EFFECTIVE INQUIRY FOR INNOVATIVE ENGINEERING DESIGN
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by

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5. Designing the Intervention: Differentiating Designing from Problem Solving
   5.1 Deriving Requirements for the Design Experiment 65
   5.2 Addressing the Requirements 72
   5.3 Meeting the Requirements: The Pilot Experiment 83

6. Learning from the Pilot Experiments: “Good” Questions and Discoveries
   6.1 Improving the Experimental Methodology 85
   6.2 Augmenting the Hypotheses: Discovery Making as another Internal Performance Metric 88
   6.3 Refining the Hypotheses: Characterization of a “Good” Question 91
   6.4 The Augmented Hypotheses 93

7. Conducting the Redesigned Experiment: Putting the Question Asking Aspect of Design Cognition under the Microscope
   7.1 Data Collection and Analysis Procedures 95
   7.2 Data Analysis and Results 104
   7.3 Revisiting the Hypotheses 126

8. Synthesizing a Question-centric Design Thinking Model
   8.1 Question Asking as a Process 130
   8.2 Question Asking as Creative Negotiation 131
   8.3 Question Asking as a Mechanism for Managing Convergent and Divergent Thinking Modes 133
   8.4 Implications of the Verified Hypotheses 134
   8.5 A Question-centric Design Thinking Model 135
   8.6 Potential Applications of the Design Thinking Model 136

Appendix 139

References 147

Index 153
Preface

Engineering Design is a question-driven process?

This is not a punctuation error. It is the essence of Eris's book. A declarative statement, a decision made, is actually a constellation of questions. Can there possibly be decisions without questions? Ozgur Eris has some striking answers. I see them as a breakthrough. You need to know about them.

Engineering Design is a question-driven process!

This insight was first inserted into my awareness by Professor John Arnold, founder of the Design Division of the Department of Mechanical Engineering at Stanford University in 1960. My subsequent experiences in Robotics, Mechatronics, Human-Machine Integration, Knowledge Management Systems, and New Media Design have individually and collectively confirmed the proposition. Looking beyond personal experience, it has become a mature "belief system" in Stanford's Design Education and Design Research community. While it is less well-appreciated elsewhere, it may be one of the distinguishing features of Stanford's unique role in the Silicon Valley and beyond.

Unfortunately, direct evidence of the "question-drive" has proven to be elusive. Eris's book, building on over 20 years of inquiry and a dozen PhD theses, finally brings together the evidence, a working taxonomic framework, and a well-reasoned argument for duality between questions and decisions. Together, they forge a new plateau in our understanding of the "effective inquiry" process in innovative engineering design. In operational form, we
have a refreshingly new “Design Thinking” model that is empirically grounded, an advance in Design Research Methodology.

Absent evidence, an alternative view, one derived from the study of decision-making has taken hold and matured to become Design Decision Theory. In part, its utility rests on the fact that decisions are usually found in formal documents, and at least some related consequences can be traced in other document citations. The same cannot be said of questions, especially those posed during the informal, formative, pre-publication phase of design thinking that is rich in questioning behavior, but rarely recorded. Curiously, failure to record seems to extend to our memory of these events, hence contemporary digital recording technology played a key role in capturing and dissecting the phenomena.

If questioning is so important, why haven’t you been reading more about it? If it is so prevalent, where and how does it express itself? Even if one suspects that it is important, how does one go about fostering one’s own questioning performance, and that of others? Figure-1 suggests that you not imagine a straight and narrow “path ahead,” but that you purposefully craft a divergent path that is more likely to corral the essence of the decision space and bring you to identify and decide upon, the best idea.

Figure 1. The optimal path ahead may not be straight.
A fine artist, Ergin Sargin, has captured the essence of our quest to understand the insight that engineering design is all about questioning. The decision lies at the center. We find the decision space and define the decision options by a spiraling path that is mapped by the questions we ask. There is little value, and high risk, in taking the straight and narrow path, so well represented by the decision maker's exclamation mark. No decision can be better than the options created through effective questioning. Eris's book brings you evidence to support this metaphor and guidelines for formulating good questions.

