"ADVANCING INVENTIVE CREATIVITY THROUGH EDUCATION"

THE LEMELSON-MIT PROGRAM
School of Engineering
Massachusetts Institute of Technology

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FOREWARD

This draft document comprises a Report and Notes of the discussion from a workshop held in Lenox, Massachusetts in October 2003, as part of a larger study on invention and inventiveness. The study will culminate in an "Invention Assembly" in Washington D.C. in April 2004. The study is supported by the Lemelson-MIT Program and by the National Science Foundation. The Assembly will be hosted by the National Academy of Engineering.

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Findings

- **Invention, Design and Creativity are Central to Human Existence:** Invention, design and creativity are and always have been defining features of human existence. Our focus is on technological invention, but we link the three concepts since invention requires creativity and since invention is the most creative version of design. Invention has been a major driver for immense improvements in the quality of life, particularly in the past 200 years. The future challenges for humanity seem to require continued and an even more challenging scale and scope of invention. The aim is not to create inventors at the level of Edison by the multi-thousands. Rather, it is toward a more broadly distributed appreciation and capability for invention, design and creativity. The process of invention and the traits of the inventive mind can be cultivated by education and fostered by appropriate societal support. Simply put, we believe that a culture of inventiveness at all levels can be fostered to the benefit of society.

- **Goal Re-orientation Needed for Education:** A long-term and major shift in people's work is underway towards what often is referred to as "knowledge work" and towards what this report terms 'inventive work." A key finding is that education in general is yet somewhat aimed at fulfilling industrial needs as opposed to enhancing currently needed creative capability. The role that education plays in fostering technological invention through helping people develop deep technical knowledge is widely recognized. However, at K-12 and the university level, education is not focused on inventiveness as a goal. Some symptoms of this lack of focus on invention include over-emphasis on deductive learning, separation of the learning of principles from their application, inadequate self-discovery, overly-rigid formats, pre-determined outcomes, lack of open-ended problems, too little emphasis on learning from failure, and a lack of teaching of visual thinking. Our focus is on higher education, but we note links across all levels of the educational system.

- **"Islands of Success," but Inadequate Diffusion:** Many of the "disconnects" just described have been successfully overcome in isolated cases. Therefore, the important prior work has mostly led to "islands of success," which have not had the benefit of support to ensure that they are sustained. The lack of sufficient mechanisms to help instructors develop the capability to foster inventiveness, as well as the lack of mechanisms linking together instructors who are innovating in this field explains the slow-to-non-existent diffusion. Behind these ineffective mechanisms lies the fact that rewards and incentives for faculty including appointment, promotion and tenure criteria only rarely emphasize invention and teaching of inventive creativity. Indeed, these institutional arrangements often directly or indirectly discourage these activities.

- **Importance of Appreciating Enduring Dilemmas:** The re-invention of education so as to better align with societal needs for improved inventive capability is *enabled* by careful attention to a set of enduring dilemmas or tensions. These dilemmas involve pairs of seemingly incompatible factors that are simultaneously necessary for the teaching of inventiveness (and for invention as well). Among such enduring dilemmas is the importance of individual vs. group effort in invention, the value of disciplinary expertise vs. open-ended exploration, the essential roles of cooperation vs. competition, the need for reflection vs. quick exploration, as well as the roles of intrinsic vs. extrinsic motivation. Effective educational approaches (and effective inventing) must be structured to honor ***both*** poles in each dilemma.

Recommendations

1. We recommend that inventive creativity should be made an explicit goal of education at all levels for overwhelmingly important societal reasons. Specifically, inventive creativity should be clearly stated in the National Standards for Education (K-12), in ABET criteria (engineering education) and university education goals in general. Similarly, inventive output should be explicitly considered and heavily weighted in college admission criteria, educational outcome assessment at all levels, university rating systems and in teacher evaluation.

2. We recommend that higher education institutions:

   a. Offer a wide variety of courses on invention and the inventive process, including hands-on activities, visual thinking experiences, and "how things work" exercises for all students—spanning majors in humanities, social sciences, engineering, natural sciences, the arts and other field or domains. These courses should be based on up-to-date cognitive science findings on invention and on how people learn.

   b. Infuse design-oriented activities and realistic, open-ended application into all courses—where the primary aim is to teach the important principles of a field in ways that will promote creativity in the application of these principles. If students experience design-oriented activities in all disciplines, they will be more likely to develop a deeper understanding of the creative process itself, independent of any discipline.

   c. Lead in the development and energetic use of exchange mechanisms for the sharing of materials and approaches for effectively teaching of inventive creativity. This includes sharing within universities, among universities, between universities and secondary/primary schools, and between educational institutions and industry.

   d. For engineering schools in particular to implement tenure and promotion criteria that give importance to invention and teaching of inventiveness. This will involve a corresponding decrease in the weight given to deductive scientific achievements and teaching of principles not tied to application contexts.

   e. Similarly, for engineering schools to encourage the development of a new set of learning materials that unites the teaching of principles and the fostering of invention. This can be achieved, in part, though the inclusion of new sets of open-ended problems through which the principles are learned.

3. We recommend the effective infusion of inventive creativity into the K-12 education agenda. This requires the development and execution of extensive workshops allowing all teachers to learn by experience how to effectively lead a project-based classroom. The teaching of this skill should be generally incorporated into the pre-service curricula in education schools so that new teachers have the background and expertise to integrate design-oriented activities into their practice.

4. We recommend a substantial increase in research on the process of invention and teaching of inventiveness. This should include research aimed at a deeper understanding of the creative mind and creative environment, as well as research on the measurement of inventiveness, diffusion of teaching of inventive creativity, and the study of rapid learning as part of the boundary transgression that is at the heart of invention.

5. Finally, we recommend the creation of an extensive network of community centers, "invention homes" or "free workshops" (to use a term that parallels the Carnegie free library concept) for invention that would involve the accessible tools, materials and flexible space so important to invention. This initiative would build on the current trend in developing major science/technology/industry museums, which are already becoming important in the development of the inventive capability of our society and nation. We envision a much more extensive and linked set of sites of various sizes. We draw the parallel to the "free libraries" established by Andrew Carnegie a century ago. Our concept is to make these "invention homes" or "free workshops" as vital to educational development now as the libraries were to education of that time. We encourage industry and foundations to play a strong role in creating such local centers where invention is practiced, learned and celebrated.

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Problem Statement and Goals

Technological invention has made countless contributions in advancing the quality of life for people on a global basis [1]. With invention has come an equally countless number of unintended consequences, some beneficial and others destructive. Looking to the future, continued and even increased inventive output will be necessary for further advances in addressing core societal challenges, including global social, energy, security and environmental concerns—challenges that not only threaten the continued improvement of human quality of life but in some analyses even threaten the existence of the human species over the course of the next century.[2]

Basic societal shifts are occurring that are potentially as significant as previous historical shifts—first from hunting/gathering to farming, and then from farming to industrial production. As with

[1]See, for example, Lemelson-MIT History of Invention Workshop Report, 2003

these past shifts, the basic nature of human work is changing. The current transition has been variously referred to as an era of "flexible specialization," an "information revolution," and various formulations centered on "knowledge-driven work" or the "knowledge economy."[3] However, the creative use of knowledge is the essence of what is needed to succeed as an individual or nation in the modern world, so we give particular emphasis to the aspects of the shift that involve the growing importance of what can be termed "inventive work."[4]

Thus, from clear needs and from apparent trends, it is appropriate to examine invention and to recommend changes to strengthen our societal ability to invent. This has been undertaken by the series of Lemelson-MIT workshops, in which this workshop has the role of examining education relative to invention. It has been widely recognized that education, broadly defined, is central to the shifts in the nature of work and society. Education is the major process for acquiring base knowledge and for then building on this base through the acquisition of further knowledge. In this regard, education plays a crucial role in fostering technological invention. It is through education that deep technical expertise is acquired and it is possible, through education, to foster habits of creativity and principles of design. However, the primary focus of education at the university level (in engineering and other fields) and at K-12 is not centered on invention as a goal. This "disconnect" might be explained by reference to the previous era where education and socialization of industrial workers did not require or even desire fostering inventive creativity. These shortfalls associated with not having invention as an educational goal were the major focus of the Lemelson-MIT Workshop on Advancing Inventive Creativity Through Education."

Some symptoms of the lack of focus on invention described at the workshop include disparities between the education methods/mindsets and invention processes, such as:

- An over-emphasis on deductive learning and an under-emphasis on experimental and inductive learning.
- A separation of principles from their context, use and application.

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[2] See, for example: Martin J. Rees. 2003. *Our Final Hour: A Scientist's Warning: How Terror, Error, and Environmental Disaster Threaten Humankind's Future In This Century--On Earth and Beyond* (New York: Basic Books);
[3] See, for example: Michael Piore and Charles Sabel. 1984. *The Second Industrial Divide* (New York: Basic Books)
[4] See for example, Richard Florida, The Rise of the Creative Class, (New York: Basic Books, 2002)

- Curricula providing insufficient support to individual initiative and self-discovery—specifying instead narrowly construed learning outcomes with pre-conceived answers.
- Rigid Separation between disciplines ignoring the need for multidisciplinary approaches to real-world problems.
- Highly structured learning formats that constrain the expression of ideas.
- A rapid pace of learning (such as endless problem sets) that can undermine the open-ended reflection and self-assessment necessary for invention.
- An inadequate balance between the importance of discipline in building a body of knowledge and the importance of the creative use of the knowledge (such as insufficient use of open-ended problems).
- Insufficient attention and appreciation of the important role of failure and learning from failure
- Rewards and reinforcements in educational institutions, including appointment, promotion and tenure requirements, that usually do not emphasize invention or teaching of inventive creativity and that may even discourage these activities.
- Inadequate appreciation for the importance of individuals developing and constructively channeling their personal passions which are crucial enablers of invention in society

The workshop goals were to make recommendations that might alleviate these symptoms and also recommendations to address the following set of broader problems associated with inventive creativity in education:

- There are identifiable “islands of success” where the teaching of invention and design, has been done well, but broad diffusion has not occurred.
- There are insufficient mechanisms to help instructors develop the capability to foster interactive, self-directed learning.
- There are insufficient mechanisms linking together instructors who are innovating in the way that they teach about design, engineering and creativity—all of which are essential elements of invention.

- While the culture of the engineering and design professions which host invention has been changing, there are still barriers encountered by women and minorities.

Assumptions and Enduring Dilemmas

The workshop participants arrived at a consensus set of assumptions or beliefs about invention and education that are important to note as background for our recommendations. These assumptions have a central role in guiding the overall education redesign recommendations that are featured in this report. Some of these assumptions are about invention and inventors and some about education relative to invention.

At the outset, we note that invention, design and creativity are and always has been defining features of human existence. Nonetheless, there is variation across societies and the role and value placed on invention. Probing deeper, we see that there are various attitudinal dispositions to invention, which can be described as mindsets or habits of mind.[5] 4) The motivation to innovate is inextricably linked to larger motivations, including the motivations for financial gain and other improvements in personal circumstances, and beyond personal (or societal) gains, fundamental impulses to explore and construct embedded deeply in human nature. While the larger aims or purposes of invention was not the focus of this workshop, we note that these are fundamentally subjective, value-based issues that must be considered in conjunction with teaching invention.

