Final Report from the NSF Innovation and Discovery Workshop: The Scientific Basis of Individual and Team Innovation and Discovery

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Executive Summary

A critical component of the future of the American economy is the ability for U.S. companies to be innovative, consistently and efficiently, in their approach to product and service development and to be able to benefit from a steady stream of new scientific discoveries. The National Science Foundation has the opportunity to play a key role in the support of this approach by funding fundamental research in the science of innovation and discovery. The interface between cognitive psychology, social psychology and engineering provides a natural and as yet minimally explored environment to deeply understand the theory, processes and mechanisms of innovation and their influence on the design, creation, and discovery processes.

On May 17 and 18, 2006, key individuals currently researching the process of innovation and discovery held a workshop. This workshop allowed these individuals to present state-of-the-art research findings, breakout into cross-disciplinary working groups, and explore critical areas of near-term and long-term research in this area. This NSF report communicates the findings of this workshop. In particular, five "umbrella" research areas are identified as critical pathways in helping the U.S. lead in the process of innovation:

- studies that expand understanding of the cognitive mechanisms of innovation/creativity and the ways in which strategies and external tools influence these cognitive mechanisms;
- computational modeling and agents simulations of innovation/creativity that allow for theoretical development across levels of individual, group, and organizational analysis;
- empirical studies and computational models that explore the temporal dynamics of individual and group factors on creativity/innovation;
- interdisciplinary programs of research that coordinate psychology laboratory and design engineering experiments; and
- empirical studies that unpack cognitive and social/motivational factors of group cognition in more realistic group settings: horizontally integrated across disciplines, vertically integrated (with leaders), and evolving group structure over long time periods.

The Context

A Growing National Issue

Understanding the psychological foundations of individual and team innovative engineering design has taken on new urgency. A National Science Foundation-commissioned report from the National Academy of Engineering warned: “Leadership in innovation is essential to U.S. prosperity and security. In a global, knowledge-driven economy, technological innovation, the transformation of new knowledge into products, processes, and services, is critical to competitiveness, long-term productivity growth, and the generation of wealth. U.S. leadership in technological innovation seems certain to be seriously eroded unless current trends are reversed.” [1] A second NSF-commissioned study by the American Society of Engineering Education concurs, “U.S. engineers lead the world in innovation,” but “this great national resource is at serious risk because America has an engineering deficit.” [2] It is difficult to overemphasize the economic importance of innovative design. Sixty-five percent of total revenues for technology-based companies have come from products that are less than five years old. [3] Cross-national studies show a high correlation between patents per million and a nation’s standard of living. [4] The Design Council (U.K.) found that companies known for innovative design outperformed the average Financial Times Stock Exchange Index by 200 percent from 1994 to 2003. [5] A recent research study found that the top 25 companies with patents most often cited by papers as well as other patents far outperformed the Standard & Poor’s 500 from 1990 to 2003. [6]

These findings are compounded by the fact that an increased global competition is clearly threatening the U.S. economy and undercutting its competitive advantage, as indicated by the following facts:

- In 1963, the U.S. filed more than 81 percent of the world’s patents. Since that time, other countries — particularly Japan, China, South Korea, and India — have made substantial gains, filing more than 52 percent of world patents in 2001. [7]
- Asia is forecast to have 90 percent of all practicing engineers by 2010. [7]
- The U.S. will graduate 60,000 engineers in 2005, while China is forecast to graduate nearly 500,000 engineers. [8] (China’s own estimates are 800,000. [9])
- U.S. college graduation rates increased by 26 percent from 1985 to 2000, while graduation rates for engineers decreased by 23 percent during the same period. [10]
- In some countries, 10-20 percent of the engineering curriculum is devoted to design. By contrast, in most U.S. engineering schools, design makes up only 5-7 percent of the curriculum and innovative design even less. [11]

A similar story could be told regarding the U.S. and science. Currently, the U.S. has a large percentage of the scientists in the world. But the graduation of new scientists in the U.S. is shrinking whereas it is growing at large rates in China and India. Moreover, recent data show a drop in foreign enrollment and graduates in the U.S., as students from India and China, which produces a fifth of the world’s supply of Ph.D. graduates in science and engineering, increasingly find educational opportunities in other OECD countries, such as Australia and the UK.

We need to become more efficient and effective in our efforts to innovate. Dr. Arden Bement, Director of the NSF, highlighted these concerns in the NSF FY 2007 Budget Request to Congress: “Our nation’s future depends more and more on the quality of our new ideas, the vitality of our science and engineering workforce, and the innovative use of new knowledge generated through our research and education enterprise.” (p. 1).

Needed: A Psychological Science of Individual and Team Innovation and Discovery

In order to work towards a long-term solution to these crises in science and engineering in these days of shrinking budgets and strong competition for government funding, the scientific basis of our knowledge of the factors underlying innovation and scientific discovery needs to be strengthened. Without understanding the mechanism of innovation and discovery, attempts to change the environment that supports innovation and discovery (e.g., tools and training) are haphazard and unlikely to be generally effective.