There are important practical consequences for, amongst others, engineering design, innovation management, discovery science, and metadata design. Going beyond the big effects, there are also everyday implications for creative activity any time, any where with anyone.

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Chapter 1

INTRODUCTION

Designing is question intensive. Experienced designers treat inquiry as an influential cognitive mechanism in their thinking. However, our formal understanding of the specifics of that mechanism, and at a higher level, the role of question asking during designing, is limited. The research presented in this book explores the issue from both theoretical and empirical perspectives. The findings allow for the development of a question-centric design thinking model. The framework that forms the basis of the model characterizes the process of inquiry in design thinking at an operational level, relates that characterization to existing decision making theories by arguing for a duality between questions and decisions, and maps the proposed duality onto the broader context of the design process. The validity of the model is demonstrated empirically by the discovery of a correlation between the question asking processes of design teams and their performance.

This book not only articulates those insights for the reader who is curious to learn more about the role of question asking in design, but also demonstrates the uniqueness of design thinking by identifying a specific class of questions that are characteristic of design situations. My intention is for the reader to walk away with a heightened awareness of the power of questions, and to encourage him/her to apply the fundamental elements of the effective inquiry process outlined in the model in his/her own design practices.

In this introductory chapter, I will discuss my motivation for focusing on the subjects of inquiry and cognition within a design context, and outline the guiding research questions and the main constituents of the work.
1.1 Why Study Question Asking?

Prior to discussing my personal motivation for focusing on the process of inquiry in design, I would like to mention two external and broader factors that influenced my decision: the value system that is embedded in the research and teaching institution I have been a part of while formulating and conducting this research, Stanford University’s Mechanical Engineering Design Division, and the information technology revolution that began in the early 1990s.

The pedagogical principals employed in design education at the Design Division are fundamentally based on the premise that design is a question-driven socio-technical activity. Graduate students in engineering design are repeatedly exposed to this premise through various methodologies while completing their coursework and prior to formulating their research. These methodologies communicate the significance of asking questions during semi-structured need finding, problem (re)definition and (re)framing, and conceptualization exercises. They are most effective when practiced in project based settings, and are rather intuitive and informal. Even though the informal nature of these methodologies makes it difficult to attribute them to specific individuals, I can easily reference the instruction I received from Leifer, Roth, Faste, and Adams as having influenced me to appreciate the value and relevance of question asking in design [Leifer 1994, Roth 1995, Faste 1995, Adams 1996] as well as having influenced related research that has been conducted within the community [Baya 1996, Mabogunje 1997].

The implications of the information technology boom of the 1990s for the field of design research have been significant in drawing attention to the topic of inquiry. The need for “knowledge systems” that would support practicing designers were recognized, and initial feasibility studies regarding their design and implementation were undertaken. These studies highlighted two problematic areas: identifying the relevant information to be captured and stored, and accessing and retrieving it. Inquiry was identified as one of the mechanisms through which these issues could be tackled. If such systems could mimic the information requests of actual designers—their information seeking questioning behavior—they would be more effective. Kuffner & Ullman’s early work in this area, followed by Baya’s, were influential [Kuffner 1990, Kuffner & Ullman 1991, Baya 1996]. More recently, Ullman summarized the “progress toward the development of the ideal mechanical engineering design support system” [Ullman 2002], and Marsh and Wallace identified question asking as a mechanism that facilitates information flow between expert and novice designers in industry [Marsh & Wallace 1995, Marsh 1997].
Chapter 1

The subject of question asking behavior of design teams caught my attention as a potential research direction during a video interaction analysis session. Data for the analysis were collected during a two week design project carried out by graduate engineering design students whose goal was to design, prototype, and race a paper bicycle. During the analysis, I began to pay close attention to the questions raised in the interaction, and their effect on the design decisions that followed. Some questions seemed to have a strong effect on pivotal decisions, and others dissipated and had no discernable impact. In either case, questions and decisions struck me as being tightly coupled at a conceptual as well as a pragmatic level.

One way of exploring that connection was to identify all of the questions and decisions that occurred during the interaction, and construct a “question-decision map.” The intent was to test if such a representation might be useful in confirming the existence of a connection, and discovering relationships between the nature and timing of the questions and the decisions they led to.