Routine problem-solving and invention represent opposite ends of a design continuum, with increasing specification and predictability associate with routine problem-solving and increasing “boundary transgression” and uncertainty associated with invention. Technological invention requires both the necessary depth of knowledge as well as the practice of invention and creativity. Education must address this full spectrum.

Education aimed at advancing invention is almost sure to need to redesign in many respects. Most of the changes can be anticipated to be incremental but some workshop participants believe that more far-reaching and fundamental changes may also be needed to effectively accomplish our goal of advancing inventiveness through education. Our most important belief is that while there is no expectation of creating "Edisons" by the thousands, the traits of the inventive mind and the processes of invention can be cultivated by education and fostered by appropriate organizational structures. We seek a more broadly distributed appreciation and capability around invention, trusting that the individual geniuses will emerge independently, as they always have done.

In addition to the guiding assumptions, the workshop participants found a set of enduring dilemmas that surround inventive activity.[6] Although the dilemmas are particularly relevant to the educational experience, they are also at play in industrial settings where invention is practiced. These dilemmas are not barriers to progress but the effective negotiation of the tensions associated with these dilemmas is the essence of recasting education in order to advance inventive creativity.

The enduring dilemmas are:

- **Individual vs. Group Capability:** Creativity and innovation depend on developing both individual and group capability, with a constant tension and synergy between the two.

- **Discipline vs. Open-Ended Exploration:** Discipline and Exploration have the potential to be both barriers and enablers for each other—and both are essential to creativity and innovation.

- **Cooperation vs. Competition:** Competitive pressures can be powerful motivators and powerful inhibitors for learning about invention. Cooperative processes are essential to design, engineering and invention, which can be both undercut and reinforced by competitive dynamics. Competitive pressures and cooperative partnership are both essential to innovation in the "real world."

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[5] Adams, James L. 1986. The Care and Feeding of Ideas. Addison-Wesley, Reading, Mass.

- **Reflection vs. Action:** Time and "space" to reflect are essential to invention, but so too is rapid exploration and intensive experimentation.

- **Preparatory Learning vs. Just-In-Time Learning:** Key principles and concepts need to be learned as part of a core curriculum in any domain, but dialogue with inventors reveals that substantial learning occurs on a "just-in-time" and "just-enough" basis – which call for vastly different educational delivery systems.

- **Extrinsic vs. Intrinsic Motivation:** Innovation is driven both the extrinsic and intrinsic motivations – neither can be ignored.

- **Evaluative Assessment vs. Supportive Facilitation:** To promote inventiveness, supportive mentoring appears essential, which points to the need to differentiate and balance formative and summative feedback given to students.

- **Outcome vs. Process Focused:** The aims to produce a final product and the importance of having a successful learning experience are frequently in tension—particularly since there are time constraints on the learning experience.

Future Vision

The workshop began the process of constructing a vision of success that would result from this and other related workshops if the full range of recommendations were effectively implemented. The results of this exercise also provide background for the recommendations and are given here:

- ***Improved Quality of Human Existence:***
    - Much improved societal capability for invention enables continuing dramatic gains in the quality of human existence particularly in domains where society

[6] We define an enduring dilemma as having three elements: 1) A clear choice is involved; 2) The choices have important consequences; and 3) Decisions once made are in important respects irreversible.

is especially vulnerable, including health care, energy, environment, safety and security.

- ***Widely Shared Value Placed on Invention:***
    - The vast majority of educators see the development of capability in inventive creativity as being at the core of educational at all levels—primary, secondary, undergraduate, graduate, and continuing education.
    - The vast majority of citizens have awareness of basic design principles and appreciate the importance of creativity, invention and design in society.

- ***Integration Into Curricula:***
    - There exists a robust combination of courses throughout the curriculum specifically on design, visual thinking and invention.
    - Problem solving, invention and design are a key organizing framework for courses teaching fundamental principles in engineering, and in other domains, including the sciences, the social sciences and the humanities. Thus, direct connections are made between specific principles and personally meaningful application contexts.
    - Systematic building of the capability to explore "why is this the way it is?"

- ***Balanced Individual and Group Development:***
    - Curricula provide opportunities for individuals to develop their own personal "voice" or "style" as a designer, inventor and engineer, as well as an understanding of their own strengths and weaknesses.
    - Curricula provide opportunities to develop the social and technical competencies needed to be a successful member and leader of a design team.

- ***Balance Between Discipline and Creativity:***
    - Appropriate attention is given to the way that disciplined capability can enable pushing at boundaries and thinking "outside the box."

  - Discipline-focused courses also stress the importance of "boundary transgression."

- ***Appropriate Attention to Initiative, Expression, and Pace:***
  - Curricula give sufficient support to individual initiative and self-discovery, without always pre-specifying expected learning outcomes and answers.
  - Expression of ideas is not always bound by pre-determined formats.
  - There are periodic places in an education experience to allow for open-ended reflection and self-assessment.

- ***Aligned Rewards, Reinforcement and Supporting "Infrastructure:"***
  - Educational organizations and institutions have few if any disincentives for teachers and professors to devote the time and energy needed to advance invention in the curriculum.
  - Educational organizations and institutions invest substantial resources to support educational innovation with respect to interactive and self-directed modes of learning, project-based courses, field-based assignments, instructor-to-instructor exchange of learning materials, and other related enablers.
  - Facilitated exchange across primary, secondary, university and industry settings.

- ***No Barriers to Entry in the Profession:***
  - The profession is appropriately reflective of societal demographics—for example, half of engineers and inventors should be women
  - The community of engineers and inventors is characterized by mutual respect, dignity, and appreciation of diversity (in perspectives, background, and other dimensions)

"Free workshops" and "Local invention homes" are widespread, thriving, connecting students at all levels with one another and inventors, and are operating so as to minimize all barriers to entry to the invention profession

Implications and Recommendations

An overriding implication of the workshop results is that inventive creativity should be made an explicit goal of education at all levels. We believe this policy is essential to promote the national and global human quality of life – now and in the future. Recommendations that embody such a policy include placing inventive creativity explicitly into the National Standards for Education for K-12 and into the ABET criteria (university level engineering accreditation) and other higher level education goals. Similarly, inventive output should be explicitly considered and heavily weighted in college admission criteria, educational outcome assessment at all levels, university ratings systems and in teacher evaluations including tenure considerations at the university level.

A further recommendation we strongly propose is the creation of "invention homes" or "free workshops" for inventive activity in all parts of the nation. We applaud the emerging activities of "science and industry/technology museums" in this regard but envision a much more intensive and widespread initiative resulting in centers of significantly varying size. The larger of such centers are expected to host science fairs, FIRST contests, etc. while the smaller ones might host individuals and teams working in order to participate in such activities. We call on industry to play a strong role in creating these local centers where invention is practiced, learned and celebrated. The centers would involve accessible materials, tools and flexible space that are essential to invention. This is an idea we would also like to have foundations and philanthropists consider seriously. We envision something of the significance and scale of the "free Carnegie Libraries" that were so important to educational progress in the U. S. (and U.K.) a century ago.

Teaching and Education Practice Implications and Recommendations

The policy recommendations above obviously require actions at the Educational Institutional level including explicit placement of invention on their agendas. In addition, we recommend that institutions of higher education (particularly engineering schools working with foundations):

- Develop and implement workshops in instruction that utilize interactive modes of pedagogy.
- Lead in development and energetic use of exchange mechanisms for effective teaching of inventive creativity within universities, among universities, between universities and secondary/primary schools, and between educational institutions and industry.

- Initiate joint development of teaching modules by invention-oriented cognitive scientists and engineering faculty for use in invention process-oriented courses. Such course modules would foster the spirit and craft of "purposeful boundary transgression," which is at the heart of invention.
- Develop and implement doctoral qualifying examinations that stress invention as well as analysis.
- Implement tenure criteria that weigh invention, teaching of invention and contextual application at least as highly as deductive scientific achievements and the teaching of disembodied principles.

We also recommend that University level education institutions and foundations jointly and aggressively pursue a new series of learning materials that integrate application context and learning of principles. Such learning materials would provide open-ended problems and environments (utilizing modern computer-assisted learning tools) that should replace the current set of standard assignments in foundation courses. These materials would thus provide the basis for uniting the currently separate activities of application and learning about foundational principles. The problems would be designed to cover the spectrum of learning of principles needed for proficiency in given discipline areas. The model for such an effort is the Ford Foundation support of the Gordon Brown MIT textbook project after WWII that added greatly to the establishment of the national "engineering science" thrust of that era. Other, more distributed models may be possible.

In order to appropriately execute these recommendations, engineering schools will need to foster development of many more courses where the inventive process are fully integrated with learning about fundamental principles. This will require use of creative assignments to drive the just-in-time and just-enough learning modes essential to inventive creativity. This problem-based learning will thus build upon the results from Aalborg University in Denmark that has proven very effective over the past 25 years.[7]

Four other recommendations are intended for all institutions of higher education:

Implement widespread teaching to all students of Visual Thinking as pioneered by R. H. McKim of Stanford 30 years ago,[8] as this is essential to the development of inventive creativity. Visual thinking should grow to balance the necessary but possibly excessive attention to symbolic manipulation and language skill learning that is currently emphasized in education.

- Early, continuous and intensive learning about how things work – for all students, not just in engineering education
- Implement both individual inventive learning courses as well as team invention learning courses throughout all curricula. At present, the tendency is to only stress team design/invention, but this approach is as flawed as would be an insistence on only individual invention. Both are needed in society—they are not alternatives but instead necessary complements.
- Provide easy access to hands-on and individually-driven inventive activities that extend beyond courses.

A final recommendation in the higher education arena is aimed particularly at engineering schools. We encourage a wide-ranging and extensive examination of the current four-year model of engineering education. The practitioner's need for breadth of learning including ethics, business and humanities for the effective practice of invention suggests that a professional graduate school model for engineering education be seriously considered. Currently, there are a range of professional practice degree programs in many engineering schools and these have the potential to become a central vehicle into the profession, comparable to law schools, business schools, medical schools and others.

The implications at the K-12 levels are at least as significant as those affecting higher education and because of the dispersed and extensive nature of the K-12 system, may involve more challenging implementation issues. Only a few of the necessary changes are highlighted here. To

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[7] Finn Kjersdam, Sig Enemark, *Project Innovation in University Education* 1994 : Aalbourg University Press, ISBN 87-7307-480-2

[8] McKim, Robert. 1972. *Experiences in Visual Thinking*. Brooks-Cole.

make the suggested policy change meaningful, perhaps the most important step is to develop and implement workshops to help all teachers learn how to manage/survive/enjoy a chaotic, project-based classroom in which students pursue projects based on their personal passions. Such skills and experience are essential if inventive learning is to be achieved. Effective models for allowing teachers to acquire such skills have been demonstrated in the Carlson and Sullivan initiatives throughout the state of Colorado[9] and by the MIT Edgerton Center interaction with primary school teachers. Both of these programs involve the participation of K-12 teachers in inventive, project-based experiences and are thus successful in allowing them to learn how to run such activities with high reward for necessary chaos.

Our final recommendation for the educational and teaching practice arena is to continue pursuit of sharing and cooperation mechanisms for best-practice teaching such as those established and funded through NSF [10]. These consortia, however, should consciously focus on invention and the successful teaching of inventive skills more so than they have thus far.

