



Enhancing inventiveness

for quality of life, competitiveness,

and sustainability

I N V E N T I O N

REPORT OF THE COMMITTEE FOR STUDY OF INVENTION

sponsored by the

Lemelson-MIT Program *and the*

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P R E F A C E

This report summarizes findings and recommendations of a yearlong study of invention and inventiveness. We have aimed, through an interdisciplinary approach to the subject, to shed new light on invention and on the special kind of creativity involved in inventing.

While much has been written about innovation and entrepreneurship, there is a paucity of literature dealing in an interdisciplinary way with invention and inventiveness. While there is much literature dealing with creativity generally, there is little that deals deeply with the specific form of creativity that is inventiveness.

The study began with a series of workshops held during the calendar year 2003 and culminated with an “Invention Assembly” on April 23, 2004 at the National Academy of Sciences in Washington, DC, at which this report was issued. The report contains our collective findings and our recommendations to policy makers in their efforts to encourage inventiveness in young people, to enhance the climate for invention, and to enhance the value of inventions to society. The five workshops held during 2003 were:

- 1) **“Historical Perspectives on Invention and Creativity,”** March 14-16, 2003; Cambridge, MA. Merritt Roe Smith, Massachusetts Institute of Technology, Chair
- 2) **“Architecture of Invention,”** August 21-23, 2003; Cambridge, MA. David Perkins, Harvard University, Chair
- 3) **“Advancing Inventive Creativity Through Education,”** October 17-19, 2003; Lenox, MA. Christopher Magee, Massachusetts Institute of Technology, Chair
- 4) **“How Does Intellectual Property Support the Creative Processes of Invention?”** September 11-13, 2003; Cambridge, MA. Mark Myers, University of Pennsylvania, Chair
- 5) **“Invention and Innovation for Sustainable Development,”** November 19-21, 2003; London, England. Julia Marton-Lefèvre, Leadership for Environment and Development International (LEAD), Chair

A total of 56 individuals from a wide range of academic disciplines, including history, cognitive science, psychology, engineering, medicine, and law participated in the workshops. Participants included academicians, industry and foundation leaders, and independent inventors. Those of us involved in the

study were struck, as the study progressed, by the great degree of commonality across the workshops and across the disciplines of perceptions of the central issues involved in enhancing inventiveness. This document is based primarily on detailed reports of each of the five workshops; it comprises a summary report followed by five position papers representing each of the workshops. The full reports of the workshops may be found on the Lemelson-MIT Program Web site (<http://web.mit.edu/invent>).

This study has had primarily a domestic (United States) focus, although the portion addressing sustainable development took a more international perspective due to the global nature of that challenge. Sections of the report dealing with sustainability consider how much the United States and all countries have to gain by unleashing the creative potential of inventors throughout the world to focus on the challenges of poverty, inequality, and sustainability.

The study was carried out under the auspices of the Lemelson-MIT Program at Massachusetts Institute of Technology, with additional support from the National Science Foundation. The Assembly was hosted by the National Academy of Engineering. It represents, in the mind of many participants, the first phase of a continuing effort to better understand and enhance inventiveness in the United States and globally.

STEERING COMMITTEE

Merton C. Flemings, Massachusetts Institute of Technology, *Chair*
Christopher L. Magee, Massachusetts Institute of Technology
Julia Marton-Lefèvre, Leadership for Environment and Development International
Mark B. Myers, University of Pennsylvania
Arthur P. Molella, Smithsonian Institution
David Perkins, Harvard University
Merritt Roe Smith, Massachusetts Institute of Technology

COMMITTEE FOR THE STUDY OF INVENTION

Members of the Workshop

“Historical Perspectives on Invention and Creativity”

