select the most appropriate method available to get to a solution. This distinction is also made by other researchers in design thinking by stating that designers do not follow a straight-forward path from problem to solution, but instead oscillate between problem(s) and solution(s). For instance, Cross indicates that designing does not proceed in a sequence of stages that targets each one of the (partial) problems initially identified or outlined. Instead, designing appears to proceed through an iterative form of interplay between partial problems and their solutions. "During the design process, partial models of the problem and of its solution

12 Gabriela Goldschmidt, "The Dialectics of Sketching," *Creativity Research Journal* 4, no. 2 (1991): 131-32.

13 Bryan Lawson, *How Designers Think - The Design Process Demystified* (Oxford: Architectural Press, 2005).

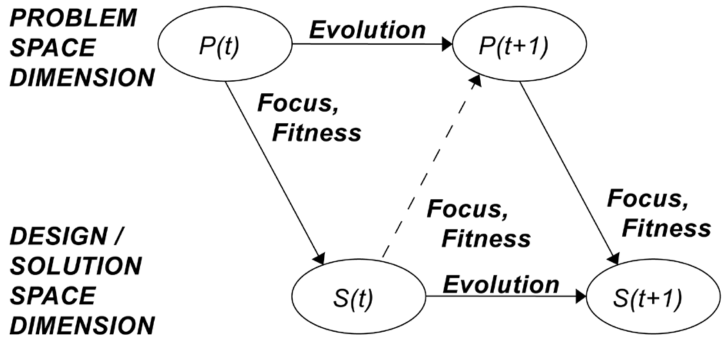
14 Bryan Lawson, "Cognitive Strategies in Architectural Design," *Ergonomics* 22, no. 1 (1979): 59-68.

15 Lawson, *How Designers Think*, 138.

16 Margaret A. Boden, *The Creative Mind: Myths and Mechanisms* (London: Weidenfeld and Nicolson, 1990), 29-36.

17 Donald Schön, *The Reflective Practitioner: How Professionals Think in Action* (London: Temple Smith, 1983), 40.

Figure 1
Maher and Poon's "Problem-Design Exploration Model" (courtesy of Mary L. Maher and Josiah Poon).



are constructed side-by-side, as it were. The crucial factor, however, is the bridging of these two partial models by the articulation of an apposite concept [...] which enables the models to be mapped onto each other."[18] Dorst and Cross link the interplay between partial problems and solutions to the notion of "co-evolution" of problem and solution.[19] This notion of co-evolution was suggested previously by Maher and Poon.[20] According to the concept of co-evolution, both problem and solution evolve during a combined process of exploration as depicted in Maher and Poon's "Problem-Design Exploration Model" (see Figure 1).[21]

Finally, a similar approach is also put forward by Herbert Simon in his "sciences of the artificial."[22] In his discussion of the problem-solving process preceding any artifact, Simon dissociates himself from the traditional, rational viewpoint, in which the outer environment would be modeled as a combination of, for example, cost and revenue curves, so that one can "easily" calculate the optimum through a process of "substantive rationality."[23] In reality, the problem is far more complex, says Simon, because one is required to cope with numerous elements of uncertainty and with quality (vs. quantity) criteria. Thus, "at each step toward realism, the problem gradually changes from choosing the right course of action (substantive rationality) to finding a way of calculating, very approximately, where a good course of action lies (procedural rationality)."[24] As a result, Simon eventually concludes that a designer is essentially a "satisficer"—a person who aims at a good enough alternative, starting from a set of combinations of possible problem descriptions and corresponding solutions.

Design Representations and Guiding Principles
Two elements are crucial in the sense-making process of designers: (1) what designers experience at design time (task environment/target patterns) and (2) what designers have already experienced before (background knowledge/base patterns). Both elements are also considered central in the notion of a "design problem space,"

18 Nigel Cross, "Descriptive Models of Creative Design: Application to an Example," *Design Studies* 18, no. 4 (1997): 439.
19 Kees Dorst and Nigel Cross, "Creativity in the Design Process: Co-evolution of Problem-Solution," *Design Studies* 22, no. 5 (2001): 425-37.
20 Mary L. Maher and Josiah Poon, "Modeling Design Exploration as Co-evolution," *Microcomputers in Civil Engineering* 11, no. 3 (1996): 195-209.
21 Josiah Poon and Mary L. Maher, "Co-evolution in Design: A Case Study of the Sydney Opera House," in *Proceedings of the Second Conference on Computer Aided Architectural Design Research in Asia*, ed. Yu-Tung Liu, Jin-Yeu Tsou and June-Hao Hou (Taipei: Hu's publisher, 1997), 441.
22 Herbert A. Simon, *The Sciences of the Artificial* (Cambridge: MIT Press, 1996).
23 Ibid., 25-30.
24 Ibid., 27.

as defined by Goel and Pirolli: "a formalization of the structure of processing molded by the characteristics of the information-processing system [the designer's knowledge], and more importantly, the task environment [the designer's experiences]."[25] By endlessly combining both elements, designers continuously form renewed understandings of their design (target pattern) and of their background knowledge (base pattern).