Research Implications and Recommendations

Given the importance of invention to the nation and society more broadly, a strong case can easily be made for more research in this area. The recommended actions need not await the results of the research but can proceed and be adapted as new research findings are established. One key area for research is to develop a design-oriented rather than a naturalistic view of knowledge (epistemology). Such a development would help transform much of the way knowledge is thought about and thus taught. A second key area for research is to study metrics of creative behavior that go beyond the current literature on creativity as a personality trait and will perhaps build upon the idea of an individual "invention portfolio" to measure inventive capability and productivity. Such metrics would enable research on environments conducive to invention as well as study of different educational programs on inventive capability and productivity.

[9] see for example http://itll.colorado.edu/ITLL/
[10] see for example http://www.wcer.wisc.edu/cirtl/
[11] Cite to literature on creativity as a personality trait

A further area of useful research would be to study the educational backgrounds of large numbers of successful inventors. The study of "quick learning" techniques used by a similarly large number of inventors would also be of significant use in achieving a deeper understanding of these techniques so important in invention. In addition, careful studies of the diffusion of invention-related educational innovations would be useful in determining the factors important to successful diffusion and the opposing forces most important in retarding the spread of these methods.

A further critical research question involves the effect of stressing self-learning, pursuit of personal passions and invention in education on attraction/retention of students to the technical fields that host inventors. Particularly significant is the influence that such educational methods have on attracting and retaining women and minorities to these fields. Although many workshop participants have reason to believe that focusing on invention in education can significantly contribute to the solution to the barriers to entry problem, there is no incontestable evidence of which we are aware.

We close this section by recommending careful research on the costs of education that is effective in fostering inventiveness as opposed to the costs of education that is ineffective as measured against this goal. It appears quite possible that the mentoring and interaction currently essential to invention learning is more time consuming and costly and if so, research to investigate more cost–effective methods would be appropriate. Over all, it is our strong belief that education which significantly advances inventiveness is clearly cost-effective on a societal basis, even if more expensive on a per-student or per-course basis.

Appendix A: Session Notes, Stories of Creativity and Education Gone Awry

- Back in the early 1980s an experience with a team training workshop doing an "artic survival" exercise where one individual who was not well liked by the group and ignored by them. Yet, he did much better as an individual than the group on this decision making task. When asked by the group how he did so well at estimating what would be needed for artic survival, he said that he was in the military reserves and was an artic survival instructor! The group then asked why he didn't tell them, he responded, "I tried to and you didn't listen, just like you haven't been listening to me for the past ten years."
- Pre-college art education under the influence of psychology to not interfere with natural creativity by exposing to art – we have now learned that kids are stronger than that and can be exposed to art and even technique
- I published the Mind's Best Work a number of years ago and a company had asked for a workshop on creativity. Then over lunch the engineers said that the basic problem was that the chief was jerk – calling people in at any time for a full report on the status a project, instilling fear. It was this chief who had extended the invitation and he never followed through on subsequent workshops.
- Work back in mid 1980s with early efforts to link legos to Apple II computers – when doing this, would work with kids who came up with all sorts of creative inventions. When it came to market, first just to schools, and found a teacher who had proudly demonstrated how all the kids had to follow the rules to build the exact model and then had a test afterwards on what a gear is, etc.
- When I was in High School and College I did not do as well on the verbal part of standardized tests and was directed into engineering, it was not till my 40s that I published my first book (note added later by editor is that this individual has now published at least 10 highly successful books)
- Stifling creativity in the context of engineering science at MIT – a student was not doing well on the problem sets, but said would like to do an undergraduate research project – not typical with the poorest student in the class – but very skilled with his hands and had a grad student who needed help with a wind tunnel and they made a wonderful team – ended up with a masters fellowship and it was the best year of his life
- Had just started teaching in Stanford – teaching the capstone design class – a student had cerebral palsy with difficulty in standing up – advice about which specific approach to use was given as faculty member – I am not happy I told them to go to the safe solution in part because of it being a graded environment – contrast with experience of 15 year child in school now where creativity is being supported – including critiques
- Year after graduating from college took a job teaching art in a parochial school in South Philadelphia – getting ideas from others – wire from telephone company to make sculptures, paper on the walls, and they were not reacting well to this open ended approach – teacher did lesson how to draw a log cabin exactly – and they were thrilled that they could do it exactly – and was deflated
- When I was 14 I had to shovel the driveway, so I build what was perhaps the first snow blower for use in a private home. It worked very well, so I looked around to see if someone would be interested and thought a lawn mower manufacturer might be interested – they gave me 1500 cash and 5% royalties. The first snow storm in Dayton caused a test to be performed but on a gravel driveway and the invention broke the factory windows

- Junior year at Carnegie Institute of Technology, learning to melt iron ore to make iron. I was supposed to follow the instructions and our group decided that we would add more air and prop this up on sticks. And the Teaching Assistant said that in this lab we don't do experiments.

Appendix B: Session Notes from October 18

Welcome

- Fundamental tension between the need for deep knowledge for invention and the need not to stifle creativity

Session 1

William Murphy

- I would like to begin with something we have not dwelled on, but that should be re-considered. First a bit of personal background: My father was a physician and nobel laureate, mother the first female dentist in Massachusetts – grew up with a view that the world was wide open to new thoughts.
- Appalled at the inadequacy of the equipment in my father's hospital – not taking advantage of the capabilities in the engineering world. It was even improper for a doctor to talk to an engineer at the time.
- Went to medical school and then became involved in the first group to develop the first artificial kidney, which I found very appealing. It was with a person who might be considered the founder of bio-engineering, Pim Kolff, from Kapen, Holland and did it under the noses of the Germans without their knowing it. I was involved as a medical engineer and led to my involvement in subsequent dialysis machines
- At the time there was not in the way of support for this type of research in Holland, so Pim Kolff came to the US
- A key question – why was the US so attractive to apply this sort of technology? There is the freedom to do this and the opportunity to get rich. That financial motivation is an important part of what drives innovation.
- We shouldn't forget what deeply motivates creativity – education is important, but that alone won't explain why people struggle so hard with a potential invention
- Much that we take for granted – clean water and so many other things around us – are a product of freedom and creativity
- Others are copying what we do – but we can't forget the motivation to create that is tied to the personal desire to improve personal well being
- This freedom is basic to our success as a nation – we must not lose it – the opportunity for wealth is a key motivation and we need to think about this as we explore what it takes to implement creativity in education
- A fundamental concern with oppression that diminishes creativity – whether from government, schools or other sources

- We talk about "big" and "little" inventions – the idea of treating a patient's blood outside their body is a very creative idea, but the technology to do this was initially very clumsy. It took a team of ten people, five of whom were doctors, working a full day to just treat one patient. Contrast this with a hollow fibre system that a patient can use on their own while they sleep. This took a brilliant beginning and made it accessible to millions of people.
- I have spent my life looking for new ways to do things and this is useless if there aren't ways to apply the creativity – to see it put into use.
- Keep in mind the need to provide the surroundings that encourage and cause people to be creative, but don't forget the intrinsic desire or motivation – the desire to improve one's circumstances. This is built into the soul – to want to have a better life.

Discussion:
- These are very important ideas – consider what it means for education. How to take this into account with the educational process.
- This is a very honest assessment – others may or may not agree.
- The motivation to be creative is empowered by knowledge – the two are inter-related. Consider the Sterling Cycle engine – it depended on advances in metallurgy.
- Many educators see their job primarily as passing knowledge on, rather than fostering creativity. This idea of invention and entrepreneurship has taken off in part because of the environment – we see this at MIT – so the culture does make a difference.
- What motivates people to be creative? Here are some thoughts: Financial gain, improving living conditions (family and community), recognition
- It is generally the case at most universities that the politics of the faculty are against this approach. So the role of wealth as a driver of creativity will generally be discouraged by the climate on campus – perhaps with engineering faculty being more conservative (at least historically so).
- Built in the soul is a desire for a better life – but this means many things to different people – John Dewey comments that the purpose of education is not just to make a living, but also to make a life – this includes creativity
- Recognition of the divergent political dimensions that might flow from these thoughts
- Consider the fundamental issue of the joy of invention and exploration – which seems to hold true for animals as well as people – the opportunity to explore is what behaviorists term a primary reinforcer – an end in itself, rather than a means to other ends. This must have adaptive advantage. Do not neglect the joy of inquiry.
- Consider the distinction between invention and innovation.

Henry Petroski
- I recently wrote a book, *[Paperboy],* about what influenced me to become an engineer.
- Most of my research has been on failure – failure as a motivation to do better.
- I would like to focus on existing university and science institutions that are a barrier to invention and creativity – we learn from a deeper understanding of what we are doing wrong.
- What are we doing wrong?
    - An overemphasis on team projects: Students can go through a curriculum without ever having to do a project on their own. In this context dominant personalities will undercut the learning of others – some end up in managerial roles and others

in more menial roles. In a student team of three people, we may be losing two out of three potential inventors.

- Over 6 million patents have been issued in the US and the vast majority are single author patents.
- When I assign students to work on their own there is surprise that they will not be working in teams – this has now been indoctrinated in primary and secondary schools. Yet many write about the process of individual discovery and learning in their reports.
- Why are students in college? Very few for the pure love of learning – most see this as a vehicle to earn a living.
- If creativity is a part of engineering, then we might look to the fine arts – where the individual is the model. Look at writing, art, poetry, musical composition – these are primarily single individual accomplishments. Engineering is a creative act, like art in this respect.

Discussion:

- At MIT there is a Sophomore individual project and a Senior team project. I was surprised to find that it was the individual experience that was more salient for many students.
- There are people who are not looking for leadership roles – people who do not want to be responsible for failure.
- One area where more work is needed is in assessment of team projects – particularly with respect to individual contributions to team projects. Particularly the role of peers for in providing feedback.
- People differ in their personalities – for example extroverts and introverts – people who get energy form interactions and people who are drained by the same. There is a need for environments where both types of personalities can thrive.
- Research on engineers as a population points to a high percentage of people who score high on the introvert dimension.
- Most engineering projects are extremely complex – so it is rare for one individual to be a sole inventor.
- The very nature of work and society is changing – away from a top-down bureaucratic model and toward more of a network, distributed leadership, team model. Yet, this too still depends on individual leadership and creativity.
- This is not a pure dichotomy between the individual and the team – the two are interdependent.
- Providing the more introverted individual with creative experiences will help them to engage more effectively – it won't change them from being introverts, but it may help them interact more successfully.
- We use a simpler form of a Myers-Briggs tool and it does teach that it takes all types to be successful.

Mitchel Resnick

- This workship is focused at the university level, but I will be bringing in lessons from work with younger kids.
- What are new types of construction tools – legos have traditionally taught kids about structures and constraints on design – lessons about constraints and flexibility.

- We are trying to develop new materials to learn from and play around with dynamics and interaction in the world.
- Consider, for example, programmable bricks – where lego constructions can be programmed to do fun things – with demonstration of two lego carts that dance when they are faced toward each other.
- **Connect powerful ideas with individual passions and interests** – the experience where things went awry included cases where passion or interest was disconnected from powerful ideas.
- Consider what drives people to care deeply – things that are personally meaningful.
- Concern about the focus on building one type of thing – whether it was an exact replication of a lego vehicle or even something more open such as a robot competition – it still may or may not connect for the students.
- Example of workshop with 12-14 year old Girls Scouts building lego house for hamsters, roller blade speedometer, diary security camera – engages learning in key math/science ideas in ways that have deep personal meaning, such principles of feedback and control in mechanical systems
- Project faculty make connections of these personally meaningful projects to powerful ideas
- Example of girls stopping the completion of a merry go round to build a refreshment stand, a wall around the park and other features of the larger context. It would have been tempting to have them focus just on the merry go round to teach principles of dynamic motion, but it is important to hold back and see the whole context come together – providing literal and physical space for learning.
- Recent conference in Singapore to foster creativity in addition to dedication for high scores in math and science exams. Visited a local school and saw the challenges of trying to integrate invention into the disciplined education program by just adding the invention at the end of the school day and not even considering it for insertion in the core curriculum.

