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The Cognition of Engineering Design—An Opportunity of Impact

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In May, 2006, the National Science Foundation hosted a workshop entitled "The Scientific Basis of Individual and Team Innovation and Discovery" (Schunn, Paulus, Cagan, & Wood, 2006). An important outcome of the workshop was a focus on the emerging research opportunity of the cognition of engineering innovation. To advance industry's ability to be innovative, a fundamental understanding of how individuals and teams are innovative must emerge. Such an understanding would enable more effective tools and methods to assist the innovation process, to make it more efficient and productive. Cognitive science offers the possibility of not only acknowledging that creative breakthroughs happen, but how they happen, when they happen, and, from that, how to help them happen. Such understanding will provide the basis for a science of innovation, and that scientific basis will provide the means to improve design innovation outcome.

A rich direction of research is needed. Design is a complex human phenomenon, so research must couple basic theoretical and experimental findings with their application to more realistic design settings, short time frames with longer time frames, and individual mechanisms with group mechanisms. Cognitive science must contribute to the core mechanisms that contribute to these situations.

I believe that to be most impactful, collaborative interdisciplinary partnerships should be pursued. Although cognitive psychologists are in a position to explore the mechanisms of creativity independently, innovation requires the pragmatics of application, of how engineers solve problems and what is important to the engineers in solving those problems; engineers are also driven to place the research in the context of application. I have benefited from a collaborative research approach to understanding the cognition of innovation for more than a dozen years with Kenneth Kotovsky, a cognitive psychology professor at Carnegie Mellon. We have co-advised psychology students and engineering students, working to make inroads in understanding this complex human endeavor.

There are a few key areas that I feel are critical to explore: understanding fixation—what causes it and how to overcome it; understanding representation—how it aids in problem solving and how it changes to improve outcome or overcome fixation; group cognition—how

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the cognitive processes of individuals combine and collaborate for a group level representation and performance; computational studies—how models of cognition can be emulated on the computer, how those models can improve design tool performance, and whether exploration of those models can give insight into cognitive mechanisms of innovation; analogical reasoning—how analogies stimulate novel solutions to difficult engineering design problems; and expertise—how richer representations and knowledge can accelerate design performance. To highlight a few:

- Mechanical engineering students gain a deeper representation of mechanical search spaces through their education. Seniors are better able to reason about functional transformations and energy flow than freshmen, leading to a deeper understanding of how mechanical systems work (Moss, Kotovsky, & Cagan, 2006).
- One interesting characteristic of fixation in problem solving is demonstrated by the effect of open goals on the acquisition of problem relevant information; hints presented implicitly aid problem solving, particularly in the presence of open goals, but in some situations the hints are most effective prior to reaching an impasse (Moss, 2006).
- Computational simulations of human performance can emulate exploration versus final path phases of search. A simulated annealing algorithm that dynamically updated its objective function imitated findings from cognitive studies of people solving puzzle problems such as the Chinese Rings Puzzle and Tower of Hanoi (Cagan & Kotovsky, 1997).
- Cognitively motivated computational models of design processes can lead to better model performance. Agent-based methods are able to synthesize electromechanical devices by reasoning about their functionality and instantiating their form with each agent motivated by the same overall goals (Campbell, Cagan, & Kotovsky, 1999). However, synergistic collaboration, with agents working together to reach resolution of constraint and goal conflict, performs far better than each agent making independent design modifications (Olson & Cagan, 2004). The ability to learn what chunks of a generated design are likely to transfer to other design problems can accelerate the solution of those new problems (Moss, Cagan, and Kotovsky, 2004).
- Simulations of highly complex conceptual design tasks reveals that collaborative approaches to problem solution lead to far better performance than individual, independent contributions; such collaborative methods include small group work, large group work, and individual work in balance. Agent-based models of such interactions provide a forum to design better teams, and improve design tool performance (Olson, Cagan, and Kotovsky, 2006).

Several cognitive psychologists, some in collaboration with engineers, have made other inroads toward better understanding the fundamental mechanisms of engineering innovation such as analogical reasoning (e.g., Christensen & Schunn, in press; Linsey, Murphy, Markman, Wood, & Kortoglu, 2006), fixation (e.g., Jansson & Smith, 1991) and design observation (e.g., Shah, Smith, Vargas-Hernandez, Gerkens, & Muqi, 2003). Together, this work is just beginning to lay the foundation for an exciting field of study.

A goal of cognitive science is to seek generalities beyond domains where participants' background knowledge influences performance. For engineering innovation, domain knowledge plays a crucial role in outcome effectiveness and efficiency; still, the principles learned through cognitive research into engineering innovation are generalizable and extendible to other domains such as scientific discovery (Cagan, Kotovsky, & Simon, 2001). A complex, little-explored, broad-reaching field, the study of the cognition of engineering innovation holds promise for new and important findings that will not only advance the field of cognitive psychology, but have the potential for critical impact on the economic advancement and well being of society.

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