Sketches are among the most obvious examples of *experiences* that designers go through at design time.[26] As Goldschmidt indicates, sketches are not only visual expressions of what one wants to express; they also are elements for reinterpretation and thus for generating all kinds of new knowledge.[27] Cross similarly refers to the importance of sketching because it enables a designer to explore several solutions and problems to a certain design situation at once, thereby considering several levels of detail at once.[28] Schön, in turn, refers to the habit of many a designer to continuously make representations of the design situation at hand in documents, plans, and sketches, thereby allowing a designer both to answer a previously generated problem situation or design situation, and to frame the design situation anew into an alternative perspective.

A valuable theory of the role of *background knowledge* of a designer is formed by Lawson's theory of so-called "guiding principles" or "design philosophies."[29] These concepts can be understood as the background knowledge or the knowledge by experience of a designer—the set of familiar design patterns that the designer might use in making analogies with new design experiences. According to Lawson, these guiding principles include not just objective, factual information but also information involving, for instance, motivations, beliefs, values, and attitudes. Guiding principles may be very intense and clearly structured, and they might be vague and unclear, but they always influence design decisions one way or another. In some research initiatives, they are almost considered part of a "personal religion," thereby implicitly redefining design as "a very complicated act of faith."[30] With sometimes profound intensity, designers hold to these personal guiding principles, believing it "morally right" to follow them.

A Reasoning- and Principal-Based Design Process

From the investigation of existing theories, we can construct a possible outline of the design process. As displayed in the outline in Figure 2, the design process proceeds by making analogies between encountered situations in the physical world and guiding principles in the human mind. The resulting analogies can be considered the designer's interpretations of encountered situations. By making an analogy, the designer generates hypotheses and predicts that the rest of the familiar pattern also applies to the encountered situation. In other words, new knowledge is created

25 Vinod Goel and Peter Pirolli, "The Structure of Design Problem Spaces," *Cognitive Science* 16, no. 3 (1992): 399.

26 A.Terry Purcell and John S. Gero, "Drawings and the Design Process: A Review of Protocol Studies in Design and Other Disciplines and Related Research in Cognitive Psychology," *Design Studies* 19, no. 4 (1998): 389-430.

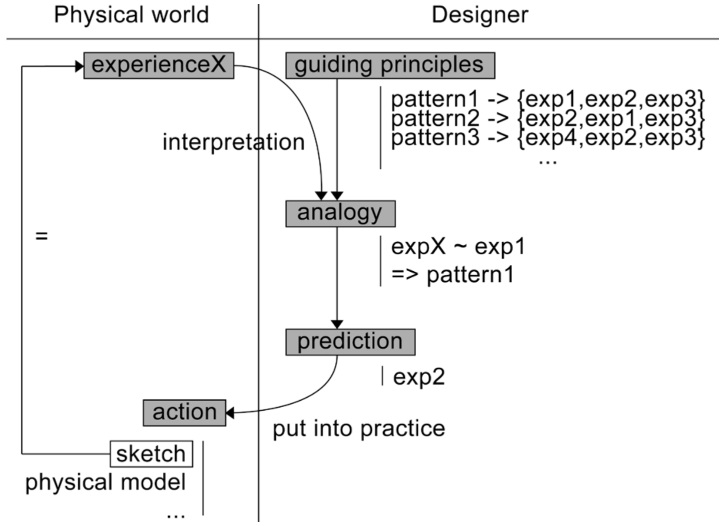
27 Goldschmidt, "The Dialectics of Sketching," 123-43.

28 Nigel Cross, "Natural Intelligence in Design," *Design Studies* 20, no. 1 (1999): 25-39.

29 Lawson, *How Designers Think,* 159-80.

30 John C. Jones, "Design Methods Reviewed," in *The Design Method,* ed. Sidney A. Gregory (London: Butterworth, 1966), 295-310.

Figure 2
Possible Outline of the Design Process.



by the analogy. The designer finally tests the prediction made, thereby creating a new situation or experience that either confirms or refutes the original analogy. When refuted, an alternative analogy is sought. When confirmed, the pattern is added to the background knowledge, thereby indirectly changing the guiding principles of the designer. This process continuously starts anew: "[The designers] shape the situation, in accordance with [their] initial appreciation of it, the situation 'talks back,' and [they] respond to the situation's back-talk."[31]

A Reasonable Explanation of Human Design Thinking

Several parallels can be made between the schema in Figure 2 and theories of human reasoning processes in general. Earlier work by Purcell and Gero draws similar parallels with cognitive psychology, in which they aim at learning and refining theories in design thinking with concepts from cognitive psychology and vice versa.[32] We mark out four main elements that can serve as a basis for documenting such parallels. Based on these parallels, we try to find a reasonable explanation of processes underlying human design thinking:

1. The importance of *analogical* or *abductive reasoning* in producing creative ideas,
2. The concept of *co-evolution* of problems and solutions,
3. The physical world with which the designer interacts *(experiences),* and
4. *Guiding principles* or background theories built up by experiences.