Scientific discovery and innovative engineering design are complex cognitive, social, and sociological acts and have been studied at many different levels. The history, sociology, and philosophy of science and technology are thriving entities, with large conferences and highly competitive journals. Researchers in these disciplines are making important contributions to our understanding of the larger scale levels of discovery and innovation.

By contrast, much less is known about the cognitive and social psychological levels of innovation. The psychology of science is a small field historically, and has few members currently. The area has no journals and no conferences. The psychology of design is a more recent development and overall a smaller field still. Thus, we do not yet know whether design innovation and scientific discovery are psychologically the same entity (e.g., forms of complex creativity influenced by heuristic search and analogical insights) or psychologically different entities (e.g., primarily analytic reasoning vs. primarily synthetic reasoning).

There are several likely factors underlying this state of affairs. Psychology tends to analyze simple tasks that can be studied in laboratory settings over short time periods. By contrast, scientific discovery and engineering innovation are very complex tasks that are difficult to study in the lab, and usually unfold over relatively long periods of time. The psychology focus on simple tasks was likely exacerbated by a move towards neuro-scientific understandings of behavior, which place greater emphasis on simpler tasks studied in laboratory contexts.

Another factor in the case of engineering is that psychology has more in common with other sciences than it does with engineering. Cognitive and social psychologists, chemists, biologists, and physicists share a core element: using variations of a scientific method whose goal is to produce general knowledge about how the natural world functions. While psychologists carry out some design (of theories, of experiments, and perhaps of code or instruments), they have little formal training in design as a general process. A cognitive or social psychologist is highly likely to have taken courses in biology, chemistry, and physics, but not engineering, and therefore they have little understanding of what engineers do. Thus, there is a large knowledge gap that must be overcome for psychologists to study engineering innovation.

A solution to such knowledge gaps is to create interdisciplinary partnerships. The typical funding structure at NSF of single PI grants makes it difficult to support such interdisciplinary partnerships. Yet, the psychological science of individual and team innovation and discovery is critical to the advancement of the U.S. economy. Such a science will provide for the methods, environments and tools (including computational tools) to enable more consistent, effective and efficient innovation in products and services. It will also provide a framework for training the U.S. workforce to be innovators, using the processes, methods, tools and environments that compose the framework.

Workshop Overview

To better direct its support of innovation and discovery, the U.S. National Science Foundation has an opportunity to fund research that improves our understanding of the factors (including cognitive and social psychological) that improve or increase innovation and discovery. To know how those funds should be profitably directed, a workshop was sponsored with the task of understanding the state-of-the-art and providing a vision for critical future research directions.

Such a workshop was conducted on May 17^{th} and 18^{th}, 2006. The workshop took place at NSF, to allow for maximal input and impact on NSF employees, providing further timely information with the emergence of this new funding direction. The workshop was lead by researchers from cognitive science (Christian Schunn), social psychology (Paul Paulus) and engineering (Jonathan Cagan and Kristin Wood).

The workshop included 24 researchers who represent the current state-of-the-art in the psychology of science and engineering. Approximately one-third came from cognitive science, one-third from social psychology and one-third from engineering. The researchers presented their recent contributions in this area in the form of short talks, and considerable time was left for post-presentation discussions and breakout sessions after each cluster of talks with focal questions, moving towards the large open questions that should be addressed next. Table 1 summarizes the presenters and their presentation titles for the workshop.

Table 1. Presenters, Research Areas and Presentation Titles.