Discussion:

- Discussion on the role of an all-girls workshop – with boys more drawn to some of these construction toys. It is problematic to over-generalize around gender differences, but we do observe boys being more likely to focus on the machine that goes faster with the girls more likely to worry about the context as well.
- In teams there are dynamics of leadership that are not necessarily gender based. The issue there is that only some types of leadership are evident in team projects – contrast leadership in writing up results versus leadership in driving the group agenda.
- Another source of inspiration – motivated by the Deadalus articles – seeing kindergarten as a source of inspiration (invented about 200 years ago in Germany, with the focus on pattern blocks and other tools to learn about numbers, size, shape and color in a playful spirit). It is hard to take that approach at other ages. Goal is to see how much can we preserve of the spirit of kindergarten and still foster new skills and capability.
- Concern that being playful is not sufficiently serious – just play might be problematic, it is important to make the connections to larger principles – which is even true in kindergarten.
- Reflection on a school experience that tried to foster the kindergarten experience up through eighth grade – no homework and invention – where the translation to traditional high school has not been a problem.
- Discussion of UK curriculum on design and creativity at all age levels.

- This workshop is focused at the university level – but it would also be helpful to highlight any K-12 implications as well (though this is a vast domain) and any lessons from K-12 for the university level. The two are interdependent.
- National technology framework is near completion – with attributes that could be expected at different grade levels – so we should see if that is linked to principles of invention and creativity. There have been reports on technological fluency that mirror early reports on science fluency ten years ago. These come from very different perspectives – reflecting a larger domain of public perception of science and technology.
- Most important is awareness building on inventive thinking – it is not on the table from a policy point of view. Advocacy of the importance of this dimension is important. The politics of pre-university education are horrendous, but we should at least help get this on the agenda.
- There are basic distinctions between more deductive learning and more integrative learning. The aspect of public understanding of invention is very important – pre-college – in part to help inform people who will later be in societal leadership roles who are not inventors or technologically oriented. Then we get a deep skepticism of new developments – the opposite climate of the 1940s enthusiasm for the potential of new inventions. There may be one required college course in mathematics or science, but that may have no content relating to technology and invention.
- Invention and creativity are not specific to technology – they pervade our lives – a key is raising the consciousness of the general population about the ways that they are creative and innovative in a general way. New book on *Small Things Considered* by Henry Petroski around the fact that designs are not perfect. Ordering from a menu in a restaurant does not produced a perfect meal but it is still a successful creative process. There is public receptivity to these ideas – beyond the engineering world – it takes helping people to see what they do in their own lives. In this sense, engineering is a basic human endeavor. Don't complicate it too much – it is complicated in carrying out the details, but the basic concepts are not complicated at all.
- Issues of risk in medical devises is central – educating people that there is always risk is important.
- Fundamental biases in human decision making that involve being risk adverse.

Key themes so far:
- Motivation for individuals to improve their circumstances – deep in the soul. Don't forget about the importance of financial motivation.
- Appreciation for individual accomplishment and creativity, not just team accomplishment and creativity.
- In education we must connect to powerful ideas and to individual passion. Appreciation for fun, but making deeper connections to powerful ideas and passion.
- Underlying concern with the individual in context.

Illustrative Video Tapes
- How Fast is Fast – MIT Video on Doc Edgerton and strobe photography.
- Hard work and playful joy of living – linking the science of electricity with the art of photography.

- ***Edgerton Quote: "The trick to education is to not let the students know they are learning something until it is too late."***
- "Bring the real world into the classroom and provide lots of encouragement."
- "It is exciting to help people see something they never saw before – to see them learn."
- "If you are not actively testing your ideas you are wasting your time."
- "Every experiment is a success – the ones that don't work out often teach more than the ones that do."
- "Work hard and have fun – tell everyone you know. Close a deal with a handshake. Believe in your ideas."

Discussion:
- Doc Edgerton grew up in a small farming town and was probably educated at lest partially in a one-room school house
- Story that his tenure case was difficult – he was an inventor, not a scholar – an issue to return to around inventiveness in the university

Session 2

Joel Cutcher-Gershenfeld
- Personal experience with what was termed the "quality of work life" movement – fostering employee involvement to value people's heads and hands
- Experience fostering creativity in the context of adversarial bargaining, reflected in co-authored book – Strategic Negotiations (1994)
- Focus on the cross-cultural diffusion of innovation, as reflected in the co-authored book – Knowledge-Driven Work (1998) – which was also written as a team of 12 authors (all writing together)
- Research on knowledge and skills in the aerospace industry, as reflected in the co-authored book – Lean Enterprise Value (2002) (also a team project with 13 co-authors), including fundamental issues of impending retirements and changes in the decline in opportunities for new products and platforms on which to work
- A concern with engineering educational innovation, as reflected in the MIT Engineering Systems Learning Center (ESLC) – with dual mission of advancing "engineering systems" as a field of study and helping to transform engineering education
- Forthcoming book on organizational learning, Valuable Disconnects (2004) that highlights the importance of learning from disconnects
- Underlying concern with fundamental assumptions about people and work, as reflected in commissioned Sloan 50th Anniversary paper

Discussion:
- The notion of creating and sharing learning materials links to the experience with NEEDs – National Engineering Education Delivery System – with limited success in fostering exchange
    - Idea to make innovation accessible – such as mechanical dissection and electro-mechanical systems
    - Not transportable as a full course – had to be transportable

    - There is continuing NSF funding through Berkeley
    - There are also issues of quality and recognition
    - Annual award with John Wiley – for curriculum with pedagogy materials and a review panel

Christopher Magee
- What special attention should be paid to the most talented students?
- Distinguish between the expression of creative talent and the enhancement of creative potential
- Can non-creative teachers teach about creativity?
- How to assess the depth of science education in the post-Sputnik era?
- Importance of teaching visual thinking and the use of active problem-solving.
- What are the constraints on the diffusion of innovative educational materials.
- The art of teaching analysis at a level so that it is simple enough to be fully grasped, but complicated enough so as to reflect reality
- How to recognize and measure creativity?
- Sharing of modular learning materials to connect cognitive science findings with engineering work around invention and creativity
- Neglect may be the most serious barrier to inventive creativity
- How to deal with the view that, "anything that students enjoy can't be a serious educational activity?"
- ABET – the engineering education accreditation agency – is a potential enabler and barrier
- The importance of connections to the humanities

Discussion:
- How much serious thought is being given to radical change in engineering education – certainly there is debate around the degree to which engineering should be predominantly a graduate or an undergraduate activity (note the contrast to the legal or medical models at the graduate level).
- If engineering were to shift to the graduate level, there might then be more of a focus on humanities education at the undergraduate level, but with more technology integration
- Note that MIT almost became a graduate program at Harvard University, but this was blocked in the early 20th century by the Massachusetts Supreme Judicial Court.
- Carnegie Funded research at the graduate levels has surfaced dissatisfaction with graduate curriculum after the first year – so that would require thought about what would be an alternative education model
- Issues of life-long learning and institutions that are oriented that way
- Contrast between expanding the scope of engineering and integrating engineering in other domains – Rosalyn Willams book on "Retooling" focusing on the integration of engineering into humanities curriculum
- What is the best way to frame this – there will be more societal support for broader exposure to engineering ideas and more controversy about making engineering more professional
- Key issue of instilling pride and professionalism among engineers
- We are highlighting multiple audiences for this report
    - National Academy Engineer 2020 report – intended to be revolutionary, but is too complicated

    - Ultimate audience are the policy makers – university presidents, NSF and other funding agencies, and others
- Many important issues raised about engineering education – one big change at MIT was with the "Lewis Report" that elevated the importance of humanities (which also maintained the four-year model)

Decker Walker
- Program in Learning, Design and Technology at Stanford
    - In the school of education – with the technology focus primarily on information technology.
    - Aim is to prepare people to develop innovative materials using interactive computer-based technologies.
    - A one-year program bringing in people from museums, publishers, and many other settings
    - At the core is a focus on learning – so that design teams have deep knowledge about learning (not just content experts and graphic designers).
    - Point of reference should not be primarily centered on books.
    - Students begin with real design problems that continue throughout, but also with core principles of learning (socio-cultural, psychological, etc.) that also continue throughout.
    - Example of a project with Stanford on-line to help professors and TAs to be effective in an on-line learning environment – this is comparable to an engineering design problem – identifying design objectives, constraints, etc.
    - There is a focus on multiple perspectives in the design and on a range of different responses from users (getting beyond the view that "all users are like me").
    - Finally, a focus on a learning community – valuing a range of skills in programming, design, and other domains.
    - Also, self-organized seminars in which students share expertise and opportunities to do a self-directed design project
- Key principles around invention and creativity
    - Initiative: Students take the initiative – not just having faculty assign the projects and structure the course of study
    - Expression: We teach symbols for writing, math, and others, but mostly teach how to use these to solve problems that we set for the student. Invention should mean using the symbol set to solve problems of the student's own choice in their own way.
    - Pace: The constant rush through the program – the main differentiator of success at a place like Stanford is sustaining the pace for a large volume in routine learning. Changing the pace is key – to circle back to ideas, focusing in on a detailed problem, and understand deep ideas.
    - Shift Context for Application of Ideas: Gain deep understanding of a discipline by applying it to other disciplines. Apply physics to biology. Beyond compartmentalization of knowledge – minors required in different domains where you apply what you know from your major in the minor domain. This would strengthen work in the discipline.