However, during my initial attempts to construct a map, I realized that our formal understanding of questions—as they occur in a design context—was not comprehensive and operational enough to allow me to study their relationship to other subjects such as decision making. It was necessary to know more about the nature of questions and to be able to formalize descriptors of their occurrence before they could be related to descriptors of other subjects. A review of the design research literature revealed insights that were limited to the application of information seeking questions in design knowledge systems (as discussed above), and in the architecture domain, among others paradigms, to a theoretical paradigm that frames designing as inquiry at an abstract level [Schon 1983, Gedenryd 1989].

Therefore, instead of focusing on question-decision maps, I decided to develop a comprehensive framework on the nature of questions occurring in design contexts, operationalize that framework, and attempt to validate it in a series of quasi-controlled laboratory experiments. It is important to note that differentiating between questions that are asked in design and non-design contexts has implications. I will list them here, and discuss them in depth in Chapter 2.

This research is based on two fundamental premises:

1. It is valid and useful to treat designing as a “way of thinking,” and thus, as a specific type of cognition.
2. Question asking while designing is influential to the thinking of designers. It is related to the cognitive aspects of their problem solving, creativity, decision making, and learning processes, and consequently, to their overall performance.
1.2 Why Study Design Cognition?

For the most part, research in engineering is focused on understanding and predicting the behavior of innovative artificial (man-made) systems by way of studying the physical, chemical, and more recently, biological principles that govern them. In practice, the fundamental competency of engineers is seen to be their ability to understand, synthesize, and apply principles associated with the natural sciences in creating new technologies that ultimately result in new products.

There is no doubt that we, as engineers, benefit greatly from studying and applying such principles. However, as our knowledge of them has grown, it has become apparent that our personal involvement in the design process as human beings is also important, and that there is a need to understand the principles that govern our behavior as designers. While the scientific understanding new technologies are based on is constantly advancing, the discrepancy between our knowledge of those technologies, and knowledge of ourselves as designers, is growing. Bridging this gap by addressing the human dimension is now seen as an opportunity for increasing design performance in industry.

One of the most intriguing components of that human dimension is related to the thought processes we employ when we design; our thought processes—our cognition as designers—govern the behavior of the systems we design as much as the scientific principles we apply to create them. Therefore, it is relevant to be concerned with what design cognition is, and how it can be studied, taught, and improved.

It is not clear when the term "design cognition" was first used. In a keynote speech, Pahl presented a brief history of the collaboration between cognitive scientists and design engineers, and argued that the knowledge of technical systems was not sufficient in understanding the thought processes that led to the synthesis of designs, and that studying those thought processes was critical in improving the proposed design methodologies [Pahl 1997]. Recently, several Ph.D. dissertations have been published as explorations in design cognition [Dylla 1991, Fricke 1993, Dorst 1997, Mabogunje 1997, Gedenryd 1998, Brereton 1999], and different research groups have began to address the topic directly (Birkhofer, Gero, Lindeman, and Leifer to name a few). Also, there are at least two internationally recognized conference series that are centered on the topic: Design Thinking Research Symposium (DRTS), and the International Conference on Design Computing and Cognition (DCC). The growing interest suggests that design cognition is becoming a prevalent approach in design research, and supports the first premise outlined in the previous section.
1.3 Research Questions and Approach

The research presented in this book consists of theoretical and empirical dimensions. The two dimensions build on each other; the results of the exploration in one dimension feed into and influence the exploration in the other dimension. The research questions that guided me throughout those explorations are summarized in the following sections.

1.3.1 Theoretical Dimension: Characterization of Question Asking in Design

The theoretical dimension addresses the following research questions:

- How can the nature of questions that are posed by design teams be characterized and categorized at an operational level?
- Is there a relationship between question asking and decision making in design? If there is, is it possible and meaningful to develop a unified question-decision centric theory of design?
- Does the relationship between question asking and decision making—if it exists—influence design performance? What is a relevant framework for measuring design performance?

1.3.1.1 The Nature of Questions Asked while Designing

One way of studying the nature of questions that are asked while designing is to develop a comprehensive taxonomy of questions, and use it as a coding scheme to analyze the thinking of designers. When developing the taxonomy, various principles can be applied to differentiate between the types of questions. For the purposes of this research, I focused on two such differentiating principles that are related: conceptual meaning of questions, and a convergent-divergent thinking paradigm that is reflected in questions.