Speaker	Area	Title
Steve Smith *Texas A&M*	Cognitive	*Alignment of Research on Creative Cognition Across Levels of Complexity and Ecological Validity*
Art Markman *UT-Austin*		*Tools for Moving Beyond Incremental Innovation*
Jeremy Gray *Yale*		*Cognitive Neuroscience of Discovery and Innovation: An Example Research Strategy into Cross-Domain Analogical Reasoning*
Gary Bradshaw *Mississippi State*		*Edison's Bright Idea: Mental Models, Heuristics, Strategies of Invention, and the Electric Light*
Ken Kotovsky *Carnegie Mellon*		*Sources of Insights in Engineering Design*
Ashok Goel *Georgia Tech*		*Exploring Design Innovation: The AI Method and Some Results*
Christian Schunn *Pitt*		*The Role of Artifacts on Analogy in Innovative Design*
Nancy Nersessian *Georgia Tech*		*Interdisciplinarity on the Benchtop: Model-Based Reasoning in Bio-Science and Engineering Research Laboratories*
Tory Higgins *Columbia*	Social	*Creativity Differences in Promotion Versus Prevention Regulatory States*
John Levine *Pitt*		*Innovation in Task Groups: Newcomers as Change Agents*
Mihaly Csikszentmihalyi *Claremont*		*On the Phenomenology of Discovery*
Keith Sawyer *WUSTL*		*Inside the Black Box of Collaborative Creativity*
Linda Argote *Carnegie Mellon*		*Transferring Innovations across Groups in Organizations: Evidence from the Field and the Laboratory*
Paul Paulus *UT-Arlington*		*Enhancing Group Creativity—The Effects of Training, Diversity, and Attitudes Toward Diversity*
Vincent Brown *Hofstra*		*Some Speculations on Facilitating Creative Idea Generation in Groups and Individuals: Cognitive Underpinnings*
Kris Wood *UT-Austin*	Engineering	*Empirical Studies of Collaborative and Analogical Product Design: Implications on Innovation and Discovery*
Jon Cagan *Carnegie Mellon*		*Cognitively-Inspired Computational Design Methods*
Panos Papalambros *U. of Michigan*		*Observations on Creativity and Innovation in Student Design Project Teams*
Maria Yang *USC*		*A Study of Prototypes, Design Activity, and Design Outcome: A Design Data Analysis Approach*
Dan Frey *MIT*		*The Role of Experimentation in Individual and Team Innovation and Discovery: Possible Forms of its Scientific Foundations*
Larry Leifer *Stanford*		*Surprise and Delight: Design-Thinking in Practice and Theory*
Jami Shah *ASU*		*What We Have Learned from Empirical Studies of Design Ideation Methods*

Definitions and Coordination Across Disciplines

What does innovation/creativity mean?

An interdisciplinary analysis often stumbles over disciplinary confusion and conflict over definitions of core terms, which fundamentally frame the research and conclusions, but also tend to be elusive and abstract. There cannot be productive interdisciplinary collaborations without developing a common understanding of the core constructs.

A number of analogies, documented historical cases, contemporary research, and key words lead us to definitions of innovation and creativity. Creativity involves the introduction of new variables, significant leaps, and novel connections. A subset of creativity, innovation, involves the creation of a new idea but also involves its implementation, adoption, and transfer. Innovation and discovery transform insight and technology into novel products, processes, and services that create value for stakeholders and society. Innovations and discoveries are the tangible outcomes. Creativity is needed to produce these outcomes. Innovation and discovery processes should be formal processes that harness creativity to those ends.

From a product perspective, creativity usually reflects aspects of novelty and/or utility of the products. From a process perspective, creativity involves the social, cognitive, and/or physical processes situated in individual, team, and organization contexts that repeatably produce innovative products. Creative outcomes can occur through serendipity, but it is the creative processes that regularly produce creative outcomes.

Similarities and differences in approaches to research between the different disciplines

Different disciplines examining a common large problem usually frame the core issues in substantively different ways and develop very different methods/contexts of investigation. To understand what opportunities exist for integration of findings or for the development of new multidisciplinary and transdisciplinary work, the similarities and differences must be understood.

A number of similarities and differences exist among the disciplines. These similarities include mutual respect for disciplinary skills, good qualitative and quantitative science, a shared enthusiasm for collaboration, and a fundamental belief that the innovation process is repeatable, explainable, and systematic. The disciplines agree that innovation and creativity can be studied and that it can be modified and learned. They also agree that significant and recognizable acts of innovation, creativity and discovery likely break down into basic cognitive and social processes, although the way in which those basic cognitive and social processes function in the complex settings of engineering and science is far from understood. An understanding of the mechanisms and interactions of the processes is our scientific pursuit and mantra. Intradisciplinary research has provided our state-of-the-art understanding of innovation and creativity. *Inter*disciplinary research is expected to uncover a much more fundamental understanding, especially in the complex environments of engineering and science.

Differences among the disciplines include how problems are formulated and represented, real world versus laboratory experiments, holistic versus precision approaches, approaches that seek understanding versus application, the worth, value, or historical labeling of creativity, and research methodologies. The differences reflect a tension between two different studied situations. The psychology approach of theory-oriented experimentation is contrasted with the more iterative/applied approach of the engineers. On the one hand, there are application-oriented studies that used subjects with high knowledge/skill, complex tasks, and were examining context-specific processes. For example, many studies have examined the impact of different brainstorming/early conceptual design techniques on the creativity of engineering student designs in a classroom project. On the other hand, there are phenomenon-driven studies that used subjects with low knowledge/skill, simple tasks, and examined domain-general processes. For example, there are many studies that have examined the causes of functional fixedness in brainstorming by conducting experimental manipulations on psychology lab subjects trying to generate remote associates, like the word that is associated with each of the words falling, actor, and dust (answer = star).

These similarities and differences paint an exciting picture for interdisciplinary research in innovation and discovery. The similarities provide a natural foundation for which research can successfully proceed. We do not need to specially train the disciplines to work together. There already exist the prerequisites, overlapping interests, and excitement to proceed. The differences in the disciplines build on this foundation, indicating a high likelihood of potential success. Each research discipline brings its own skill set to bear on the fundamental research problems. Each discipline brings domain knowledge and past results that may be integrated and explored collectively. Each discipline also brings complementary models of innovation and discovery from which new insights may be derived.