Rational Problem Solving

Many theoretical views exist on the reasoning mechanisms underlying natural human thinking. Several of these views originate from research on discovery and explanation in science.

31 Donald Schön, *The Reflective Practitioner,* 79.

32 Purcell and Gero, "Drawings and the Design Process," 389-430.

33 See Atocha Aliseda, *Abductive Reasoning: Logical Investigations into Discovery and Explanation* (Dordrecht, The Netherlands: Springer-Verlag, 2006), xii; Atocha Aliseda, "Logics in Scientific Discovery," *Foundations of Science* 9, no. 3 (2004): 339-63.

Aliseda indicates how "traditional" views on this topic mainly focus on a "context of justification" and maintain that topics like creativity, idea generation, and hypothesizing belong to a separate "context of discovery," which is considered outside the realm of philosophical reflection and cannot be subject to any formal treatment.[33] From this point of view, explanations are "logical substitutes rather than real processes" or "rational reconstructions," or they are "thinking processes in a way in which they ought to occur if they are to be ranged in a consistent system."[34] This approach forms the basis for the early work on problem solving in the 1960s. When following this approach, researchers focus mainly on the context of justification, thereby limiting their investigations to the "rational reconstructions" in problem solving (i.e., well-structured problems).[35] Such well-structured problems can supposedly be solved by selecting the appropriate heuristic methods.

By focusing solely on the context of justification, the first step in the problem-solving process is largely excluded. In this step, problem solvers convert a real-world problem into a well-structured problem, or, in other words, they construct a "problem space" through a process of problem structuring. In the context of design (see Figure 3), this step is the one in which designers creatively interpret physical experiences using their background knowledge or guiding principles. In the traditional problem-solving approach, the element of creativity thus remains left out, resulting only in methods for solving artificial, well-structured problems. In terms of the four main elements outlined previously, this rational problem solving approach considers only the element of co-evolution (2). Analogical reasoning for producing creative ideas (1), the physical world or task environment (3), and the guiding principles (4) are largely left out.

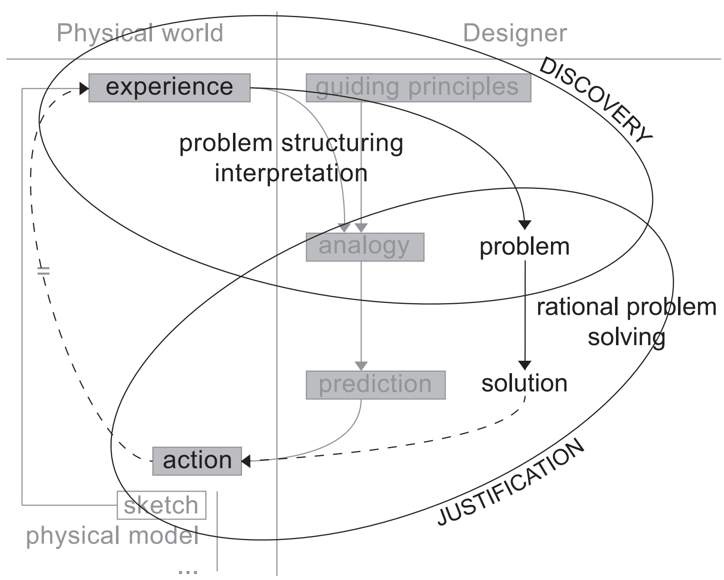


Figure 3
The Context of Discovery and the Context of Justification in Design Thinking.

34 Hans Reichenbach, *Experience and Prediction: An Analysis of the Foundations and the Structure of Knowledge* (Chicago: University of Chicago Press, 1938), 5.

35 See Allen Newell, Cliff Shaw, and Herbert A. Simon, "The Processes of Creative Thinking," in *Contemporary Approaches to Creative Thinking,* ed. Howard E. Gruber, Glenn Terrell, and Michael Wertheimer (New York: Atherton Press, 1963), 63-119; Allen Newell and Herbert A. Simon, *Human Problem Solving* (Englewood Cliffs: Prentice Hall, 1972).

Peirce's Process of Scientific Inquiry

More recent theoretical views on human thinking try to recombine both contexts (i.e., discovery and justification) again into one "process of inquiry" and try to reassess to what extent the diverse aspects or stages in this process can be subject to a formal treatment.[36] Charles Sanders Peirce, whose work informs most of these theories, was one of the first to reconsider the process of coming to discoveries and producing justifications as *one* "process of (scientific) inquiry." Peirce's theories of reasoning and human thinking change a lot during his research, which is reflected throughout the eight volumes of Peirce's papers collected from 1931 (vol. 1-6) to 1958 (vol. 7 and 8).[37] That Peirce differentiates between three types of reasoning—namely, deductive, inductive, and abductive reasoning—is now more or less accepted. According to Peirce, reasoning should not be limited solely to a "correct" or "rational" kind of reasoning (i.e., deduction and induction), but instead should reflect a combination of all possible thought processes of the human mind (which includes abduction). In comparison with traditional viewpoints, Peirce thus suggests the addition of this third kind of reasoning, abductive, which encompasses our ability to generate hypotheses about the world and to choose one of them as a possible explanation.