The first principle, the conceptual meaning of questions, has been articulated and used in the formulation of semantic question categories by Lehnert [Lehnert 1978]. Her approach will be discussed in detail in section 2.1. Prior to adopting her categories and/or constructing additional ones myself, I reviewed five other published taxonomies of questions. The second principle, a convergent-divergent thinking paradigm that is reflected in questions, is an outcome of my analysis of those taxonomies. It yields two meta-classes, which are made up of some of the question categories constructed through the application of the first principle.

The understanding embodied in these two principles resulted in the adoption of Lehnert’s semantic categories, and in the formulation of
divergent question categories. Together, the categories formed a comprehensive and operational taxonomy of questions that are asked while designing. The specifics of that framework will be discussed in Chapter 3.

1.3.1.2 Question-Decision Duality

As I mentioned in the beginning of this chapter, I perceived a strong conceptual link between questions and decisions while observing a series of design team meetings. Although I concluded that I needed to characterize questions asked by designers in a comprehensive fashion prior to attempting to formalize that link, I still perceived benefit in considering the issue on a philosophical level. The result was an analytical argument regarding the existence of a duality between questions and decisions.

The duality is based on the premise that it is imperative to ask questions in order to make decisions, and make decisions in order to ask questions. In section 2.2, this argument is presented in detail and illustrated with transcript segments from one of the design team meetings. Moreover, the findings of the empirical dimension allowed me to revisit and validate certain aspects of this relationship by allowing me to map it onto the design process. That mapping will be discussed in Chapter 8.

1.3.1.3 A Perspective on Design Performance

The recognition of design cognition as a topic in design research is advancing our understanding of design performance. Traditionally, when considering engineering design performance, researchers have been predominantly concerned with developing ways of evaluating the performance of the systems engineers design, and focused on the outcome of the design process, the product. The recent focus on the human dimension of designing, and on design cognition, has introduced another perspective for considering design performance, the designer.

These two viewpoints suggest the existence of two types of design phenomena that can be evaluated: what occurs during design activity, and what results from and persists after design activity. Naturally, the metrics for evaluating the performance associated with each phenomenon will differ. If one grounds himself/herself in design activity and takes it as the reference point, it is appropriate to treat activity-based metrics as being “internal,” and outcome-based metrics as being “external.”

As outlined in the second premise listed in the previous section, this research supposes the existence of a relationship between design cognition and performance. Since design cognition is a phenomenon internal to design activity, a framework for measuring internal design performance is required to study that relationship. When developing a framework in order to satisfy
that requirement, I utilized the activity-outcome distinction in formulating a question-centric internal design performance metric. The specifics of that framework will be discussed in Chapter 4.

1.3.2 Empirical Dimension: Three Experiments

The empirical dimension of this research entails making a series of detailed observations in two distinct settings, and analyzing the data according to the frameworks developed in the theoretical dimension. The first setting was a real-life design project, and lent itself to ethnographic observation techniques. The second setting was a quasi-controlled laboratory experiment, and lent itself to video interaction analysis. The research conducted in these settings can be summarized in three progressive steps:

1. Detailed observation and analysis of a real-life design situation for hypothesis generation.
2. Design of a laboratory experiment to test the hypotheses.
3. Redesign of the pilot version of the experiment, and the execution of the final version.

The following are the guiding research questions associated with these steps:

- What hypotheses can be constructed regarding question asking in design?
- How can those hypotheses be tested? How should a design experiment be characterized in terms of its requirements? Is that characterization applicable to design experimentation in general?
- How should a design experiment be executed?

In taking each step, I was influenced by a design research methodology that has been used at the Stanford Center for Design Research for over 15 years. It advocates that the researcher should go beyond merely observing and describing design activity to constructing meaningful interventions to test the gained insights by iterating a cycle composed of three phases: observe, analyze, and intervene. The structure associated with each empirical step is outlined in the following sections.