State of the Art from the Disciplines

We begin with a brief summary of the state of the art from each discipline, with pointers to workshop presenters whose presentations elaborate each of those points (for copies of the presentations, visit http://www.lrdc.pitt.edu/schunn/innov2006/talks/schedule.htm).[1]

Social Psychology Research on the Science of Discovery and Innovation

Social psychology has focused on personal, environmental, and social factors that influence creativity and innovation. The main focus of early research was on the impact of personal qualities or experiences on creativity and creative achievements. Although personal factors do appear to be influential, it has become clear that contextual factors also play an important role (Csikszentmihalyi; Sawyer). Some contexts enhance motivation for creativity. For example, research by Amabile and others have shown that a context that allows for a high degree of autonomy is important for innovation. Cesario, Grant, and Higgins showed that motivational styles are also important in reactions to social contexts [12]. One could extrapolate from this research that individuals who are concerned primarily with gains (promotion focus) or losses (prevention focus) may show creativity under very different circumstances. The motivational or

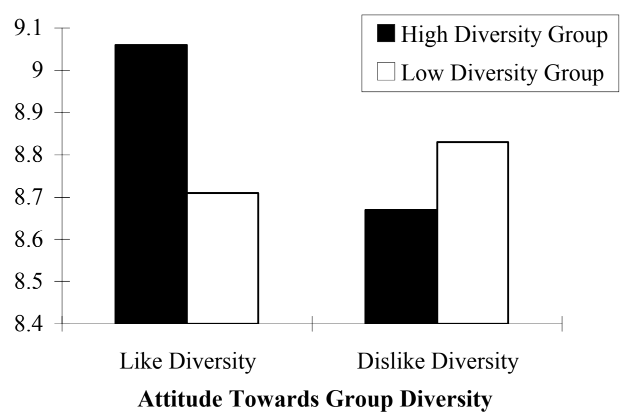
[1] Participants' names relevant to topics are listed in parenthesis in this section.

self-regulatory focus of scientists and engineers could influence their research strategy and collaboration. Those who are promotion focused will take an eager strategy of moving from the present state to a more advanced state. Promotion regulatory focus would seem to fit best with an innovative phase that involves much divergent thinking and a broad consideration of alternatives. However, when it comes to choosing among many alternative innovative directions for the one to which resources will be committed, a prevention focus may be more appropriate. Prevention focus is a more vigilant strategy that is concerned with avoiding losses or making mistakes. It is important to learn what role these motivations play in the creative and innovative processes of scientists and engineers and how this understanding can help us enhance their success at various stages of the creativity/innovation process.

Groups Factors. More than ever the complexity of science requires group efforts as teams of scientists from diverse backgrounds work together to make discoveries and solve problems. Much research has shown that group interaction can be detrimental to the creative and innovative process (Paulus, Brown). Groups may lower motivation, inhibit creative responses, and distract from the deep reflection necessary for scientific discoveries. However, groups that function in an efficient manner and mix reflective periods with appropriate and attentive group interactions can be quite innovative (Brown; Sawyer). The time to be alone or allowing for socially stimulated ideas to incubate is an important part of the innovative process (Brown, Csikszentmihalyi). Trained groups, groups with diverse perspectives, and groups that effectively integrate newcomers are most likely to exhibit a high level of innovation (Levine, Paulus). A critical factor in the cognitive stimulation of creativity in groups is the extent to which ideas from others stimulate the use or combination of unique categories of knowledge (Brown, Paulus).

There are significant gaps in our understanding of the optimal distribution of knowledge and skills in a team. Assuming limits in time for skill and knowledge acquisition, how should expertise be distributed in a team? How much overlap? Is it important to have more than one of a particular knowledge area (for both intellectual and social support) in a team? What types of leadership are required for effective functioning of diverse teams? What about team size? Is there an optimum size for certain stages of investigation or certain fields? It is presumed that groups with diverse knowledge domains/skills will inevitably have a greater chance of innovation than less diverse groups. However, the literature suggests that diversity in groups has positive effects on innovation only under specific conditions [13]. One important factor is the attitudes team members have toward diversity. Teams with positive attitudes are more likely to show enhanced creativity in diverse groups [14]. Individuals were assessed for their attitude toward working in diverse groups. They generated ideas in groups of three or four. Groups that were ethnically and linguistically diverse and that had a positive attitude toward working in diverse groups generated higher quality ideas (see Fig. 1).