Discussion:

- The power of analogies as a way of learning – more powerful understanding where you see things out of context (not bound by your assumptions).
- Architecture is an interesting domain as a complementary field for engineering. Most architectural training is humanistic – how buildings fit into particular social contexts – something that has not been emphasized as well in engineering.
- The media lab at MIT does operate in this spirit. This form is less important than the broader principles.
- A key theme is to counter the narrowing of engineering.
- When you learn to paint to begin by painting pictures rather than by learning to do parts of a painting and only doing a full painting in your senior year.
- Example of the toy symphony – were you could begin as a composer.
- What is the capacity of faculty to teach in these ways? We are trained and promoted based on deep skill in reductionist thinking.
    - One reinforcing feature is the enthusiasm of the students – the problem looks more fearful in anticipation
    - In fact it is remarkably self-managing in operation
    - There are trade-offs as you scale up from 15 students to 50, for example
- There are core issues around rewards and reinforcement for faculty, issues coordination of cross-disciplinary teaching teams, and other matters

ABC News Video: IDEO Shopping Cart Re-Design

- Being playful is hugely important to innovation
- Fail often to succeed sooner

Learning Materials Exchange:

- Examples:
    - Egg Drop Exercise
    - Origami Ball Exercise
    - Card Tower Exercise
    - Delta Design Exercise
    - Lego Car Building Exercise

Discussion:

- Design competitions raise issues around how many can win
- Issues of pitting designs against each other
- Is competition good or bad for creativity
- A key motivation for creativity is that the work is public – so this is a competitive driver
- How to learn about the real world environment where there are proprietary ideas that cant' be given away
- What you want at different stages of learning may be different – you don't want to always go to a full competitive model when learning fundaments
- Yet, the real world is full of competition
- Consider the work of people such as Alphie Cohen in the book *No Contest* who have challenged the educational value of forced competition

- Issues of design evolution and roles that require estimates and calculations that depend on "freezing" the design
- Development of rules and guidelines that are derived from the experience to guide subsequent design work
- All creativity design exercises have some form of constraint and some form of design objective – key issue around cross learning
- Ability to "patent" ideas in Lego car building exercise where others have to give up points to copy your idea

Session 3

Sheri D. Sheppard

- Taking Stock: A Look at Engineering Education for the 20^{th} Century and Beyond – sponsored by the Carnegie Foundation
- The foundation has a long history of studies on engineering education – including the Carnegie Classifications for educational institutions and research on scholarship (issues of scholarship on discovery, integration, application, teaching)
- Preparation of Professions Project, begun in 1997 on law, engineering, and clerical education
- Commonalities:
    - Service to others
    - Theoretical understanding
    - Domain of professional practice
    - Domains outside of professional practice
    - Professional community
- Key question: What are teaching and learning attitudes and present practices in current undergraduate education, especially with regard to the development of professional engineering practitioners?
- Proposed (ideal?) model:
    - Four quadrants:
        - Communications
        - Knowledge
            - Science, Math, Social science, Ethics. . .
        - Engineering Mindedness
            - Optimism, perseverance . . .
        - Continuing to learn
    - At the core:
        - Problem solving – the four quadrants are all in service of problem solving
- Three problem solving domains:
    - Problem solving with evidence – labs
    - Problem solving with models – analytic models
    - Problem solving with ideas –design classes
- In fact, the engineering curriculum is not balanced across these domains – over 60% is work with models
- How to mimic authentic engineering work
    - Thoughtful ambiguity

    - Real world needs
    - Real world hardware
    - Product and process focused – how you get to the answer is as important as the answer
    - Students engaged in the work
    - Students work on "what is the problem?"
    - Engages students in multiple activities – reflecting multiple ways of learning
- Example from engineering statics – 100,000 text books a year – focused on the Newton's first and third law – systems in equilibrium
    - Appreciation of the role that analysis and modeling play in design
    - Analytic skills as related to the evolution of structural integrity
    - Ability to communicate about systems using mathematical and visual means
- Use of real world examples and real world items – Hyatt collapse, teeth on a bike gear, etc.
- Transformation of traditional lecture-based classes
- National Science Foundation Center for the Advancement of Engineering Education

Discussion:
- This has to integrate across all education courses – not just a little bit of the curriculum
- One of the problems with engineering curricula is that students drop out – does this way of teaching statics increase retention?
- Additional motivation given the demographics in a number of professions – for example the aerospace workforce (professional, technical and production) faces what we have termed a "demographic cliff" with somewhere between 30% and 50% of the workforce is eligible to retire in many facilities and the training apprenticeship programs and degree programs have fewer people in the pipelines
- Also major challenges as jobs are moving off-shore

David Perkins
- What can be said about teaching innovative thinking?
- This builds on teaching instructional design, which I have done for many years, and research on innovation, which I have also done
- Story in six questions:
    - How can one foster creativity and deep learning at the same time?
        - Idea to teach "inventive" thinking and to be open to many dimensions of invention
    - Why is this the way it is?
        - Bring together the process of invention with an inventive mind-set – asking basic questions about design, materials, features, and other aspects of every day objects – a well as other matters, such as why is there a line at the bank?
    - How could it be different? How could it be better?
    - Can you design a gadget to pick apples from a tall tree while you are standing on the ground?
        - Aim to root knowledge in tasks that did not require technical knowledge
    - Can you design a table for a very small apartment where most of the time you don't have room for it?

        - Question given to treatment and control groups – groups that had instruction gave far more detail (materials, how things were fastened together, etc.), were more buildable, with twice as many features incorporated to help address the problem of the small apartment
    - Where can you find designed ignorance?
        - Governmental forums, government structures, security systems, mystery books, personal choice to not know certain things, and an alarming number of examples in everyday life
        - Book on *Knowledge as Design*
- Morals
    - Foreground powerful questions (why is this the way it is?)
    - Join the process of invention and the process of understanding something from a design perspective – joining invention and analytics
    - Cultivate not just knowledge and skills, but dispositions (what Dewey called habits of the mind) – attitudes of open-mindedness, curiosity, problem solving
    - Foster the spirit and craft of purposeful boundary transgressions
    - Foster not just individual and group creativity, but a pervasive culture of creative learning in the classroom, organization and community
    - Reach for a design-centered rather than a naturalistic view of knowledge and understanding (epistemology) that cuts across all disciplines
        - The dominant paradigm is centered on the natural sciences, but a strong case can be made that this is a mistaken view – design in context with purpose is much more characteristic of the human experience

Discussion:
- Incentives for invention is a key additional dimension – schools (secondary and universities) are not as good on this
- Broad goal of designed creativity is laudable – but question about the model of a single course
    - Trade-offs between a separate design course and integration of design into courses on other topics
    - The pure infusion approach alone doesn't take since teachers have other priorities
    - It is the combination of stand-alone courses and bridging
- Is invention the same as design? What about the word "engineering?"
    - Design involves making things that serve purposes – which may be tangible items, interactive processes and many other things
    - Some designs involve more radical boundary transgressions and hence more invention
    - Design can be predicted in terms of time to accomplish, while invention has more unknowns
    - One view suggests that engineering involves the use of materials, methods, and technologies that are known
    - Certainly everything we do involves design – science is applied engineering
    - Invention is less predictable – Engineering was defined in the 19th century as the art of directing the great sources of power in nature for the use and convenience

of man – which is more integrative and has values embedded in it, which can change over time
    - Importance of design criticism – just like art criticism
    - Design can have some unpredictable elements, but that is where it turns to invention
    - Invention as the creation of something new and original, not previously known or existing
    - Is it a continuum:

      Design ←→Invention
    - Design can have specifications, while invention may not and need not
    - Inventiveness is a mindset

J. Kim Vandiver

- Empowering students to pursue their passions
    - Began with self-selected Experimental Study Group (ESG) of about 50 students
    - Key example of students self-motivated to teach a subject on a given topic (such as kitchen chemistry topic)
- Edgerton Center
    - Hands on project center for MIT students – shops with tools have vanished
    - Centralized support for student teams
    - Solar electric vehicle teams
    - Robotics and electronics cooperative
        - bathroom.mit.edu
    - MIT Rocket Team
    - Project ORCA – autonomous underwater vehicle
    - Mars Gravity Biosatellite
- Student competitions are not risk free – it requires constant attention around what you are allowing students to get into – issues around how to manage risk in this context
- No course credit – all about passion and incentive
- Link to Lemelson undergraduate prize – Amy Smith winner in 2000 for work with appropriate technologies for use in developing countries
- Service Learning at MIT:
    - MIT Public Service Center linked to The Edgerton Center
    - For subjects that already exist – develop design project that will help people with real problems
    - Particular links with international students in service of home community
    - IDEAS Competition – public service projects to address community needs
- Balance between competitive, but nurturing and empowering environment – with a clear social purpose
- Note as well UROP – undergraduate learning opportunity to work on faculty projects for pay or credit – the discovery that can take on a project and succeed – all about self confidence.

Discussion:

- The importance of mentoring at all levels

- Question about long-term assessment of undergraduate research programs – hasn't been rigorous, but there are careful records and surveys to seniors and alums do track UROP experience
- Undergraduates have more unencumbered, inventive enthusiasm than the graduate students
- University research is a chance to apply skills to real problems
- 80% of undergraduates do at least one UROP
- Value of students who get wired into a project early in their experience and stay for many years
- Also value in students working in a lab and discovering that this was not a domain in which they wanted to work in later life
- UPOP program in engineering – undergraduate practice opportunities program that involves a week in January and the potential for a summer internship
- Issues around field projects:
    - Capstone design course for senior at Stanford are all industry sponsored projects
    - Requires instructors ensuring that the project is not on the critical path for the company and the company recognizing that they are contributing mentorship
    - Principle of being a good camper (leaving the woods as you found them) – "do no harm"
- Lemelson High School Program
    - Sponsorship for invention teams – now working with 10 high schools – focused on inventing something of value to community or school – with a budget and staff support for regular communications
    - Enough funding to build up to 25 high schools – raising issues of sustainability
    - Variation on whether it is in the class versus as an extra-curricular activity (linked to engineering and robotics clubs)
        - May be more sustainable where in the curriculum
        - Growing federal support for after-school programs in school buildings – 21st Century Department of Education initiative and similar potential for interest in NSF and the Fund for Improvement in Post-Secondary Education
- Discussion of contrast between metrics and English units

Emerging Categories, Themes, Frameworks and Findings

- Learning by doing
    - Design puzzles in facilitating this form of learning:
        - What types of experiences are appropriate?
        - Where do the mentors and teachers come from?
- Teaching visual thinking
    - Learning how to convey an idea with drawings and by other means
    - Learning to observe
- Iterative design cycles
    - Rapid proto-typing
    - Enabled by visual representations
- Participation in "real" projects with more experiences mentors
- Connecting powerful ideas and passion
    - Role of values

- Invention could be at the core of every aspect of the education curriculum – not just and add-on component
    - A different type of problem solving
    - Central to understanding who we are and what we are
    - The ability to ask why is this so?
- Design is ubiquitous throughout human history
- Challenges of educational reform
    - Time constraints for faculty
    - Promotion and tenure decisions
    - Limited number of years available for education
    - An over-determined system – many constraints on innovation
    - Sneak it in as non-credit activity (MIT UROP determines credit (if it is for credit) only at the end to be sure it is a fair representation of what emerged)
- Inventiveness and creativity can be learned
    - Corollary – it can be taught
- Compare against "seven" morals
- Collaborative nature of invention and the individual nature of invention
    - Interdependent
- Discipline as a barrier and an enabler for creativity
    - The way imposed discipline can stifle creativity
    - The way depth of discipline can enable creativity
    - An enduring dilemma
- Different ways that the ideas fit into the structure of our education
    - Implications for what are already design courses
    - Implications for courses that might have design integrated in
    - Implications for learning outside of formal courses

Towards a Success Vision: If this and other workshops are fantastically successful, what would be the implications for education over the next decade?

- We will stop total dependence on the computer – we will see more of core capabilities like hand drawing – these ideas are ubiquitous to human development
- 50% of engineering students are women
- Able to live 150 years and be productive for 145 of those years
- An economy with a higher proportion of jobs oriented toward better design
- A survey of teachers at all levels of the education system have over 90% seeing design as central
- Another survey of the broad public has 90% seeing engineers (not just scientists) as creative
- An unlimited source of energy enabling our society
- An understanding of the appropriate place of engineering and creativity in the curriculum
- K-12 education giving equal status to engineering/design
- Three times as many people in congress with engineering backgrounds
- A broadly distributed capability to ask "why is this the way it is?"
- A sense of quality of design that is closer to the surface (contrast with the pervasiveness and acceptance of bad design)
- A richer, fuller life of engineering graduates as a result of feeling and being creative

- A national understanding of the importance of invention and innovation in the quality of life – in this country and the world
- Our society focused on the things that are important to the success of our society – for example, the availability of energy or the continued assurance of oxygen to breathe
- Crisp and clear findings that have impacted policy and the work that people do

Session results from October 19

The remaining notes started from Elements in specific topical areas prepared by Joel Cutcher-Gerschenfeld on the early morning of October 19 and the notes below were derived from that framework during the regular workshop session that morning.