1.3.2.1 Hypothesis Generation in the Field

The first research setting, a real-life design project, enabled me to freely observe a design situation where a team of graduate engineering design
students designed, prototyped, and raced a paper bicycle. A colleague and I “shadowed” the design team, videotaping the nine design meetings the team held over a period of two weeks.

During those observations, I paid close attention to the questions raised in the interactions, considered potential relationships between question asking and decision making, and began to regard question asking while designing as a process. Most of the research questions outlined in the theoretical dimension of this work stem from those initial observations and conceptualizations. A detailed discussion of those insights, and their transformation into testable hypotheses is provided in Chapter 4.

1.3.2.2 Characterizing and Designing a “Design” Experiment

The second empirical step is the design of a laboratory experiment. I identified seven design requirements under three experimental design criteria that needed to be satisfied for the experiment to test the hypotheses. The framework for categorizing questions (as outlined in the synopsis of the theoretical dimension in section 1.3.1.1), the hypotheses, and experimental considerations specific to design research served as natural design criteria.

The nature of the requirements, and the specifications for meeting them, are discussed in detail in Chapter 5. The requirements under the first two criterion, question categorization and hypotheses testing, are specific to this research. However, I would like to stress that the third design criterion is relevant, and even necessary, for design research in general as it tackles the broader issue of what constitutes an “experiment” in a design context. The requirements for the third criterion address the need to simulate the inherent complexity of designing by:

1. Favoring quasi-control as opposed to full-control when inserting control elements into the design scenario used during the experiment.
2. Promoting designing as opposed to problem solving in the experiment.
3. If multiple hypotheses are to be tested, advocating that they be tested in a single experiment.

The specifications that satisfy the requirements under all three criteria are discussed in the latter sections of Chapter 5. And finally, a known design scenario—the bodiometer design exercise—that embodies the specifications was identified, described, and modified. In the exercise, designers are asked to design and prototype a measurement device, which can be moved along human body contours to measure their length.
1.3.2.3 Redesign of the Pilot Experiment: The Definition of a "Good" Question

The third empirical step aims to augment the hypotheses, and ensure that the design exercise did indeed satisfy the requirements.

I conducted two pilot sessions of the experiment with six graduate mechanical engineering design students. The pilot runs proved to be very effective in achieving both goals. They resulted in changes to the structure of the design exercise and the design performance framework. Although most of those changes were minor individual adjustments, their combined contribution to meeting the requirements was significant. For example, observing a need to increase the duration of the exercise by 30 minutes during the pilot runs provided the teams in the final runs enough time to complete the number of design iterations they needed, which meant that the exercise was more realistic.

The pilot runs also allowed me to reflect on the relevance and validity of my hypotheses, and to refine them as necessary. They prompted me to consider what a "good" question might be in a design context, and to incorporate its characterization into one of the existing hypotheses. I also perceived the need to construct a new hypothesis when I considered the consequences of a "good" question as opposed to its characterization. After revisiting my observations of the paper bicycle design team, I postulated that good questions are associated with, and followed by, conceptual leaps, or discoveries.

I then conducted the redesigned version of the experiment with 36 graduate mechanical engineering design students working in 12 teams, analyzed the data according to the two theoretical frameworks, and tested the validity of the hypotheses. A detailed discussion on the redesign of the experiment and the modification of the hypotheses is provided in Chapter 6. The analysis of the data collected during the redesigned experiment is presented in Chapter 7.

Finally, a question-centric design thinking model is synthesized from the theoretical and empirical findings and presented in Chapter 8.
Chapter 2

QUESTION ASKING: A FUNDAMENTAL DIMENSION IN DESIGN THINKING

As mentioned in the introduction, this work operates under two premises:

1. It is valid and useful to frame designing as a “way of thinking”, and thus, as a specific type of cognition.
2. Question asking while designing is influential to the cognition of designers. It is related to the cognitive aspects of their problem solving, creativity, decision making, and learning processes, and, consequently, to their overall performance.

These premises have two major implications. The first implication is that studying design cognition is a distinct and relevant approach to design research. The second implication is that treating decision making as the fundamental cognitive mechanism driving design performance—a prominent position within the field—requires further consideration.