Fig. 1



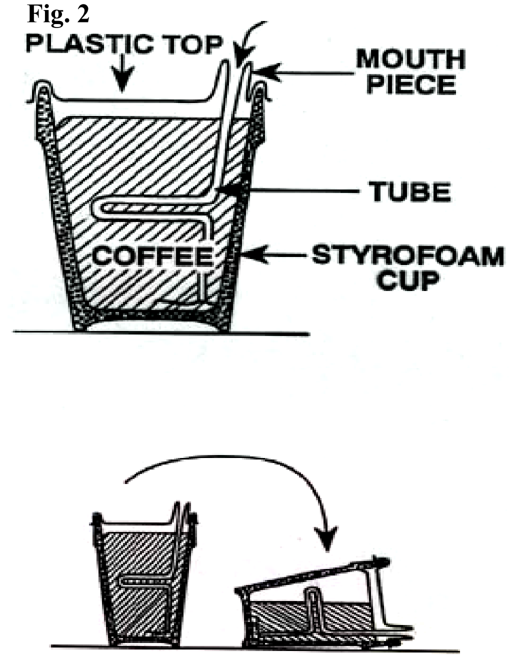
Organizational Factors. Even if organizations have creative individuals and groups, there are no guarantees that they will be innovative (Sawyer). Innovative teams or organizations require loose structures, appropriate distribution of expertise, effective communication, and distribution of creative activities throughout the organization (Sawyer). Artificial boundaries in organizations can inhibit knowledge transfer among groups or units. When there is a shared identity among units, there is a greater transfer of innovations (Argote). Kane, Argote and Levine had groups of three with specialized roles produce Origami sailboats. After one trial, one member rotated to a second group. Half of the groups were trained in a somewhat superior production routine and half of the groups were induced to have a common group identity (the two groups were presumed to be in one organization). It was found that knowledge transfer was most likely between the two groups when the rotating member had a shared identity and knowledge of the superior routine. These two factors were also related to enhanced performance of the group. This study suggests that the training or knowledge of new group members and their feelings about the group can have a significant impact on the innovative potential of groups.

Cognitive Science Research on the Science of Discovery and Innovation

The cognitive science community has studied, in depth, three different cognitive processes that have been shown to play an important role in innovation and discovery.

Memory (Markman, Smith, Kotovsky). The human mind stores a vast set of knowledge that is relevant to developing creative and effective solutions in discovery and innovation. Unfortunately, problem solvers frequently get stuck on a particular ineffective solution (either given or self-generated), and the presence of the ineffective solution inhibits the retrieval of information related to a more effective solution [15]. For example, physical images in the environment as starting examples related to the blocking solution make the problem worse. Fig. 2 was a starting example given to students asked to design a new inexpensive spill-proof coffee cup with the explicit instructions of not using drinking straws or mouthpieces—providing the example increased the likelihood of developing solutions that had straws and leaked [16]. Instituting strategic delays reduce the overall block, reduce the effect of blocking stimuli, and increase the ability of external information consistent with a better solution to help the problem solver.

Fig. 2



Analogy (Schunn, Markman, Goel, Bradshaw). Often a very novel solution is obtained not directly from retrieving the solution from memory but rather from working by analogy to a solution to a (perhaps distantly) related problem. Similar to the role of memory in creativity, a cognitive difficulty to this mechanism is a retrieval problem: people are much more able to retrieve superficially related situations than situations with an analogical, abstract relationship to the current problem. Interventions can be introduced to change the underlying problem representation to emphasize structural/abstract features, which then improves analogical retrieval. The external environment also plays an important role in shaping retrieval. For example, Christensen and Schunn studied the design meeting conversations of a highly innovative medical plastic design group and found that this group used a large number of anoglies, both from other medical plastics firms (within-domain) and from many different everyday situations (credit cards, shopping, cars, toilet paper, etc) [17]. But when there were highly detailed physical prototypes in front of the group, they were much less likely to bring up between-domain analogies than when sketches or no design images or objects were in front of the group (see Fig. 3)—consistent with the memory work, concrete images seem to inhibit retrieval of related cases.

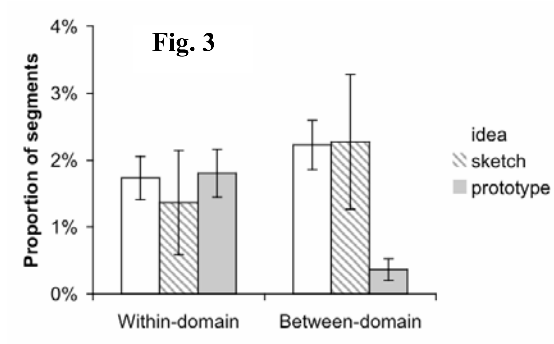


Fig. 3

Models (Nersessian, Bradshaw, Markman, Goel). Innovation and discovery involve creating, sharing, modifying, and integrating a variety of kinds of models of the innovation/discovery situation, and these models strongly shape what kinds of memories and analogies are used, how the science/engineering team functions, and what other kinds of reasoning processes are brought to bear (e.g., verbal vs. visual processes). Some of the models are entirely mental and perhaps implicit, but often they are also situated in a variety of physical forms. For example, a recent analysis of Edison's invention of the light bulb by Gary Bradshaw documents how Edison's fixation on his initial mental model of a self-regulating platinum bulb (as shown in Fig. 4) almost lead to his downfall.