Merritt Roe Smith, Massachusetts Institute of Technology, *Chair*
Merton C. Flemings, Massachusetts Institute of Technology, *Vice Chair*
Evan I. Schwartz, Author and Independent Journalist, *Rapporteur*
Claire Calcagno, Massachusetts Institute of Technology
Rayvon Fouché, Rensselaer Polytechnic Institute
Robert Friedel, University of Maryland
Lillian Hoddeson, University of Illinois at Urbana-Champaign
Thomas P. Hughes, Massachusetts Institute of Technology
Victor K. McElheny, Massachusetts Institute of Technology
David A. Mindell, Massachusetts Institute of Technology
Joel Mokyr, Northwestern University
Arthur P. Molella, Smithsonian Institution
Mark B. Myers, University of Pennsylvania
Nathan Rosenberg, Stanford University
Rosalind H. Williams, Massachusetts Institute of Technology

Members of the Workshop “Architecture of Invention”

David Perkins, Harvard University, *Chair*
Merton C. Flemings, Massachusetts Institute of Technology, *Vice Chair*
Evan I. Schwartz, Author and Independent Journalist, *Rapporteur*
W. Bernard Carlson, University of Virginia
Vera John-Steiner, University of New Mexico
Lillian Hoddeson, University of Illinois at Urbana-Champaign
Christopher L. Magee, Massachusetts Institute of Technology
William P. Murphy, Jr., Inventor and Founder, Cordis Corporation
Mark B. Myers, University of Pennsylvania
Raymond Nickerson, Tufts University

Stellan Ohlsson, University of Illinois at Chicago
Linda Stone, Consultant
Thomas B. Ward, University of Alabama
Robert J. Weber, Oklahoma State University

Members of the Workshop “Advancing Inventive Creativity Through Education”

Christopher L. Magee, Massachusetts Institute of Technology, *Chair*
Merton C. Flemings, Massachusetts Institute of Technology, *Vice Chair*
Joel Cutcher-Gershenfeld, Massachusetts Institute of Technology, *Rapporteur*
William P. Murphy, Jr., Inventor and Founder, Cordis Corporation
David Perkins, Harvard University
Henry Petroski, Duke University
Mitchel Resnick, Massachusetts Institute of Technology
Sheri D. Sheppard, Stanford University
J. Kim Vandiver, Massachusetts Institute of Technology
Decker F. Walker, Stanford University

Members of the Workshop “How Does Intellectual Property Support the Creative Process of Invention?”

Mark B. Myers, University of Pennsylvania, *Chair*
Merton C. Flemings, Massachusetts Institute of Technology, *Vice Chair*
Evan I. Schwartz, Author and Independent Journalist, *Rapporteur*
Anthony Breitzman, CHI Research
Q. Todd Dickinson, Howrey Simon Arnold & White
Rochelle Cooper Dreyfuss, New York University
Robert Gundlach, Xerox Corporation
Bronwyn H. Hall, University of California, Berkeley
Karl F. Jorda, Franklin Pierce Law Center
Stephen A. Merrill, National Academies
Lita L. Nelsen, Massachusetts Institute of Technology
David H. Staelin, Massachusetts Institute of Technology
Sidney G. Winter, University of Pennsylvania

Members of the Workshop “Invention and Innovation for Sustainable Development”

Julia Marton-Lefèvre, Leadership for Environment and Development
International, *Chair*, UK
Merton C. Flemings, Massachusetts Institute of Technology, *Vice Chair*, USA
Evan I. Schwartz, Author and Independent Journalist, *Rapporteur*, USA
Shereen El Feki, The Economist, UK
David Grimshaw, Cranfield School of Management, UK
Pamela Hartigan, Schwab Foundation, Switzerland
Ashok Khosla, Development Alternatives, India
Zhang Lubiao, Chinese Academy of Agricultural Sciences, China
Ehsan Masood, Journalist, UK
Penelope Mawson, Leadership for Environment and Development
International, UK
Nick Moon, Appropriate Technologies for Enterprise Creation, Kenya
Adil Najam, Tufts University, USA
Julia Novy-Hildesley, The Lemelson Foundation, USA
Anna Richell, Design Council, UK
Ammon Salter, Imperial College London, UK
Eugenio Singer, Environmental Resources Management Group, Brazil
Rory Stear, Freeplay Energy Group, South Africa

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R E P O R T

I. OVERVIEW

Five to seven million years ago our human ancestors were, we presume, still sitting in the trees. Three million years later we were standing upright, using simple stone tools. Two million years later we were still using stone tools, though somewhat improved. Along the way we discovered fire, and some of us began to bury our dead. The world changed slowly then, and whatever inventiveness these early peoples may be said to have had, it was a pale shadow of what was to come.