The three reasoning modes are typically explained in the context of scientific inquiry. A good review of Peirce's understanding of this process of scientific inquiry is given by Flach and Kakas:

> When confronted with a number of observations [they] seek to explain, the scientists come up with an initial hypothesis; then [they] investigate what other consequences this theory, were it true, would have; and finally [they] evaluate the extent to which these predicted consequences agree with reality. Peirce calls the first stage, coming up with a hypothesis to explain the initial observations, abduction; predictions are derived from a suggested hypothesis by deduction; and the credibility of that hypothesis is estimated through its predictions by induction.[38]

This description illustrates how the three reasoning modes should be understood as parts of one whole—parts that continuously flow into each other and that underlie human thought, including problem solving and design. In this understanding, Peirce's theory of human thinking is in accordance with our schema of the design thinking process (see Figure 4), including each of the four elements previously outlined.

36 See Hans R. Fischer, "Abductive Reasoning as a Way of Worldmaking," *Foundations of Science* 6, no.4 (2001): 361-83; Oliver Ray, "Automated Abduction in Scientific Discovery," in *Model-Based Reasoning in Science, Technology and Medicine*, ed. Lorenzo Magnani (Berlin: Springer-Verlag, 2007), 103-16; Atocha Aliseda, *Abductive Reasoning: Logical Investigations into Discovery and Explanation;* and Atocha Aliseda, "Logics in Scientific Discovery," 339-63.

37 Peirce, *Collected Papers of Charles Sanders Peirce.*

38 Peter A. Flach and Antonis C. Kakas, "Abductive and Inductive Reasoning: Background and Issues," in *Abduction and Induction: Essays on their Relation and Integration*, ed. Peter A. Flach and Antonis C. Kakas (Dordrecht: Kluwer Academic Press, 2000), 6.

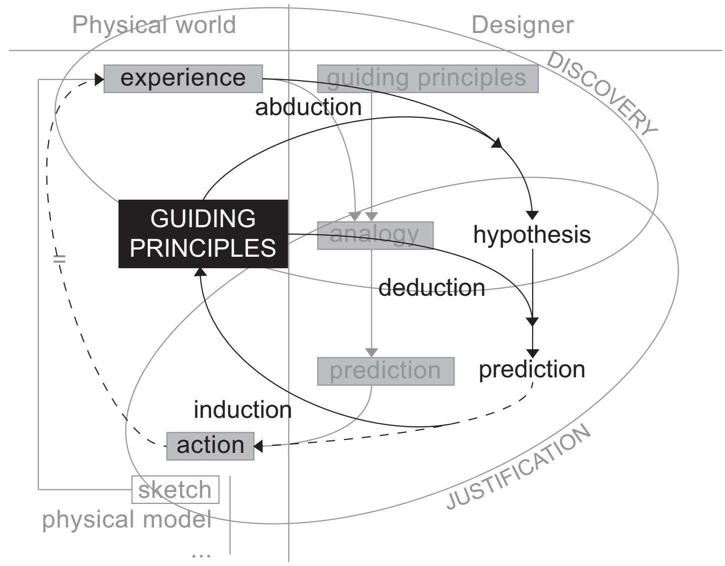


Figure 4
The Intertwining of Abductive, Deductive, and Inductive Reasoning in the Context of Design Thinking.

Abduction, Deduction, and Induction
Peirce's understanding of each of the three reasoning modes differs substantially from the "traditional" understanding that focuses solely on the context of justification. We give a brief summary of Peirce's discourse on these three reasoning modes in the following paragraphs.

Abduction is described by Peirce as the process of generating and choosing hypotheses in the process of inquiry: "From a collection of observations which are judged according to some background information to be similar or related, we draw hypotheses that generalize this observed behavior to other as yet unseen cases."[39] This process is most often explained using a visual observation example, in which a person makes hypotheses or tries to explain a visual observation. It is very often also associated with the "flash of insight" or the "eureka-moment" in a discovery.[40] The important caveat to keep in mind is that inferences resulting from abductive reasoning are hypotheses and not absolute truths, and they can be refuted through a series of contradicting observations. *Deduction* plays an important role in the overall reasoning process. Considered separately, however, its breadth of influence appears limited in Peirce's understanding because he points out that all deductive conclusions are determined by the premises. In the context of Peirce's process of scientific inquiry, these premises are the background knowledge of the reasoning instance and the hypothesis obtained through abduction. In the terms displayed in Figure 4, a set of guiding principles and a hypothesis determine the prediction, but one still has to provide these premises. This part of the process can be recognized in the creation and usage of more traditional computer applications. Most of the application logic is written beforehand in a complex combination of objects, classes, and relations. Based on some user input, the application

39. Ibid., 12.
40. See Peirce, *Collected Papers of Charles Sanders Peirce,* 5.181; Aliseda, Abductive Reasoning: *Logical Investigations into Discovery and Explanation,* 171; Flach and Kakas, "Abductive and Inductive Reasoning: Background and Issues," 7.

generates a certain result. The quality of this result directly depends on the quality of the premises—in this case, the application logic and the user input. The most challenging part in producing and using such applications thus lies in creating a sufficiently intricate network of premises, and not in the deduction itself.

