Epistemology and the Science of Design

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I teach and conduct research in systems engineering, design methodology, and statistics. Because of my concerns about the fundamental basis of knowledge in these fields, I have become interested in the philosophy of science. Natural sciences such as physics and biology seem to improve over time through the interplay between theoretical development and observation. This process has helped to make natural science a tremendously successful enterprise. Currently, a research community is emerging that aims to develop a science of design. Design is a complex, value-laden, human activity. As a science of the artificial[1], the science of design may require different epistemological foundations than natural science. Then again, it may not. In this position paper, I pose four epistemological questions related to design. I also discuss possible answers, but my goal was primarily to spark discussion rather than solidify a position.

Can Popper's falsifiability criterion be applied to design theories? An important question to ask ourselves as we develop a "science of design" is whether our theories actually lie within the domain of science. Karl Popper proposed a "falsificationist" criterion of demarcation between science and non-science. Only hypotheses capable of clashing with observation reports are allowed to count as scientific[2]. By this criterion, some existing theories of design and software engineering are not scientific. Such a classification is not necessarily pejorative. For example, ethics and probability theory are important to the field of design but neither is a science. Ethics is a subset of philosophy. Probability is a subset of mathematics. When we seek to develop a science of design, we should check whether what we're really doing is math or ethics. I think a science of design is a worthwhile goal deserving NSF support, therefore NSF should ensure that a large fraction of the funded research involves development and testing of falsifiable hypotheses.

Can the science of design include normative statements? Design is an activity concerned with creation of value. Design involves not only what *is* but what *ought to be*. Therefore some researchers include normative or imperative statements in their design theories. Such statements fail Popper's "falsificationist" criterion and, in my opinion, they are not scientific hypotheses. To make a scientific hypothesis based on a normative statement, one might stipulate the observable consequences of violating the rule. Table 1 lists two examples. The statements on the left are normative or imperative. The statements on the right are falsifiable, scientific hypotheses that can be subjected to empirical tests.

Table 1. Normative statements about design and related falsifiable hypotheses.

normative statement	falsifiable hypothesis
The preferred choice (among alternative designs) is the alternative that has the highest expected utility.[3]	Engineering design performed without the axiomatic framework of decision theory will result in an attendant loss which is on average a factor of two or more in profitability.[3]
Maintain the independence of functional requirements.[4]	Designs whose functional requirements are coupled have < 1% probability of meeting their functional requirements.

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[1] Simon, H., 1969, *Sciences of the Artificial,* MIT Press, Cambridge, MA.

[2] Popper, K. R., 1934, *Logik der Forschung*.

[3] Hazelrigg, G.A., 1999, "An Axiomatic Framework for Engineering Design," *ASME Journal of Mechanical Design*, 121, pp. 342-347.

[4] Suh, N. P., 1990, *The Principles of Design*, Oxford University Press, Oxford.

Can mathematics be the primary epistemological basis of the science of design? The web site for the NSF Engineering Design program states that "preference is given to approaches that include mathematical rigor, as opposed to ad hoc and heuristic methods that have limited application." This statement suggests that the preferred epistemological basis of design science is mathematics. Mathematics is primarily concerned with developing self-consistent sets of propositions based on axioms. In science, predictive power requires not only self-consistency but also consistency with all the relevant facts of reality. Since design is an activity undertaken by people or groups of people, it follows that human cognitive limits, psychological tendencies, and social dynamics are likely to be relevant to the science of design. Any mathematical design theory whose axioms do not include a characterization of these relevant parameters may fail to correspond with reality no matter how logically self-consistent it may be. Of course, the theory won't clash with reality at all unless it is placed in the form of an empirically testable hypothesis.

Can a design theory be evaluated on the basis of its effects in practice? A primary purpose of the science of design is to improve the professional practice of design. Therefore, one way to evaluate a design theory is to observe its effects on the practice of design and evaluate its outcomes (e.g., systems, software, development costs, market share, customer satisfaction, and profitability). To consider the merits of this proposal, it is constructive to reflect upon other theoretical disciplines that have an association with a specific group of practicing professionals (e.g., medical science and statistics).

In medical science, the germ theory of disease proved its value through a positive effect on professional practice. The germ theory of disease explained why certain practices in the profession were leading to poor patient outcomes (e.g., infection) and suggested specific changes in medical practice (e.g., sterilization of instruments) which were clinically proven to improve patient outcomes (e.g., morbidity rates following surgery).

In statistics, the theory of optimal design of experiments seemed to have a negative effect on professional practice. According to George Box, statistical training currently emphasizes mathematics at the expense of science[5]. This has resulted in overuse of mathematically optimal experimental designs and other "one-shot" procedures. Such procedures undermine the experimenter's iteration between theory and experiment. In practice, this resulted in less improvement of systems than would have been achieved by response surface methods. If we accept Box's finding, we have an existence proof that self-consistent mathematical theory can lead to ineffective professional practice when it neglects relevant human factors.

Evaluating design theories on the basis of practical outcomes requires some caution. Any specific application of a design theory can lead to a bad outcome. Every design scenario is unique and impossible to replicate exactly. Therefore a single bad outcome cannot lead us to reject a design theory. Consistent with the statistical nature of design, our evaluation of design theories must be statistical. Such methods are applied in medical science. Any medical treatment can lead to a bad outcome in a specific case. A single bad outcome usually does not invalidate a medical treatment, but statistical analysis of data from clinical trials can lead us to reject a medical treatment as unsafe or ineffective. I think we need clinical evaluation of design theories.

The four questions posed above are meant to provoke thought about the epistemological foundations of the science of design. I argue that, by formulation of falsifiable hypotheses, the science of design can use the same process of interplay between theoretical development and observation that has been so effective in other fields. I also caution against exclusive reliance on axiomatic methods. Finally, I suggest the practical effectiveness of design theories should be evaluated somehow, perhaps using methods similar to those in medical science.

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[5] Box, G. E. P. and P. T. Y. Liu, 1999, "Statistics as a Catalyst to Learning by Scientific Method", *Journal of Quality Technology*, vol. 31, no. 1, pp. 1-29.