Then, suddenly, 40 to 50 thousand years ago—within less than 1% of the span of human existence—something happened to humans, perhaps as the result of a minute gene change. Whatever it was, at this time creativity took off, as recorded by specialized and compound tools, fabricated dwellings, and magnificent cave art. The material record in succeeding millennia then shows more or less continuous progression of such creative works, culminating in the birth of agriculture and cities some 10,000 years ago and the profusion of technology, art, and science that has followed in the years up to the present. However it came about, creativity is a central source of the meaning of human life. Most of the things that are interesting, important, and human are the results of creativity. When we are involved in it, we feel we are living more fully than in most of the rest of life.^{1,2}

Invention and innovation represent those aspects of human creativity that have raised the standard of living in much of the world to a level that would provoke wonder and envy among, for example, European nobles of the 16th century or even royalty of earlier times. Between 1000 and 1700 AD, real income per capita in Western Europe grew at a rate estimated to be about 0.16% per year. Between 1700 and 1750 the rate rose to 0.4%, and then during the next century and a half it rose to somewhere in the neighborhood of 1.4%, about where it has rested over the last decades. (In the last 25 years it has stood at about 1.7% in the United States.) So, the doubling time of real income was about 400 years for an individual in the Middle Ages and only about 50 years in the last century.¹

What accounted for this change as the 18th century approached? Prior to 1750, most technologies in use rested on a very narrow base of scientific or technological understanding. Inventions were sporadic and largely unconnected with one another, with chance playing a very large role in their development. The foundation of knowledge was insufficient to build a stable edifice of invention and innovation. After 1750, the scientific revolution, the broadening of technological understanding, the improving information exchange of the day, and no doubt other factors as well led to the first and second industrial

¹ F.M. Scherer, *New Perspectives on Economic Growth and Technological Innovation* (Washington, D.C.: Brookings Institution Press, 1999).

² Mihaly Csikszentmihaly, *Creativity* (New York: Harper Collins, 1996).

revolutions with their sustained outpouring of inventions, innovations, and resulting economic growth.³ Invention and innovation continue today to be the central driving forces for economic wellbeing.

Today, the products of inventors and human invention pervade our lives, from the digital revolution to medical miracles, from the alarm clock that wakes us up to the sedative that helps us sleep. They make life longer, more comfortable, more informed, more engaging, for the most part safer from disease and violence, and more productive in innumerable ways. To be sure, the advance of technology also creates problems, such as nuclear proliferation and damage to the environment. Such challenges demand serious attention and underscore the need for greater social responsibility, sustainable growth, and more inventiveness. That acknowledged, only the most ardent romantics would care to swap their lives today for ones of 500 years ago, and much of the difference stems directly and indirectly from technological invention.

Definitions

It will be useful in reading this report to have in mind some basic definitions of terms employed:

Invention, and more specifically *technological invention*, is the process of devising and producing by independent investigation, experimentation, and mental activity something that is useful and that was not previously known or existing. *Inventiveness* is the form of creativity leading to invention.⁴ Although in principle invention encompasses more than technological invention—for instance, the invention of political systems or organizational structures—the focus of this study is on technological *invention and inventiveness*. Technological invention is to be understood as having a wide range of outputs, including machines, devices, materials, processes, algorithms, and databases.

Invention rests at one end of the spectrum of *design*, and at the other end rests *routine problem solving*. Increasing specificity and predictability are associated with routine problem solving, and increasing *boundary transgression* is associated with invention. *Boundary transgression* refers to mental moves that cross the boundaries of past practice and convention, tying together academic disciplines in unexpected ways, redefining not only means but often the problem itself, and challenging entrenched beliefs about the limits of the possible. *Macro-inventions* are inventions of sufficient import that they change the way we live and spawn many improvement inventions, micro-inventions. Many of these *micro-inventions* are never patented and may not become widely used, but they nonetheless are examples of the creative, inventive spirit we all possess.