<u>Potential Elements of a "Problem Statement" on Education for/on/and Inventive Creativity</u>

- **Threats to the Quality of Life:**
  - Fundamental social, technical, economic and environmental challenges threaten our stability and the quality of life.
    - More specifics on energy shortages, etc. so a continuing need for investment and attention to inventive activity
- **Valuing Science and Entrepreneurship, but not Engineering and Design:**
  - Society celebrates successful scientists and entrepreneurs, but does not give the same appreciation to the work of engineers, designers, and inventors.
    - Issue around need for deeper appreciation for design – question whether there really is an issue with invention
    - Pervasiveness of science education, with relatively little space for design and invention – especially in K-12 – place for more engineering at earlier ages
    - Edgarton quote
- **Overemphasis on Deductive, Science and Discipline-Based Learning:**
  - A deductive, science and discipline-based approach to education is pervasive, while inter-disciplinary, problem-driven, design-oriented learning is less common.
- **Imbalance Between Individual and Group Development:**
  - At some grade levels, stages, or other aspects of the educational process, the emphasis is primarily on individual learning, while other settings have tilted heavily toward group or team-based learning – with insufficient attention to the effective integration of both modes of learning.
- **Imbalance Between Necessary Discipline and Essential Creativity:**
  - Too often, learning tilts too heavily toward either the repetitive building of disciplined capability or too heavily toward flexible learning aimed at pushing outside boundaries and thinking "outside the box." Either the emphasis on discipline stifles essential creativity or the emphasis on creativity erodes commitment to necessary discipline
- **Inadequate Attention to Initiative, Expression, Pace and Application Context:**

    - Too often, curricula to do not give sufficient support to individual initiative and self-discovery – expected learning outcomes and answers are specified in advance.
    - Expression of ideas is often bound by pre-determined formats.
    - The rapid pace of learning does undermines open-ended reflection and self-assessment.
    - The application context is too often remote from the specific principles being taught.
- **"Islands of Success," but no Broad Diffusion:**
    - There are identifiable "islands of success" where the teaching of design, engineering, and creativity has been done well and the results have been transformative.
- **Misaligned Rewards and Reinforcements:**
    - Rewards and reinforcements require most educators to assume some personal risk in emphasizing engineering, design and creativity in their teaching
    - Criteria for tenure
- **Inadequate Supporting "Infrastructure:"**
    - There are insufficient mechanisms to help instructors develop the capability to foster interactive, self-directed learning
    - There are insufficient mechanisms linking together instructors who are innovating in the way that they teach about design, engineering and creativity
- **"Disconnects" Across the Educational Landscape:**
    - Innovation in primary, secondary, undergraduate, graduate and continuing education are largely unconnected, with many lost opportunities
- **Barriers to Entry:**
    - Educational opportunities to learn about design, engineering and creativity are less available to women, minorities and the poor
    - While the culture of the engineering and design professions has been changing, there are still barriers encountered by women and minorities

Additional Discussion:

- Concern about the close parallel between the problem statement and the future vision – perhaps there is a more integrative way to state the future vision
- Personally meaningful – engagement and motivation as overarching themes
- Education today doesn't allow individuals to develop sufficiently their personal passion
- A need to be able to be crisp to engage the problem list – caution against too long a list

Need to surface the critical few – but also capture the wisdom of the full group

Potential Guiding Assumptions on Education and Inventive Creativity

- **Central to Human Existence:**
    - Design, engineering and innovation are and always have been a defining feature of human existence.
- **Principles and Skills can be Taught and Learned:**
    - Design, engineering and creativity principles and skills can be taught and learned.

- Mentoring is critical.

- **Interactive and Self-Directed Learning:**
  - The process for developing design, engineering and creativity capability must involve interactive and self-directed modes of learning.
- **A Spectrum of Design:**
  - Routine problem-solving and invention represent opposite ends of a continuum, with increasing specification and predictability associate with routine problem-solving and increasing flexibility and uncertainty associated with invention.
- **Motivation to Innovate:**
  - The motivation to innovate is inextricably linked to the larger motivations, including the motivations for financial gain and other improvements in personal circumstances, as well as the motivation of "big ideas."
- **Attitudinal Disposition to Innovate – Mindsets, Habits of Mind**
- **Values, Design, Engineering and Innovation:**
  - It is essential to explore the larger purpose or aim of design, engineering and innovation, which is fundamentally a subjective, value-based discussion.
- **Incremental and Fundamental Changes in Educational Institutions and Practices:**
  - Proper attention to education and inventive creativity will likely require a mix of incremental and fundamental changes in educational institutions and practices.
- **Fundamental Changes in Work, Organizations and Society:**
  - The need for deeper engineering and design awareness and capability is increasing as a result of fundamental changes occurring in work, organizations, and society.
- **Failure and Risk in Learning**

<u>Additional Comments:</u>

- It is problematic to lump together design, engineering, innovation, invention, and creativity
  - Engineering has a different connotation as an established discipline, for example – there is less of a home for invention and creativity – engineering is one place for application, particularly with respect to engineering design
  - Re-invigorating engineering around invention is one aim
  - Extension of invention to all aspects of society is another
  - Rejection of the societal view of engineering as just routine
- The major focus should be on invention
- The issue of the relationship between engineering science and invention – engineering science comes after the fact of invention (more oriented around controlled processed) – but note that there are many definitions of engineering science
- Engineering science is to engineering as medically oriented physiology is to the practice of medicine
- Parallel between routine and adaptive learning at the individual level, as well as phases in the life-cycle of an entire industry – there are "boundary transgressions" at all times, but they are smaller or larger
- Actionable implications for engineering education

- Striking parallels to debates along these lines in other disciplines – these are enduring dilemmas
- Are the science and design in opposition – or is there a push for appropriate accommodation – indeed, the two are interdependent – they complement each other
- Within engineering design – there is much that can be done in a more routine way to improve the approach

<u>Enduring Dilemmas on Education and Inventive Creativity</u>

- **Individual and Group Capability:**
    - Creativity and innovation depend on developing both individual and group capability, with a constant tension and synergy between the two.
- **Discipline and Open-Ended Exploration:**
    - Discipline and Exploration have the potential to be both barriers and enablers for each other – and both are essential to creativity and innovation.
- **Cooperation and Competition:**
    - Competitive pressures can be powerful motivators and powerful inhibitors for learning about design, engineering and invention. Cooperative processes are essential to design, engineering and invention, which can be both undercut and reinforced by competitive dynamics
    - Competitive pressures and cooperative partnership are both essential to innovation in the "real world."
- **Reflection and Action:**
    - Time and "space" to reflect are essential to invention, but so too is intensive experimentation and application
    - Teaching as an activity versus theory and principles
- **Extrinsic and Intrinsic Satisfaction:**
- **Evaluative Assessment and Supportive Facilitation:**
- **Summative and Formative Feedback:**
- **Outcome or Process Focused:**
    - Is the aim to produce a final product or a successful learning experience

<u>Additional Discussion:</u>

- The role of design theory and principles
- Attend to the role of dilemmas in advancing recommendations – this is not a reason to do nothing, but a way of moving forward mindful of the trade-offs and hard choices
- Education around Invention involves the successful negotiation or engagement of the dilemmas
    - Learn from past experience with negotiating or capitalizing on the dilemmas – and fund new ways to do
- More space in the curriculum on invention is a motivation for the focus on discipline and fundamentals
- These dilemmas are manifest in industry as well
- These are false oppositions – a key thought for introductory paragraph
    - A design problem

Elements of a Future Vision on Education and Inventive Creativity

- **Improved Quality of Human Existence:**
  - Excellence in engineering, design and innovation enable dramatic gains in the quality of human existence – aim for gains in the domains where society is particularly vulnerable, including health care, energy, environment, safety and security.
- **Widely Shared Value Placed on Engineering, Design and Innovation:**
  - The vast majority of educators see the development of capability in design and creativity as being at the core of educational at all levels – primary, secondary, undergraduate, graduate, and continuing education.
  - The vast majority of citizens have awareness of basic design principles and appreciate the importance of creativity, innovation and engineering in society.
- **Integration Into Curricula:**
  - A robust combination of courses specifically on design and innovation, as well as attention of engineering, design and innovation principles and concepts in course work in other domains, including the sciences, the social sciences and the humanities.
  - Systematic building of the capability to explore "why is this the way it is?"
  - Attention to different ways that the ideas fit into the structure of our education
    - Implications for what are already design courses
    - Implications for courses that might have design integrated in
    - Implications for learning outside of formal courses
    - Implications for underlying institutions
- **Balanced Individual and Group Development:**
  - Curricula provide opportunities for individuals to develop their own personal "voice" or "style" as a designer and engineer, as well as an understanding of their own strengths and weaknesses.
  - Curricula provide opportunities to develop the social and technical competencies needed to be a successful member and leader of a design team.
- **Balance Between Discipline and Creativity:**
  - Appropriate attention is given to the way that disciplined capability can enable pushing at boundaries and thinking "outside the box."
- **Appropriate Attention to Initiative, Expression, Pace and Application Context:**
  - Curricula give sufficient support to individual initiative and self-discovery, without always pre-specifying expected learning outcomes and answers.
  - Expression of ideas is not always bound by pre-determined formats.
  - There are periodic places in an education experience to allow for open-ended reflection and self-assessment.
  - Connections are made between specific principles and potential application contexts.
- **Aligned Rewards, Reinforcement and Supporting "Infrastructure:"**

- Educational organizations and institutions have few if any disincentives for teachers and professors to devote the time and energy needed to advance engineering, design and innovation in the curriculum.
- Educational organizations and institutions invest substantial resources to support educational innovation with respect to interactive and self-directed modes of learning, project-based courses, field-based assignments, instructor-to-instructor exchange of learning materials, and other related enablers.
- Facilitated exchange across primary, secondary, university and industry settings.

- **No Barriers to Entry in the Profession:**
    - The profession is appropriately reflective of societal demographics – for example, half of engineers and inventors should be women
    - The community of engineers and inventors is characterized by mutual respect, dignity, and appreciation of diversity (in perspectives, background, and other dimensions)

Additional Discussion:

- Reminding people of the history of educational institutions – bringing an agricultural workforce into an industrial society, with the need now to bring school girls into the knowledge economy
- Strong rhetorical pattern – agriculture – mass production – invention – sources of wealth in each era – knowledge society vs creative society

Selected Powerful Questions:

- Why is this the way it is?
- In your design experience, what worked well? What was difficult?
- If this design is successful, what is the best that could happen? What is the worst?