This chapter consists of three parts. The first two parts, sections 2.1 and 2.2, stem from my motivation to put those implications into perspective. Section 2.1 deals with the first implication, and entails reviewing the design research field by categorizing the current research areas into four topics, and positioning design cognition within them. Section 2.2 deals with the second implication, and entails focusing on design cognition by proposing and considering relationships between two fundamental cognitive mechanisms in designing, decision making and question asking.

The third part, section 2.3, is a review of published taxonomies of questions. It represents my initial exploration on the nature of questions, and constitutes the first step in developing a coding scheme that can be used to analyze the question asking behavior of designers.

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2.1 Contemporary Topics in Design Research

In the next four sections, I put the first implication listed at the beginning of this chapter into perspective by discussing the contemporary topics in design research and positioning design cognition within them. I classify the topics into four categories: design processes, social theories, design information, and design cognition.

After an initial consideration, one might argue that the four categories I propose overlap to the degree that they lack meaning. The categories are indeed strongly related. Nevertheless, I see them as being defined by well-pronounced differentiations within the field, strongly reflected in the motivations and products of distinct groups of researchers. On the other hand, I believe that the strong relationships, and even overlaps, between the categories can and should act as a basis for informing researchers on missing knowledge within their domains. For example, most design information and knowledge systems lack functionality that can be alleviated by utilizing the findings from the other three domains—it is poor practice to develop a design knowledge system that does not address the underlying social, cognitive, and process related elements.

2.1.1 Design Processes

Researchers studying design processes have traditionally been concerned with categorizing the workflow of designing by decomposing it to interrelated tasks. The goal is to construct formal design processes, and to extract methods for design practice from them.

Numerous influential design process models have been developed [Asimov 1962, Hubka 1982, Pugh 1986, Pahl & Beitz 1988, Ullman 1992, Otto & Wood 2001]. Since processes are abstractions, the principles for abstraction can and often do differ between these approaches. However, the basic tasks that make up processes are similar. What differentiates them are the specifics of the relationships between the tasks and procedures they embody.

In a representative model of the design process, tasks and procedures are outlined in the form of a flow chart [Hubka 1982]. Arrows between design tasks signify conceptual, logistical, and temporal relationships. Arrows pointing back at previously executed tasks identify iteration procedures and address the recursive nature of designing. A similar design process model developed by Pahl and Beitz is especially significant [Pahl & Beitz 1988]. Since its introduction, it has been recognized as an official standard in German industry, and been widely applied in the design of new products.
The tasks that serve as the basic elements in these two models are indeed similar; both processes are composed of tasks related to the generation and characterization of design requirements, concepts, representations, and specifications. However, they propose somewhat different procedures for executing them.

Design process models can be applied and practiced in two domains: product development institutions, and individual or small groups of designers. For institutions, design processes constitute directly applicable methods that can be used to structure product development projects. They also constitute frameworks for organizing human and physical resources; a group of people and space are associated with each task, i.e. requirements engineers, release engineers, test engineers, concept development laboratories, testing facilities, manufacturing plants, etc. In other words, in institutional settings, design processes have direct social and physical manifestations.

For an individual or a small group of designers, design processes constitute methods that can be internalized and practiced while designing. It is reasonable to assume that they influence the way designers think (this relationship will be discussed in detail in section 4.4.4). In order to test this assumption, it is necessary to observe how designers communicate and act since it is difficult to directly observe how they think. In other words, design processes do not necessarily have physical manifestations in the practices of individual designers, but can be assumed to influence their thinking.

### 2.1.2 Social Theories of Design

Social theories of design are essentially constructivist approaches. Researchers who are interested in developing social theories aim to describe design activity by observing, analyzing, and reconstructing the interactions of the involved parties. They primarily focus on the social elements of designing (the effects of the social relationships between the participants of the design activity on the activity itself and its outcomes) rather than the social implications of designs (the effects of the outcomes of the activity on broader social contexts such as society).

Cuff’s research has been influential as a pioneering exploration in this domain [Cuff 1982]. Her work focused on the negotiation that takes place between architects and clients in architectural design practice, and challenged the myth of the architect as the driving force. She argued that, in practice, influence is “diffused” across all participants, including clients, and that qualities such as ambiguity, unexpected outcomes, and open-endedness are