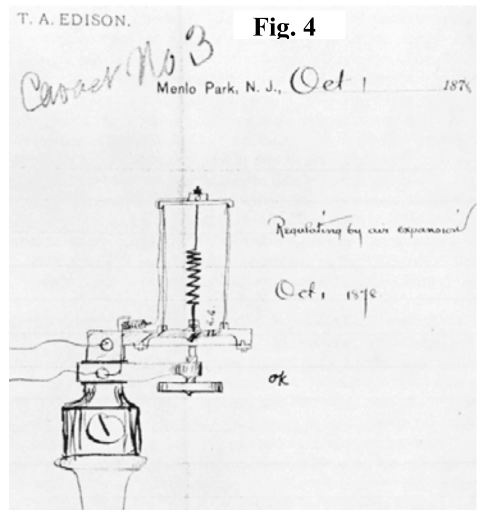


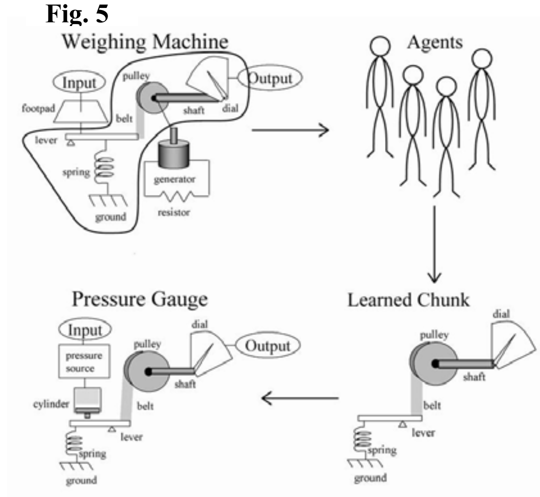
Fig. 4

A note about cognitive neuroscience (Gray). As of yet, cognitive neuroscience methods have not been the primary contributors to the cognitive science of innovation and discovery. It is important to realize that cognitive neuroscience methods used all by themselves can produce misleading and simply uninformative results because finding out about the location of cognitive activity during discovery or innovation (1) does not by itself say enough about function, and (2) is usually rather vague about exactly what set of cognitions specifically produce the observed brain activities. However, used as a source of converging evidence and as part of a focus on particular psychological processes in discovery and design (rather than discovery or innovation studied holistically), cognitive neuroscience can potentially be an important contributor.

Engineering Research on the Science of Innovation

There are three clear directions of work in the engineering communities that are moving toward a better understanding of innovation.

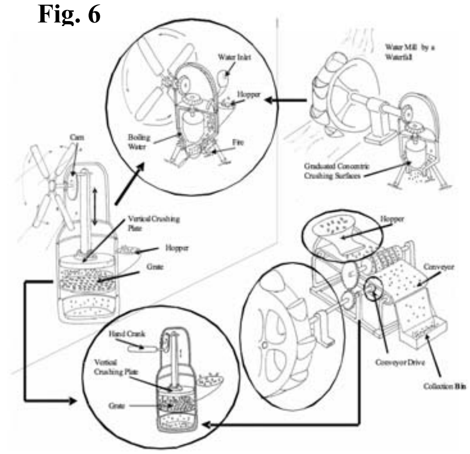
Fig. 5



Cognitive modeling. The first is a collaborative approach to understanding, modeling and using results from the cognition of innovation. Models that incorporate or are influenced by fundamental cognitive mechanisms such as individual problem solving, collaborative cognition in teams, and use of analogy are being developed, applied in practice, and implemented computationally to generate designs based on these methods and to provide an experimental platform to study their effects (Cagan, Wood, and Shah). In support of these models, experimental techniques are being studied and developed regarding their role in the innovation process and as a tool for studying this process (Frey). For example, Fig. 5 illustrates how cognitive models of innovation can advance our understanding of human creativity while also helping to improve automated design tools [18]. Cognitive-based agents use a functional "chunk" learned from one engineering design (a weighing machine) as a source of innovation for design in a different context (a pressure gauge).

Human Studies and Teaming. Studying teams and individuals in activities during the design process leads to deeper understanding of the innovation process. These include formal and scientific experiments and informal observation of the design process. Examples focus on the use of sketching, protocol studies of design activities, using cognitive methods, observation of group structures and performance (Yang, Leifer, Shah, Wood, and Cagan). Results from this work support the work on cognitive modeling and the work on educational pedagogies for innovation.