Implications and Recommendations:

Theory/Research Implications:

- Reports documenting inventions routinely – established protocols and archive – web-based format to learn from the work of inventors
- Highlighting evidence that creativity can be taught – to respond to skeptics and empower advocates
- Developing ways to measure and assesses creativity in the context of technological design
    - Metrics and other ways to achieve judgment
    - Beyond the literature on creativity as a personality trait
    - Beyond the biographical inventories
    - Consider portfolio assessment tools
- Research on the educational background of inventors
- Research on what environments and infrastructure is conducive to invention
- Research on diffusion of innovations in educational – K-12 and in higher education

- Importance of understanding better the process of "quick learning" to develop sufficient mastery of advanced ideas to be of service to the invention
    - Just-enough learning (instead of just-in-time learning)
    - Linked to a built in drive to be creative

Policy Implications:

- Establishing environments that are conducive to invention
    - Comparable to the Carnegie libraries in every small town
    - Experience with museums and computer club houses – community centers, boys and girls clubs, girls and boy scouts
    - Role of corporations
- Role of innovation in educational testing, college applications, and curricula bodies
- Addressing the goal of placing invention on the policy agenda – ABET (higher education), National Standards (K-12) – a necessary, but sufficient condition

Implications for Practice:

- Implications for what are already design/invention courses
    - Articulating foundational principles
    - Should this be a capstone for curriculum already taught?
    - When to best learn about boundary transgression?
    - Consider the contrast between paper designs and building prototypes
        - Issues of space and facilities (in radiation lab each engineer had a workshop outside of his office – Carnegie Mellon experience with CNC)
        - Issues of time to fail
- Implications for courses that might have design/invention integrated in
    - Use creative assignments as the motivator for just-in-time learning – a core dilemma in that this motivates the learning, but it can't just run free and result in gaps in the knowledge (example of new aircraft structures course at MIT)
    - Use of problem-based learning – problem of being reasonably comprehensive by being given an appropriate spectrum of problems (Finish model of 25 year old model for the full university – contrast with the University of Copenhagen – but very labor intensive)
- Implications for learning outside of formal courses
    - Opportunities for just-in-time learning for inventors
        - The internet is a powerful resource that can be leveraged
        - Issue of IP rights in being of service to inventors – concerns about loosing control and rights
- Implications for underlying institutions
    - Higher education
        - Workshops in interactive modes of pedagogy
        - Doctoral examinations reflecting design and invention
            - Many cases of encouragement and discouragement of invention at the doctoral level
        - Beyond the "problem set" as the primary mode of application of engineering principles

        - Use problem sets because they are easier to manage – reinforcing points and tracking progress in a limited way
        - Provide open-ended problems and make them as accessible as are the current problems and texts
        - An opportunity for a large grant – comparable to Gordon Brown text book project at the end of WW II
    - K-12
        - Workshops for teachers to know how to manage a chaotic, project-based classroom
        - Internship opportunities for teachers in industrial settings where invention is taking place (Larry Carlson and Jackie Sullivan in Colorado with integrated teaching and learning lab; strategy at Edgerton Center with primary school teachers – where MIT faculty and students are modeling these new behaviors)
    - Industry
        - Knowledge management systems – to hook people up with others who have needed expertise
        - Knowledge management systems that capture lore and expertise
    - Additional Institutional Implications:
        - Issue of access to tools to do fabrication – where there are safety issues – example of Bill Murphy company that supplies small quantities and unusual materials
    - Opportunities in work with plastic as a medium for fabrication
    - Appointment, promotion, and tenure criteria
    - Recognition for scholarship of innovation and scholarship of application
    - Labor intensive nature of educational innovations – potentially a dilemma

<u>Initial Comments:</u>

- The Overall Architecture:
    - Guiding Assumptions
    - Enduring Dilemmas
    - Problem Statement
    - Future Vision
    - Implications and Recommendations

Advancing Inventive Creativity in Education

- Educational approaches supporting the development of inventive creativity

Concluding, Integrative Comments and Reflections on the Workshop

Sheri:

- A productive session – my head hurts, which means that new stuff is looking for a place
- How to integrate this with the Carnegie report
- Keep the message simple and concise

Henry:

- This has been a very interesting workshop with many different perspectives
- A need for more focus – are we helping inventors or encouraging invention – I think the latter is the key and that should be our focus – students who don't yet know that they can be inventors
- Emphasize to the outside community the importance of invention to the quality of life

Mitch:
- I really enjoyed the last two days – many provocative issues
- There is a tension between being simple and focused and thinking big (be focused, but not necessarily narrow)
- It is important to rethink core design courses, but more exciting is the integration across the full curriculum
- Influence across K-12 and higher education
- Emphasize what is personally meaningful – pull from society and push from the individual
- We must go beyond the current situation of having the best educational experiences only being in kindergarten or graduate school.
- Alliances with people who have been loosing out for 100 years in educational battles – but with a fresh, new issue that doesn't have the baggage of the past

Bill:
- The basis of this effort is to improve life for us humans, though creativity and invention
- Some people are inherently creative – what is best to prepare these people to be successful – as well as to open windows for others to be creative
- Importance of visiting factories – example of buying a car and being able to visit the factory where it was built
- Importance of opportunities to use your hands – not withstanding the constraints of the legal profession
- Importance of the ability to visualize – teaching visual thinking – envisioning a design and then manipulate it (whether on paper or on a computer)
- This gathering of different outlooks here is very valuable

Kim:
- Hands-on experience is invaluable
- MIT is taking a hard look at what are our general institute requirements – this conversation should help inform this effort, which can have leverage elsewhere

David:
- This conversation has occurred on two levels:
    - University education and design for invention
    - Broader societal education for invention
- Role of a design-centered view of knowledge – with technological invention being the natural home, but with implications for many other domains (social and political)
- Spirit and craft of boundary transgressions (beyond brainstorming or juxtaposition of ideas to a habit of mind)
- I am aware that, in practical terms, the output needs to be very pointed in order to maximize the impact – a core design challenge

Decker:

- I am grateful to have been here
- Robert Frost said that a home is where you have to be taken in when you go there – invention needs a home in every community – sustained even in hard times – something beyond the high school shop

Joel:

- Appreciation for the learning here
- A concern about the overall strategy, structure and process for change based on these ideas
- Awareness of the larger context that motivates and, in fact, requires success

Chris:

- We have the chance to make a difference – in technical education and on a broader level – the approach which stresses inventive capacity of our society has a compelling story and may have a chance for success despite inertial and active resistance

Mert:

- It has been wonderful to hear the inputs – accomplished all that I hoped and a good deal more
- Thanks to Kris and Marissa in enabling this—all agree

Appendix B: Workshop Questions that were used as guides for the Participant's Presentation preparation:

1. What are some current University-level engineering and science educational approaches that foster creativity and inventiveness?

2. What are some existing University-level engineering and science educational approaches that might hinder the development of inventive creativity?

3. How might we recognize or measure creativity? How might the influence of education at all levels on creativity be measured?

4. What are possible frameworks for assessing the purpose and focus for fostering creativity in the University-level engineering and science curriculum? *Issues in this area would include the implementation of inventions (often differentiated as innovation), the social impact of inventions and also the translation of learning from the educational setting to actual use in a different context.*

5. What has been learned systemically about inventive creativity and what does this suggest about teaching to foster it? Is it useful at any level to teach students about what is known about creativity?

6. What barriers exist that impede the adoption of creativity-enhancing activities in the University-level engineering and science curriculum?

7. What opportunities exist for more robust embedding of creativity-and- invention-enhancing activities in the University-level engineering and science curriculum?

8. Within the total educational framework, what is the potential for fostering creativity and inventiveness through deliberate interactions among: 1. engineering design, 2. scientific discovery, and 3. the arts?

9. How would a focus on creativity and invention change education in particular at pre-university levels?

Participant Biographies

<u>Christopher Magee (Chair)</u>
Director, Center for Innovation in Product Development
Professor of the Practice of Mechanical Engineering and Engineering Systems
Massachusetts Institute of Technology

Christopher Magee received a Ph.D. in metallurgy and materials science from Carnegie Mellon University and an M.B.A. from Michigan State University. Among his areas of expertise are vehicle design, systems engineering, application of computer-aided engineering, and computer-aided design. The application of materials, vehicle crashworthiness, manufacturing-product interface and all aspects of the product development process, are also areas of significant personal experience and knowledge.

Prior to joining the faculty at M.I.T., Magee had 35 years of experience at Ford Motor Company. This ranged from early research and technology implementation work to executive positions in product development— emphasizing vehicle systems and program initiation activities. He has lectured internationally on vehicle design and weight reduction, vehicle crash-worthiness, and safety. He has been a participant on major National Research Council studies, whose topics span design research to materials research. Magee is a member of the National Academy of Engineering, a Fellow of ASM and a Ford Technical Fellow.

<u>Jonathan Cagan</u>
Professor of Mechanical Engineering
With appointments in Design, Computer Science, and Biomedical Engineering
Carnegie Mellon University

Jonathan Cagan received his bachelor and masters degree from the University of Rochester, and his doctorate from the University of California at Berkeley (1990). His research concentrates on design methodology, computational design tools, and design practice. His interests span from computational tools and theories to product development practice.

Cagan's research, teaching and consulting focuses on the early fuzzy front end of the product development through a stakeholder-centered, integrated product development practice. He works closely with colleagues in industrial design, psychology and business, in creating new methods for product design that incorporate ethnographic approaches and cross-functional teams. Cagan and colleague Craig Vogel co-authored *Creating Breakthrough Products*. Their annual class on Integrated Product Development leads to patentable (and often patented) products for corporate sponsors.

In complementary work, Cagan creates theories and implementations of computational design tools to assist in the early stages of design. This work explores issues in form, function and layout of systems. His premise is that computational tools must support a design process modeled by lateral exploration, followed by a focused investigation of one or more good designs.

Results include technology for the automated generation of alternative layouts of mechanical and electro-mechanical systems, shape grammars to represent the logic behind engineering and industrial designs and computer interpreters to implement those languages, and methods to reason about functionality in conceptual design and the use of agents to generate new concepts.

Cagan is a Fellow of the American Society of Mechanical Engineers and has served as the associate technical editor of the ASME *Journal of Mechanical Design* in the area of Design Theory and Methodology (DTM). He also serves on the editorial boards of *Research in Engineering Design*, *Artificial Intelligence for Engineering Design*, *Analysis and Manufacturing*, *Computer Aided Design*, and the *Journal of Engineering Design*. He has served as the chair of the ASME DTM committee and of its annual conference. Cagan has held the Ladd Development Chair of Engineering and was the recipient of the B. R. Teare Education Award at CMU. Cagan was also the recipient of the National Science Foundation's NYI Award and the Society of Automotive Engineer's Ralph R. Teetor Award for Education. He is a registered Professional Engineer.

Joel Cutcher-Gershenfeld
Executive Director, Engineering Systems Learning Center
Senior Research Scientist, Sloan School of Management
Massachusetts Institute of Technology

Joel Cutcher-Gershenfeld joined the faculty at M.I.T. in 1998. Prior to that, he served on the faculty at the School of Labor and Industrial Relations at Michigan State University for nine years and in the Olin Graduate School of Management at Babson College for two years. He holds a Ph.D. in Industrial Relations from M.I.T.'s Sloan School of Management and a B.S. from the New York State School of Industrial and Labor Relations at Cornell University.