Induction, finally, has several definitions but is most often identified with "enumerative induction:" making generalizations from a set of similar observations.[41] In this case, induction supposedly starts from a series of recurring observations, in which one sees a pattern and subsequently learns the rule behind this pattern. This understanding naturally includes a probabilistic or statistical flavor. Peirce, however, upholds a different definition following directly from his discussion of the process of inquiry (refer again to Figure 4). In his understanding, induction is identified with "a course of experimental investigation." This "experimental investigation" should be understood in a broad sense—namely, any "question put to nature." For instance, such questions include scientific experiments, design tryouts, medical diagnoses, talking and listening, etc. Note that in this understanding, abductive reasoning is the only ampliative reasoning type because it offers the only moment where new, original hypotheses or "suppositions" are put forward. Induction according to Peirce's definition does not generate new knowledge; it only confirms or refutes hypotheses that were produced previously through abduction: "Like any interrogatory, it is based on a supposition. If that supposition be correct, a certain sensible result is to be expected under certain circumstances which can be created, or at any rate with which are to be met. The question is, "will this be the result?"[42]

We want to stress that Peirce's theory is not confined to scientific reasoning but can be used in several application domains, including common-sense reasoning, idea generation, architectural design, health care, and more. A recent overview of how abductive, deductive, and inductive reasoning processes are at play in design thinking, including several real world examples, can be found in the works of both Edwin Gardner and Jon Kolko.[43]

Criticism against Peirce's Theory

Peirce's theory is not the only existing theory explaining human reasoning. In fact, notable criticism exists that argues against this theory. This criticism focuses mainly on the abductive reasoning mode. The main argument against Peirce's theory is the one given by Frankfurt, who argues that Peirce's definition of abduction is paradoxical because it is proclaimed as the sole ampliative reasoning mode, yet it typically contains its conclusion(s) already in its premises.[44] Frankfurt hereby refers to the logical form of an abductive inference, which indeed contains its conclusion already in its premises.

41 Ehud Y. Shapiro, "Inductive Inference of Theories from Facts," in *Computational Logic: Essays in Honor of Alan Robinson,* ed. Jean-Louis Lassez and Gordon Plotkin (Cambridge: MIT Press, 1991), 199-254.

42 Peirce, *Collected Papers of Charles Sanders Peirce,* 5, 168.

43 See Edwin Gardner, "Reasoning in Architecture: About the Diagrammatic Nature of Thinking with Real and Imagined Objects" (Master's thesis, Delft University of Technology, 2009); Jon Kolko, "Abductive Thinking and Sensemaking: The Drivers of Design Synthesis," *Design Issues* 26, no. 1 (2010): 15-28.

44 Harry G. Frankfurt, "Peirce's Notion of Abduction," *The Journal of Philosophy* 55, no. 14 (1958): 594.

The surprising fact, C, is observed;
But if A were true, C would be a matter of course.
Hence, there is reason to suspect that A is true.[45]

If we compare this argument with Goldschmidt's terms of "seeing that" and "seeing as," this argument would state that "seeing as" does not generate any new ideas because both the sketches and the human mind already had all the components necessary to produce the new ideas. An in-depth discussion of this argument is important but is beyond the scope of this article. In our opinion, novelty is generated by the unique combination of an external element in the physical world and a specific body of knowledge. Because this combination appears to be one of the main arguments of Peirce's process of inquiry, we consider this process of considerable value for the domain of architectural design thinking.

Analysis of Information System Support for Design Thinking

In this part of the article, we analyze how information technology currently provides support for design thinking, based on the theoretical overview provided. We try to indicate the main causes of the apparent mismatch between information system support and design thinking processes, so that we might be able to address it more appropriately. In this analysis, we distinguish between three application development approaches: (1) applications as surrogates for reasoning modes, (2) applications as tools for experimenting, and (3) applications as autonomous reasoning agents.

Surrogates of Reasoning Modes

Applications that might be understood as surrogates for the *abductive* reasoning mode in architectural design thinking are applications that supposedly create useful analogies between descriptions of a given situation and situations in memory. This process is the main driver behind the retrieval phase of case-based reasoning (CBR) applications.[46] In CBR applications, new "cases" are compared with a large collection of "known cases" to find a solution to a problem by analogy. The MACE metadata archive could be considered a recent application with a similar objective—a case base described by metadata.[47] By specifying queries in the search or browse window, users present new cases to the system, which are then used to retrieve the most appropriate analogies from the cases in the case base.

