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EPISTEMOLOGY IN ENGINEERING SYSTEMS

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The engineering systems division at MIT has adopted an official vision statement -- "ESD will be a leader in understanding, modeling, predicting and affecting the structure and behavior of technologically enabled complex systems." To fulfill this vision, I think it is worthwhile for ESD faculty to reflect on epistemology and its relationship to engineering systems. Epistemology is the branch of philosophy concerned with the nature of knowledge, justification, evidence, and related notions. By reflecting upon epistemology, we may clarify in our own minds how we come to know something about engineering systems and thereby improve our research methods. In this white paper, I pose five questions related to epistemology and engineering systems. I also discuss possible answers, but my goal was primarily to spark discussion rather than solidify a position.

Is the basis of knowledge in engineering systems different from that of the natural sciences? Natural sciences such as physics and biology seem to improve over time through the interplay between theoretical development and observation. Scientists propose theories that coherently explain some observed phenomena, but eventually may fail to explain other observations. New theories are proposed which explain more phenomena or explain the same phenomena more parsimoniously. By an evolutionary or perhaps a revolutionary process[1], better theories eventually modify or replace previous theories. This description is somewhat oversimplified, but I think it is generally accurate.

Some of the goals of engineering systems (e.g., modeling and predicting behavior of systems) seem to fall within the domain of natural sciences since engineering systems obey the same physical laws and natural systems. It would seem to follow that the method of scientific discovery in the natural sciences (as described in the previous paragraph) will apply as we seek to improve our ability to model and predict the behavior of engineering systems.

On the other hand, some aspects of engineering systems may not fall in the domain of natural science. In engineering systems we want to lead in "affecting the structure and behavior of engineering systems." In the field of engineering systems, we have a significant interest in design. Herbert Simon suggested that "we might question whether the forms of reasoning that are appropriate to natural science are suitable also for design"[2]. Simon argues that design concerns how things ought to be and that statements about design are often normative or imperative. Simon presents examples of paradoxes that arise when ordinary logic is applied to normative and imperative statements. His conclusion is that new modes of logic are required for the science of design. I disagree. I propose that by eliminating normative and imperative statements from the science of design we may be able to place it on the same methodological foundations as natural science without limiting its scope. The questions that follow provide the details of my reasoning.

Can Popper's falsifiability criterion be applied to design theories? 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[3]. 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. If we seek to develop a science of design, we should check whether we're really doing math or ethics. I think a science of design is a worthwhile goal. For ESD to engage in developing a science of design, I think we must propose falsifiable hypotheses and subject them to empirical tests.

Can the science of design include normative statements? Some researchers in design include normative or imperative statements in their theories. Such statements fail Popper's "falsificationist" criterion. There is no experimental outcome that could directly contradict a statement of the form "X should have the property Y". An observation that X does not have the property Y is not evidence for or against the normative statement. Similarly, there is no experimental outcome that could directly contradict a statement of the form "do A before B". An observation that some people don't do A before B is not evidence for or against the imperitive. To make a scientific hypothesis based normative or

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[1] Kuhn, T. S., 1962, *The Structure of Scientific Revolutions*, University of Chicago Press, Chicago, IL.
[2] Simon, H., 1969, *Sciences of the Artificial,* MIT Press, Cambridge, MA.
[3] Popper, K. R., 1934, *Logik der Forschung*.

imperative statements, one might stipulate the observable consequences of violating the statement. Table 1 lists two examples. The statements on the left are normative or imperative statements from contemporary design theories. The statements on the right are falsifiable, scientific hypotheses that can be subjected to empirical tests. I personally do not know if the statements on the right are true, but I think it is possible to find out. Such falsifiable formulations of design theory may confer a significant advantage to the research community as they enable it to employ the same processes which have advanced the natural sciences so effectively.

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.[4]	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.[5]	Designs whose functional requirements are coupled have < 1% probability of meeting their functional requirements.

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 (assuming the theory is stated in an empirically testable form).

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[6]. 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.

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

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

[6] 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.

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 it is important for ESD faculty to engage in clinical evaluation of proposed design theories, methods, and tools.

The five questions posed above are meant to provoke thought about the epistemological foundations of engineering systems. I argue that, by formulation of falsifiable hypotheses, we 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 that the practical effectiveness of design theories should be evaluated somehow, perhaps using methods similar to those in medical science.