Cutcher-Gershenfeld has co-authored or co-edited seven books and over 60 articles on new work systems, labor-management relations, negotiations, conflict resolution, training, organizational learning, public policy, economic development, and large-scale systems change. He is co-author with Kevin Ford of the forthcoming book *Valuable Disconnects in Organizational Learning Systems: Integrating) Bold Visions and Harsh Realties* (Oxford University Press, 2004). He and 13 colleagues co-authored *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative* (Palgrave, 2002). He also co-led a cross-cultural, interdisciplinary team of 14 scholars in writing *Knowledge-Driven Work: Unexpected Lessons from Japanese and United States Work Systems* (Oxford University Press, 1998), which traces the cross-cultural diffusion of new work systems. Along with Richard Walton and Robert McKersie, Cutcher-Gershenfeld is co-author of *Strategic Negotiations: a Theory of Change in Labor-Management Relations* (Harvard Business School Press, 1994; issued in paperback by Cornell University Press, 2000) and *Pathways to Change: Case Studies in Strategic Negotiations* (Upjohn Press, 1995). He is the co-editor of two additional books on workplace training. His 1991 article on "The Impact on Economic Performance of a Transformation in Workplace Relations," (*Industrial and Labor Relations Review)* won the Scholarly Achievement Award by the Personnel/Human Resources Division of the Academy of Management.

In applying theory in the field, Cutcher-Gershefeld has extensive experience leading large-scale systems change initiatives centering on the implementation of new work systems and mechanisms for joint governance. He is co-chair of the Negotiations in the Workplace initiative at the Program on Negotiations, based in the Harvard Law School. He has worked with a wide range of public and private sector employers and unions in Australia, Bermuda, Canada, England, Italy, Mexico, New Zealand, Panama, Poland, Spain, South Africa, and the United States. Joel frequently serves as a keynote speaker on issues of labor-management partnership and knowledge-driven work systems.

Merton C. Flemings
Director, Lemelson-MIT Program
Massachusetts Institute of Technology

Merton C. Flemings is Toyota Professor of Materials Processing emeritus at M.I.T., where he has been a member of the faculty since 1958. Flemings established the Materials Processing Center at M.I.T. in 1979 and was its first director. He served as Head of the Department of Materials Science and Engineering from 1982 to 1995, and from 1998 to 2001 as M.I.T. director of the Singapore-MIT Alliance, a major collaboration between M.I.T. and Singapore in distance engineering education and research. He is author or co-author of 300 papers, 26 patents and two books in the fields of solidification science and engineering, foundry technology, and materials processing. Flemings has received numerous awards and honors, including election to the National Academy of Engineering and to the American Academy of Arts and Sciences. He has worked closely with industry and industrial problems throughout his professional career. Flemings is chairman of the Silk Road Project, a not-for-profit corporation devoted to fostering creativity and celebrating local cultures and global connections.

William P. Murphy, Jr.
Inventor and Founder, Cordis Corporation
Chairman of the Board and Chief Executive Officer, Small Parts, Inc.

William P. Murphy, Jr. studied at Harvard College and received an M.D. from the University of Illinois School of Medicine. Afterward, he studied mechanical engineering at the Massachusetts Institute of Technology. Coupling his proclivity for mechanical engineering with his expertise in medicine, Murphy has revolutionized the biomedical industry. His 17 patents include inventions for the following (many developed in collaboration with various colleagues): flexible sealed blood bags; a new and efficient hemodializer (artificial kidneys); motor-driven high-pressure angiography injectors; disposable medical trays; torque-controlled selective and disposable vascular diagnostic catheters; and the first physiologic cardiac pacemaker and further improvements on the early cardiac pacemakers.

Murphy started Medical Development Corporation in 1957, which evolved into Cordis Corporation (in 1959) to develop medical instrumentation. He started Small Parts, Inc. (1963) to quickly supply small batches of materials to engineers. In 1989, Murphy helped Dean Kamen establish the Foundation for Inspiration and Recognition of Science and Technology (FIRST). He was the 2003 recipient of the Lemelson-MIT Lifetime Achievement Award.

David Perkins
Professor, School of Education
Harvard University

David Perkins received his Ph.D. in mathematics and artificial intelligence from the Massachusetts Institute of Technology (1970). He joined the Harvard University faculty as a research associate in 1970 and is currently a senior professor of education. He was a founding member of Project Zero, a research and development group that (since 1968) has addressed many aspects of cognition and their application to educational challenges. Perkins co-directed the project for almost 30 years with his colleague Howard Gardner, and they both now serve as senior directors on a steering committee. He has conducted long-term programs of research and development in the areas of understanding, creativity, problem-solving, educational and organizational development, reasoning, and the role of technology in education.

Perkins' research on creativity resulted in the book, *The Mind's Best Work* (Harvard University Press, 1981), a well-received examination of the psychology of creativity. His later book, *The Eureka Effect* (Norton, 2000), offered an analysis of the underlying logic of inventive thinking. He is also co-editor (with Robert Weber) of *Inventive Minds: Creativity in Technology* (Oxford University Press, 1992), a collection of articles by contemporary inventors, historians of technology, and cognitive psychologists that discloses insights about the process of invention. He has authored several other books concerning education, intelligence, and educational and organizational development.

Henry Petroski
Aleksandar S. Vesic Professor of Civil Engineering and Professor of History
Duke University

Henry Petroski has written about many aspects of engineering, including design, success and failure, error and judgment, the history of bridges, and the use of case studies in education and practice. His books on these subjects, which are intended for professional engineers and laypersons alike, include: *To Engineer Is Human*, which was adapted for a BBC-television documentary; *The Pencil*; *The Evolution of Useful Things*; *Design Paradigms*; *Engineers of Dreams*; *Invention by Design*; *Remaking the World*, and *The Book on the Bookshelf.* He has also written a memoir, *Paperboy: Confessions of a Future Engineer*, in which he reflects on what predisposed him to become an engineer. His books have been translated into such languages as Chinese, Finnish, German, Hebrew, Italian, Korean, Japanese, Spanish, and Turkish. His latest book is *Small Things Considered: Why There Is No Perfect Design.*

Petroski has published over 75 technical articles in refereed journals and a like number of articles and essays in newspapers and magazines, including *The New York Times*, *The Washington Post*, *The Wall Street Journal*, and *Scientific American*. Since 1991 he has been writing the engineering column in *American Scientist*, and since 2000 has been writing a bimonthly column on the engineering profession for ASEE *Prism*. He lectures regularly to both technical and general audiences, in the U.S. and abroad, and has been interviewed by various media including National Public Radio and NBC's "Today."

Petroski has been a Guggenheim Fellow, a National Endowment for the Humanities Fellow, and a Fellow of the National Humanities Center. Among his other honors are the Ralph Coats Roe Medal from the American Society of Mechanical Engineers; the Civil Engineering History and Heritage Award from the American Society of Civil Engineers; honorary degrees from Clarkson University, Manhattan College, Trinity College, and Valparaiso University; and distinguished engineering alumnus awards from both Manhattan College and the University of Illinois at Urbana-Champaign. He is a fellow of the American Society of Civil Engineers and the American Academy of Arts and Sciences, and a member of the National Academy of Engineering.

Mitchel Resnick
LEGO Papert Associate Professor of Learning Research
Director of the Okawa Center
Director of the Lifelong Kindergarten group at the Media Lab.
Massachusetts Institute of Technology

Mitchel Resnick earned a B.A. in physics at Princeton University (1978), and M.S. and Ph.D. degrees in computer science at M.I.T. (1988, 1992). He worked as a science/technology journalist for five years at *Business Week*, and he has consulted widely on the uses of computers in education. Resnick was awarded a National Science Foundation Young Investigator Award in 1993. He is author of the book *Turtles, Termites, and Traffic Jams.*

Resnick's goal is to help people (particularly children) learn new things in new ways. Resnick's research group has developed new technologies (including LEGO programmable bricks and StarLogo software) that engage people in new types of design activities and learning experiences. He co-founded the Computer Clubhouse, an award-winning network of learning centers for youth from under-served communities

Sheri D. Sheppard
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Design Division, Department of Mechanical Engineering
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Sheri D. Sheppard received her undergraduate degree from the University of Wisconsin and her master and doctorate degrees from the University of Michigan (1985). She has been at the Design Division of Mechanical Engineering at Stanford University since 1986. Besides teaching both undergraduate and graduate design related classes, she conducts experimental and analytical research on weld fatigue and impact failures, fracture mechanics, and applied finite element analysis. She is particularly concerned with the development of effective engineering tools to allow designers to make more informed decisions regarding structural integrity. In addition, she is co-principal investigator with Professor Larry Leifer on a multi-university NSF project for reforming undergraduate engineering curriculum. Sheppard is also a senior scholar at the Carnegie Foundation for the Advancement of Teaching, leading a national-level review of engineering education. She is a registered Professional Engineer, member of the ASME Design Division Executive Committee, and a fellow of ASME and AAAS.

Prior to coming to Stanford, Sheppard held several positions in the automotive industry, including senior research engineer at Ford Motor Company Scientific Research Lab. Her work at Ford involved development of a large strain, large deformation finite element code for vehicle impact studies. She also worked as design consultant, providing companies with structural analysis expertise.

J. Kim Vandiver
Professor of Ocean Engineering
Dean for Undergraduate Research
Director of the Edgerton Center
Director of Undergraduate Research Opportunities Program
Massachusetts Institute of Technology

Throughout his teaching career, J. Kim Vandiver has stressed the importance of hands-on learning. He has worked to enliven the mainstream curriculum by incorporating earlier opportunities for students to solve real-life problems, engage in research, and develop relationships with faculty. In 1992, he founded the Edgerton Center at M.I.T., which provides resources for M.I.T. students engaged in hands-on educational projects. The Center also runs a K-12 outreach program for local teachers and their classrooms.

In 1998, Vandiver was the recipient of the M.I.T. President's Award for Community Service for the Edgerton Center's work with the Cambridge Public Schools. In 2001, he was honored as a MacVicar Fellow for excellence in teaching.

A member of the Ocean Engineering Department faculty since 1975, Vandiver chaired M.I.T.'s faculty from 1991 to 1993. His research focuses on the dynamics of offshore structures and flow-induced vibration. He teaches dynamics and mechanical vibration at the graduate and undergraduate level. Vandiver received his bachelor's degree in engineering from Harvey Mudd College of Science and Engineering, his master's degree in ocean engineering from M.I.T., and a Ph.D. in oceanographic engineering from the M.I.T. and Woods Hole Oceanographic Institution Joint Program. He is a registered Mechanical Engineer in the state of Massachusetts and is an active consultant in structural dynamics with the offshore engineering industry. He is also a certified flight instructor for gliders.

Decker F. Walker
Professor of Education
Stanford University

Decker Walker received his bachelor and master degrees from Carnegie Mellon University and his doctorate in Education from Stanford University (1971). His research focuses on design studies to inform the development of technology-based products and environments for education, and on synthesis of research on information technology in schools, classrooms and other educational settings.

Walker studies the use of computers, telecommunications, and related information technologies in improving the curriculum. With his students, he researches the actual use and value of technologies by studying what happens when teachers and students use technology in the classroom. These studies focus on several areas: study of teacher difficulties in using computers to teach writing; analysis of computer simulations and multimedia to teach biology; comparative study of mathematical software on student's learning outcomes; qualitative review of computers in ear training for music theory; and collection of teacher strategies for overcoming difficulties in using informational technologies in the classroom. As director of the Learning, Design and Technology (LDT) Master's Program, Walker helps students learn sound fundamentals of designing and evaluating programs in their own areas of special interest. LDT students work at the interface of education and technology to address the issues that arise from this use of new technologies for education.