This approach is indeed very similar to the experience-based nature of architectural design thinking. The main issue in realizing such an experience-based retrieval system is the structure used to describe the cases or experiences. As we indicated earlier, architectural knowledge is formed through personal experiences and is of a highly dynamic nature. Designing and implementing a structure to describe this kind of knowledge is difficult,

45 Peirce, *Collected Papers of Charles Sanders Peirce*, 5, 189.

46 Agnar Aamodt and Enric Plaza, "Case-Based Reasoning: Foundational Issues, Methodological Variations, and System Approaches," *AI Communications* 7, no. 1 (1994): 39-59.

47 Stefaner et al., "MACE – Enriching Architectural Learning Objects for Experience Multiplication," 322-36.

or even nearly impossible, because of the ill-structured nature of architectural "problem" situations.[48] The situation is shaped by so many parameters that one single best solution does not exist; instead, many different re-solutions are available, depending on the parameters to which one attends. When molding an architectural "case" into an information structure, one similarly chooses certain parameters as characteristic of the case—called "features" in the context of CBR—thereby losing characteristics that might be crucial when retrieving cases in other contexts.

Applications that might be understood as surrogates for the *deductive* reasoning part of the architectural design thinking process are simulation and calculation environments. As suggested, the application logic of such environments is typically written beforehand and can be considered relatively static. A calculation result is obtained based on this application logic and some user input (e.g., a CAD model). The main difficulty is creating this network of premises—input model and application logic—from which the deductive reasoning starts. Creating such a network suffers from the same issue already described: Too many essential parameters are lost in translating ill-structured real-world knowledge into a well-defined information structure.

Applications that might be understood as surrogates for the *inductive* reasoning part of architectural design thinking—as described in Peirce's theory—are modeling applications. Such applications enable the production of visual design tryouts in far more diverse ways than is traditionally the case. Although designers were previously "limited" to paper-based sketching or to building physical models, they can now rely on a myriad of modeling and visualization applications to conduct experiments or create design tryouts. This process replaces the inductive reasoning mode in the sense that original hypotheses can be tested and then confirmed or refuted. However, it does not replace the inductive reasoning part in the sense that a knowledge base behind the application is adjusted according to the result of the test.

Tools for Experimenting

An alternate possibility is to consider each of the outlined information systems or applications as nothing more than parts of the physical world with which designers interact. In this approach, applications are similar to other elements in the physical world, and interaction with the applications occurs similarly to the way that Purcell and Gero articulate interaction with sketches, diagrams, and drawings.[49] When reconsidering the schema discussed earlier, such applications thus lie in the lower left corner (see Figure 5). In this part of the overall reasoning process, they provide extra environments for producing inductive experiments.

48 See Herbert A. Simon, "The Structure of Ill-Structured Problems," *Artificial Intelligence* 4, no. 3 (1973): 181-201; and Vinod Goel, "A Comparison of Well-Structured and Ill-Structured Task Environments and Problem Spaces," in *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society* (Hillsdale: Lawrence Erlbaum Associates, 1992), 844-49.

49 Purcell and Gero, "Drawings and the Design Process," 389-430.

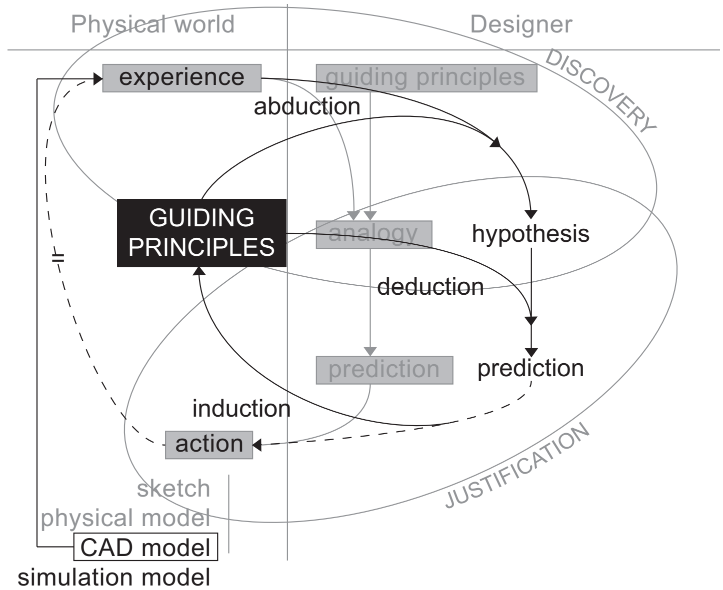


Figure 5
Information Systems as Extra Environments for Producing Inductive Experiments or Design Tryouts.