Innovation is the complex process of introducing novel ideas into use or and includes entrepreneurship as an integral part. Invention is usually considered noteworthy only if it leads to widespread use. Thus, society benefits only after innovation, not from invention alone. Much has been written, and continues to be written, about the importance of innovation to society. We do not, in this study, deal in detail with innovation, but rather with its wellspring, invention.

Map of this Inquiry

In the Workshop Findings section of this report, we view invention from the overlapping perspectives of the five workshops, asking first the following five questions, and then attempting to delineate at least partial answers:

- What is the broad role of invention and inventiveness in human history?
- How does the inventive mind work and how do people come together in society to do inventive work?
- How can schools, universities, and informal educational settings systematically address the many tensions and dilemmas around fostering inventiveness?
- How well does our current system of intellectual property support the creative process of invention? What are the ways it can be improved?
- How can the connection between invention and sustainability be encouraged?

It will be seen that the findings of the workshops present much coherence and commonality despite the differing perspectives of each. There are other disciplines we might have brought to bear on the issue at hand, and we would expect these also to present some considerable commonality and coherence of conclusions. The disciplines we chose are key building blocks in understanding invention, but they are by no means the only ones, and we may hope that there will be work following on from this study in which other building blocks may be examined.

In the Summary Findings and Recommendations section we list seven overarching findings and follow these with relevant recommendations that cut across the findings of the five workshops. These overarching findings and recommendations were drawn up by the Steering Committee and were based on the workshop reports; all participants subsequently reviewed them.

In the final section of the main report, we present our vision of what an ideal inventive society might become. We do this, not to suggest that this in its entirety is a predicted end state in the foreseeable future, but to illustrate the goal and the advantages that can accrue to our society by fostering inventiveness.

³ Joel Mokyr, *The Gifts of Athena* (Princeton: Princeton University Press, 2002).

⁴ William Middendorf, *What Every Engineer Should Know about Inventing* (New York: Marcel Dekker, 1981).

Following the main body of the report, there are five position papers, representing in large part a distillation of the five workshop discussions. They were presented in the form delivered as lectures at the Invention Assembly in Washington, DC, on April 23, 2004.

A Historical Moment

Is there anything that makes this examination of the inventive mind especially timely today? Our answer is yes. We live in a historical moment concerning the development of invention and its impact on quality of life. Both opportunities and challenges present themselves.

Opportunities exist in our knowledge base and in our social fabric. We have a deepening understanding of the inventive mind based on accelerating research from a number of disciplines. There has been an especially rich yield of knowledge in this area during the last decade. At the same time, emerging understandings of the human brain and complex social structures point to layers of insight yet to be mined. The changes of our society from being agriculturally-centered to becoming manufacturing-centered and then knowledge-centered has created fertile ground for those with ingenious solutions to a wide range of problems. Lowering costs of design, manufacture, transportation, and communication result in niche markets that represent large opportunities for products and services devised by the inventive mind. The emergence of high-speed worldwide communications and transport has created an unprecedented global environment for knowledge sharing, distance learning, and collaboration.

This moment of opportunity is also a time of challenge. The first decade of the third millennium brings us into confrontation with problems of the environment, globalization, population, poverty, disease, and other areas. Invention can be seen to have been in part responsible for some of these problems as well as for the benefits our modern society enjoys. It is now our challenge to couple invention with a strong political will and to seek sustainable solutions to the problems confronting us.

In summary, opportunities and challenges conspire to make this a period when it is increasingly possible and important to leverage human ingenuity. There is a journey ready to be undertaken—more to be learned, directions to be explored, and achievements to be pursued. Days or weeks or months may not matter, but decades will, and time on our human scale is of the essence in a commitment to inquiry, education, and collaboration toward a humane culture of invention.