Fig. 6



A study of collaborative design and different media for expressing design concepts exemplifies this work. In a study by Linsey, Artman, and Wood, design teams express solutions to a need-based problem of developing a peanut-shelling device for persons living in African village environments (e.g., see fig. 6)[19,20]. The concepts are expressed in textual, graphical, and the combination of both media. In addition, the ideas are exchanged with either a gallery method or by systematically passing the concepts around a circuit of the team members. Across a number of experiments, two particularly important findings emerged: (1) a greater quantity of unique concepts is produced through a combination of graphical and textual media (see right graph of Fig. 7), and (2) passing the concept between team members added many unique concepts not generated by the teams members working alone (see Fig. 8). Continuing studies in this vein will promote environments and methods for improving the effectiveness and efficiency of innovation from collaborative teams.

Fig. 7

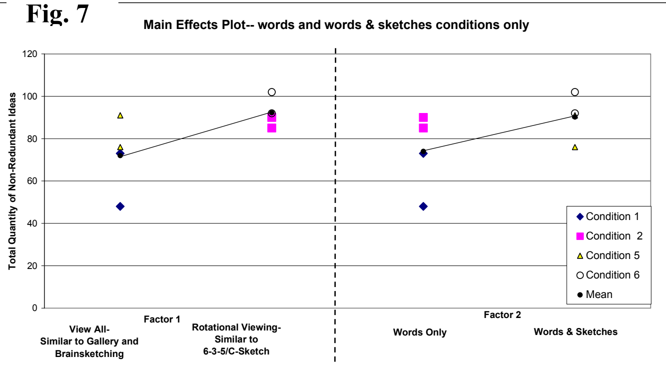
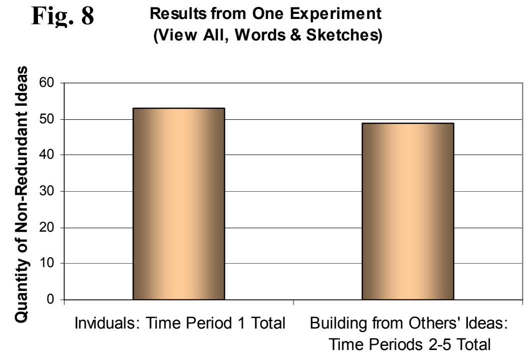


Fig. 8



Education. The engineering community has been on the frontier of education in the area of innovation. Schools like Stanford (Leifer), Carnegie Mellon (Cagan), U Michigan (Papalambros), UT Austin (Wood), and others, teach formal methods and processes in innovation, the social aspects of design, user empathy, qualitative user research methods, and other tools critical for education in the innovation process but non-traditional from an engineering point of view. The community has been active in publishing tradebooks and text books in the areas [6, 21-24].

Recommendations for the Future

Strong Potential Areas of Multi, Inter, and Transdisciplinary Collaboration

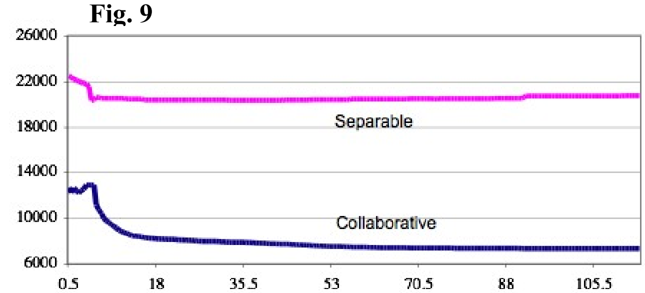
We provide an exploration of possibilities, as opposed to a definitive set, or rated set, of potential areas for collaboration. Through this approach, a number of potential areas emerge. Lists of this sort may lead to fringe topics and intractable research problems or methodologies. On the other hand, the list may lead to a number of insights for collaboration between the disciplines.

Overall, the approach for collaboration is to focus on design thinking as the common context to more clearly highlight the actual phases of the creative process. It is clear that at this time a multidisciplinary approach is expected to make significant progress because design thinking involves issues of motivation, problem formulation, evaluation, and phenomenology. Moreover, psychologists tend to focus on the process of working toward a given end state or goal while engineers tend to focus more on the outcome--the creation of end states.

There are rich areas of collaboration among the three disciplines as pairs or as a whole:

- Between engineering and cognition research areas include: effective strategies for goal directed search, the importance of representations and how they change over time, cognitive mechanisms of creativity (including impasses and fixation), understanding analogy, understanding and development of methods and tools to enhance creativity, ontologies (e.g., for functional reasoning) to enable better communication and simulation. For example, Olson and Cagan showed that in the context of an optimization-based design of a manufacturing process plan using teams of agents, collaborating teams for outperformed separable (each agent building off the other but not working together as a team) agents in terms of solution time, solution quality, and ability to explore the design space (see Fig. 9) [25].