In this application development approach, the reasoning cycle outlined by Peirce takes place entirely in the human mind, and the application is just a tool in which to conduct experiments. The assumption is that designers produce the hypothesis and prediction autonomously using their own "designerly knowledge" and abductive and deductive reasoning. The prediction generates an expectation that can be tested in an experiment or design tryout. Modeling environments are perfect examples of how applications can act as tools for experimenting. However, the experience-based retrieval systems and the calculation and simulation applications also can be considered tools for experimenting. In a system like MACE, for instance, designers already have the kind of results in mind that they expect to see when searching or browsing. The result produced by the system confirms or refutes this expectation. Similarly, when preparing a model in an application to calculate, for instance, the energy performance level, designers already have in mind what kind of energy performance level they expect the system to produce. This implicitly known result is constituted by the abductive reasoning step taking place in the human mind. Again, the result produced by the application confirms or refutes this expectation. Note that the inductive learning also takes place in the human mind in this case.

When developing and using applications in accordance with this approach, one should bear in mind that the information structure in the application has only limited use. The actual reasoning takes place in the human mind, which is perfectly fit to handle ill-structured problems and is thus far more powerful than any of the possible information structures of the application. The merit of producing applications using this approach is that the number of tools for experimenting in the physical world notably increases.

Autonomous Reasoning Agents

A third and last application development approach we consider is that of autonomous reasoning agents. In such an approach, all three reasoning modes outlined by Peirce are implemented and combined in a dynamic information system. In this setting, the information structure is completely dynamic: it evolves step by step through every single observation or experiment made by the reasoning agent. Combining the diverse reasoning modes in a continuous cyclical process—instead of focusing on each of these reasoning modes separately—theoretically allows for the development of an information system that can make hypotheses, make predictions, devise experiments, and learn—all based on the observations and experiments the system continuously goes through.

Research on such systems is ongoing, but early results are emerging. One of the most notable results is the "robot scientist" system, which was developed for doing scientific research semi-autonomously in a particular sub-field of yeast micro-biology.[50] This system implements a reasoning process similar, but not identical, to the process outlined in Figure 4 or to Peirce's process. The result is a robot that can start from an experimental observation; interpret what it sees based on the background information that was, in this case, formalized in ontologies and inserted in the robot; make hypotheses that explain the observation at hand; devise experiments to test these hypotheses; do these experiments; and learn from these experiments. This process goes on in continuous cycles. Because Peirce's process of inquiry is supposedly also at play in other application domains, a similar approach could theoretically be developed for design thinking support. For instance, semantic web technologies theoretically enable software developers to build information systems dynamically from the output of reasoning engines.[51] This could eventually result in autonomous reasoning agents. Other approaches might be equally feasible if they combine the three reasoning modes into one system, following the outline of Peirce. This combination is necessary because, as we have seen, working with separate surrogates for reasoning modes brings insufficient added value.

This kind of support would be completely different from any traditional kind of support currently provided by information systems. Similarly to the way in which it happens in the robot scientist project, the reasoning system would evolve into an independent agent reasoning about a design situation, and it would thus not directly interfere with reasoning processes of the human designer. The main support it could give to a human would presumably be similar to the support any designer gives to any other designer—namely, by simple dialogue and discussion of design alternatives, from which both generate their own interpretations and start their own reasoning processes. A similar agent-based role for information systems was suggested by Lawson.[52]

50 See Ross D. King et al., "The Automation of Science," *Science* 324, no. 85 (2009): 85-89; and Oliver Ray, "Automated Abduction in Scientific Discovery," in *Model-Based Reasoning in Science and Medicine*, ed. Lorenzo Magnani and Ping Li (Berlin: Springer-Verlag, 2007), 103-16; Oliver Ray et al., "Towards the Automation of Scientific Method," in *Proceedings of the 21st International Joint Conference on Artificial Intelligence: Workshop on Abductive and Inductive Knowledge Development* (Pasadena: IJCAI and AAAI Press, 2009), 27-33.

51 See Tim Berners-Lee, James Hendler, and Ora Lassila, "The Semantic Web," *Scientific American* 284, no. 5 (2001): 34-43; and Chris Bizer, Tom Heath, and Tim Berners-Lee, "Linked Data: The Story So Far," *International Journal on Semantic Web and Information Systems* 5, no. 3 (2009): 1-22.

52 Bryan Lawson, "Oracles, Draughtsmen, and Agents: The Nature of Knowledge and Creativity in Design and the Role of IT," *Automation in Construction* 14, no. 3 (2005): 383-91.