Merton C. Flemings

April 23, 2004

II. WORKSHOP FINDINGS

Historical

Invention, the wellspring of innovation, is the basic source of the economic wellbeing and quality of life enjoyed in the developed world today. Inequities remain, not all inventions are benign, and developing countries do not share equally in the fruits of invention. Nonetheless, for much of the world, the overall standard of living is far greater than that of our ancestors throughout history. What is the broad role of invention and inventiveness in human history?

One of the central historical questions concerning technological progress is its extreme variability over time and place. There have been enormous differences in the capacities of different societies to invent, to carry the inventions into practice, and to adopt inventions of other societies. The reasons are tied to numerous complex and subtle ways of functioning of the larger social systems as well as their institutions, values, and incentive structures. Keys to the inventiveness of a society are its existing knowledge base, culture, social priorities, and public policies. Institutions set the incentive and penalty structure for inventive people.

Humans are inherently inventive and have been so since the emergence of our modern species, but until recent times invention was limited, sporadic, not readily diffused, and not always long lasting. The scientific revolution (circa 1520 to 1750) and the first industrial revolution (circa 1760 to 1850) laid the basis for an outpouring and sustainability of inventions. The key to the first industrial revolution, beginning in the middle of the 18th century, was technology. Knowledge based on discovery and invention became more accessible. Feedback occurred between discovery- and invention-type knowledge, providing a sounder base for further inventions. The discovery knowledge of this era, however, was largely pragmatic, informal, and empirical (i.e., the science content of this knowledge was limited).

The second industrial revolution, beginning after the Civil War and encompassing the rise of corporate research laboratories, was a time of accelerated inventive activity, certainly as measured by the surge of patents issued. It has been said that this was primarily the result of applied science, which had made enormous strides in the first two-thirds of the 19th century. A better way of viewing this is that, while the feedback between discovery- and invention-type knowledge remained key, the discovery knowledge providing the base for invention became increasingly formal and consensual—what we think of today as more “scientific.”

Inventions come not from technical or cultural imperatives alone, nor from individual and institutional will alone, but from the constant interaction of

these elements. Inventions are to be understood as human creations, produced by imagination interacting with the most fundamental values and concerns of everyday existence. They rarely function in isolation, but require complementary technologies, and so it is useful to think of invention and innovation as occurring in a systems context.

Inventions are often characterized as either *macro-inventions* or *micro-inventions*. *Macro-inventions* are those that change society in a significant way, transcend the technological area of their initial applications, and lead to a multiplicity of micro-inventions. *Micro-inventions* include the process and product modifications that often constitute much of research and development (R&D). These micro-inventions, over time, bring an initially crude idea or model to commercial viability and extend the application of the original idea to fields and applications not considered by the original inventor. Micro- and macro-inventions are bound together, with each playing important roles in enabling the other. Ultimately, the distinction can only be made in retrospect, but it is important to recognize that inventions vary in scale and scope.

Economic forces, including government support of R&D, play a decisive role in the direction inventiveness takes in society. Federal support has stimulated inventiveness through funding of large systems projects in which managers have cultivated a cooperative, interactive, curiosity-driven, imaginative style of doing research and development. Federal support of individual investigators doing basic research has been effective in expanding discovery-type knowledge, but less effective in finding ways to enhance among individual investigators the creativity that we term invention.

In the past, enlightened public policies have stimulated academic environments and made them economically viable as fountains of invention. History reveals that federal, state, and local support have stimulated inventiveness through the funding of public education at the secondary, collegiate, and graduate levels. Prime examples include the state-supported public school systems that first appeared in antebellum America as well as the Morrill Land Grant Act of 1862 that established this nation's impressive stable of land grant colleges and universities. An additional example is the so-called GI Bill of 1944, which educated at least two generations of engineers and scientists after World War II. Yet little systematic research has been done on these important topics and the ramifications they have had for invention, creativity, and the growth of the American economy.

Great inventive engineers and scientists are almost always surrounded and supported by research associates and staffs that, themselves, make important contributions to the process of discovery and invention. Such people comprise an invaluable national resource. In the past, the federal government has done a number of things to insure that such an infrastructure not only existed but thrived. Two prime examples are the Morrill Act and the GI Bill. Both prepared the way for enormous spurts of growth in the American economy after

the Civil War and World War II, making the United States the richest and most powerful nation in the world.