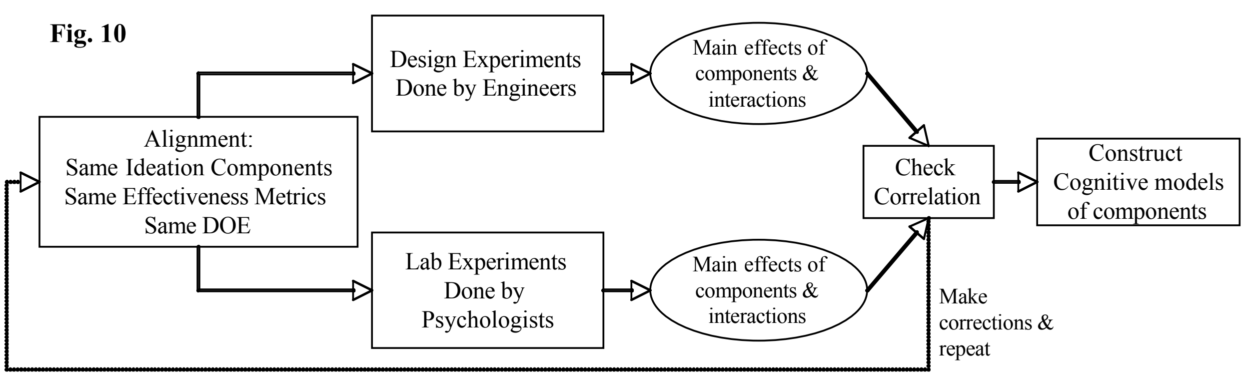
Fig. 9



- Between social and cognitive science research areas include: group mental models, cognition as a distributed activity ("group mind"), the synergy between individuals and team to improve performance. In particular, group interaction in groups with diverse knowledge structures should prime or stimulate unique combinations of ideas. However, it may be important for individuals to have some solitary time immediately after group interaction to continue to process the exchanged information and generate additional ideas. In a computational simulation of a semantic network model of group ideation, Brown demonstrated that the best sequence for idea generation may be to follow group ideation with a solitary ideation session.

- Between engineering and social science research areas include: studies of engineering teams, ways to build design teams that work more effectively, the creation of new ethnographic techniques, and the impact of disciplinary cultures on creative design. Shah and Smith propose a basic model [26], shown in Fig. 10. In this model, the goal is to combine the strength of the disciplines in laboratory experiments vs. design engineering experiments. Fundamental innovation components and interactions are hypothesized, or observed, and tested within the separate disciplinary approaches. These components and interactions are then correlated to form working models. Initial results of this model are promising, yet challenging. Great potential exists to identify the fundamental components and interactions, where the alignment and collaborative spirit of the disciplines are the catalysts.

Fig. 10



The three disciplines as an integrated whole can focus on the area of "group cognition". Historically, the study of groups has been the domain of social rather than cognitive psychologists. Recently, progress has been made to show that many of the basic theoretical pieces of individual cognition can be applied to complex group setting [27]. But there remains emergent processes by which the group is more than just the sum of the parts, and these emergent processes involve a rich interplay of cognitive and social/motivational factors: real research and design teams are typically (1) horizontally integrated such that cross-disciplinary communication and cultural practices are important, (2) vertically integrated such that apprenticeship and identity are evolving throughout the project, and (3) in contexts that are evolving such that the team must be aware of its performance and be able to adapt its processes to meet the changing context. In the lab setting, psychologists can choose to act as if these complexities are absent; it is the collaboration with engineering that brings to the forefront the complexity of the situation. Multi-level models and simulations of these processes will be needed to fully understand the interactions and effects at different time scales of examination.

The Future

In time, it is possible that the nature of research may change both in the directions of studying the process (e.g., science) and studying the way innovative design takes place. However, first and foremost, we may have to learn how to work together in an effective interdisciplinary manner.

There are several opportunities to promote and support research in this area: the support of interdisciplinary centers to study innovation/creativity; open solicitations in the science of innovation/creativity, graduate training grants (e.g., in engineering design), interdisciplinary conferences. Separate interdisciplinary panels should be created, rather than attempting to review or co-review this kind of interdisciplinary work within the traditional disciplinary panels.

With such support, we can expect the following changes. In the first five years, there will be an increase in our ability to collaborate effectively and investigate the key issues. Funding and publication opportunities will be very important for growth, so within the next five years, the rewards for this type of interdisciplinary approach must continue to grow. In 10 years, there should be some significant impact on education, the economy and the actual design processes. There may be some national centers for innovation research. In 20 years, there will be new perspectives on how we can more effectively study creativity and innovation using a solid scientific and multidisciplinary approach. At that point, there will be a sophisticated community of scholars and practitioners communicating with one another regularly about this research. Today is the starting point for this journey; the pathways are sure to be filled with excitement, dead-ends, and unpredictable breakthroughs; and the effects on our culture, society, and world economy, we are sure, will be dramatic.

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