We go through a simple example, starting from a design brief, to show how such a reasoning agent might work in an architectural design environment. The design brief is given to the reasoning agent. Similar to the human process, the reasoning agent goes through the brief line by line, word by word, at each step interpreting the contents of the brief using its own personal background knowledge. In every step, the reasoning agent actually goes through the entire reasoning cycle, thereby making hypotheses about the meaning of words in the brief *(interpretation),* predicting what it will read next, and testing its prediction *(projection)* by actually reading through the next word. At every step in this reading process, a—hypothetical and fallible—understanding of both "problem" and "solution" is constructed (cfr. co-evolution). After reading through the design brief, the reasoning agent proceeds in the way it assumes is best. This decision is again made using one or more reasoning cycles. For instance, the agent might hypothesize that the best way to proceed is to construct a 3D model of a part of the problem. Starting from this hypothesis, a whole set of additional reasoning cycles starts, enabling the reasoning agent to continuously undertake an action, reflect on the action, and make new hypotheses based on the action. Through these reasoning cycles toward a complete 3D model, the agent not only reflects on and learns about 3D modeling; it also adjusts its initial understanding of the design problem and solution into a new and more refined understanding. And the cycles continue.

Such a situation is far from being realized, and whether it can ever be realized is unknown. In the robot scientist project, a significant amount of information was formalized and inserted as a background information model for the robot. With this formalized knowledge in place, 6.6 million optical density measurements were made, eventually resulting in a formalized scientific argumentation structure that includes more than 10,000 different research units in a hierarchical structure of 10 levels. These research units are representations of segments of experimental research, including studies, cycles, trials, tests, and replicates. Note, however, that the system ultimately addresses only a very small subdomain in functional genomics.[53] Building a similar model for all "designerly" information is practically infeasible, especially when taking into account Lawson's remark that designerly knowledge also includes motivations, beliefs, values, and attitudes. For such an approach to work, the information model used by the reasoning agent will thus have to be built up by the agent. Although this model is theoretically possible using a combination of abductive, deductive, and inductive reasoning, a more challenging objective would be difficult to imagine.

A crucial issue in building such a system is that the theory requires the reasoning agent to be actively embedded in a physical world if it wants to learn anything of realistic "size." In the case of

53 King et al., "The Automation of Science," 85-89.

architectural design, the reasoning agent would have to actually go through realistic architectural design processes by itself. That anyone would ever actually allow the agent to do so is highly unlikely. But even before such a scenario could come within reach, the reasoning agent would have to be able to communicate reliably with the surrounding physical world according to the theory. In fact, such an agent would need to be able to sense (i.e., in auditory, olfactory, gustatory, visual, and tactile ways) and act similarly to the way humans do to construct useful knowledge autonomously and produce useful input to anyone. Such a development would be problematic even for the most basic sensory communication because little is known about how this process of sensing, constructing knowledge and acting accordingly occurs in the human body. Consequently, this third approach appears highly unlikely to be implemented anytime soon.

Discussion and Concluding Remarks

We have presented in this article a critical evaluation of information system support for architectural design thinking. This evaluation was closely tied to a significant number of theories, both in design thinking and philosophy. We chose to use Peirce's process of (scientific) inquiry as a helpful explanatory framework for several of the phenomena identified in architectural design thinking. This process of inquiry continuously proceeds by iteration through a cycle of abductive, deductive, and inductive reasoning, with a dynamic background knowledge and parts of the physical world as its premises.

As a result, we distinguish three main development approaches in information system support for architectural designers. In the first approach, applications are designed and implemented as surrogates for each of the reasoning modes included in Peirce's process of inquiry. Such an approach appears to be of less value because it requires both application developers and users to endlessly convert real-world problem situations, which are essentially ill-structured, into artificial, well-defined problem situations. This process is tedious and time-consuming, and compared to our own reasoning capabilities, its results are not as reliable and useful as they should be. In the second approach, all information systems providing support to a designer are considered additional parts of the physical world. Similar to a paper and a pencil, a CAD system or a simulation environment allows a designer to make inductive experiments or design tryouts. The main disadvantage of this approach is that resulting support systems are of limited use because the actual reasoning process remains completely out of the application environment. The main value of this approach is that an important number of additional, previously unavailable "test environments" can be provided to designers. This second approach is the one generally used these days, although it might not always be recognized as such. The third and last approach is to build reasoning agents that autonomously go through the reasoning cycle outlined by Peirce. This radically different approach, to our knowledge, has never been implemented in its complete form. In this case, all three reasoning modes are combined in a dynamic information system, changing continuously in response to the experiences of the reasoning agent. With this combination, such an agent theoretically should be able to make hypotheses, make predictions, devise experiments, and learn—all based on the observations and experiments which the system continuously goes through. The main barrier towards this approach, assuming that it is even feasible, is that the reasoning agent needs to be actively embedded in a physical world *and* needs to be able to communicate reliably with this world. Without such embeddedness and communication, it would never be capable of building up an adequate knowledge base, nor of communicating this knowledge to designers.

Of the three approaches, the second is the most—perhaps the only—feasible strategy toward information system support. What both designers and software developers have to bear in mind, however, is the limited effect of this approach on architectural design thinking. This approach contradicts many new and innovative proposals in information system support for design thinking that claim to provide all kinds of automation features and generative mechanisms. As we indicated in this article, such systems remain to be used mainly as useful environments for design tryouts.

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