The provision of flexible learning environments (at home and in school) have repeatedly stimulated and encouraged inventiveness and creativity in engineering and science. Indeed, the historical record is replete with examples of people, from parents to teachers to employers, who, on the basis of personal commitment, interest, and trust, have stimulated and supported young people who demonstrated promise as inventors and scientists. Yet we have no deep analytical understanding of how these processes work or what the commonalities are.

In the past, systematic exclusionary policies and cultural biases prevented women, blacks, and other minorities from contributing to the invention process in fundamental ways. This has changed only in recent decades and must be closely monitored to insure that access to careers in science and invention remain open to all who demonstrate promise and want to enter. In addition to openness, tolerance is essential in an inventive modern society. Creative people, whether artists or inventive engineers, are often nonconformists and rebels. Indeed, invention itself can be perceived as an act of rebellion against the status quo.

As a society, the United States has compiled an enviable record of scientific discovery and engineering invention. However, it has been far less effective in anticipating the long-term effects and larger implications of new technologies. We tend to be reactive rather than proactive when it comes to studying the problems (and promises) that the introduction of new technologies generates. The institutional nature and momentum of invention have changed notably in recent decades. For example, we now live in a biological world as much as a world of Newtonian physics and engineering. The implications of this change for higher education, the business world, the patent system, government, and the people are great. One may appropriately ask what forces decide what problem areas are targeted for invention, and who allocates the resources accordingly? Why do some agendas fail to find their way to the top of the list? Are we, as a democratic society, satisfied with the way agendas are set and actions taken?

Cognitive Science/Psychology

Technological invention contrasts with scientific inquiry in its focus on developing things that fulfill practical functions. These things contrast with the products of science, theories and findings that typically opt for a clean model of underlying fundamental processes while factoring out "complications". The world of invention is wide and deep. The products of technological invention include physical devices but also processes, algorithms, designed biological structures, and the like. They vary in their social impact. Some have little impact while others, like the automobile, transform society. In their knowl-

edge extension, some build on received knowledge while others, as in the area of nanotechnology, require deep research. In the system level, some occur at the level of components or elements, others at the product or process architecture level, and others deal with whole systems. How does the inventive mind work, and how do people come together in society to do inventive work?

Historically, most inventions have been anonymous. They did not have identifiable inventors. The inventions persisted and spread. They underwent refinements and diversification in a society over long periods of time, with innumerable small contributions from unknown individuals. One example is the development of modern agriculture. Persistent inventiveness continues to be central to human existence. It is only in recent centuries that the role of inventors has been defined and celebrated in society, with supporting institutional arrangements. In today's world we can focus on inventors as having a clear social role, and we can explore the process and context of invention.

Invention always occurs in the combined social, economic, institutional, and cultural contexts and must be understood in terms of those contexts. Inventors must “negotiate” their work on two fronts. On the one hand, with nature, they must ground their work in an understanding of what materials, natural processes, and so on afford. On the other hand, with society, they must arrive at inventions that find a practical and valued place.

Invention has thrived in some societies much more than in others, reflecting the needs and values of the society and indicating the profound effect of society on inventiveness. Inventors sometimes respond to social needs by tackling already recognized problems, but sometimes they, in a sense, “invent” the problems themselves, discerning a problem or opportunity that previously was not recognized as such. To put this in the language of economists, sometimes inventions are “demand-pull,” meaning that inventors respond to demands already being voiced in the marketplace. However, many important inventions are “supply-push,” meaning that they arise out of what inventors find ways to do, generating the further task for the inventor and colleagues of articulating a need that the invention fulfills and then convincing people that they have this need.

Effective inventors tend to display personality characteristics including resourcefulness, resilience, a commitment to practical action, nonconformity, passion for the work, unquenchable optimism, high persistence, high tolerance for complexity and ambiguity, willingness to delay gratification, and a critical stance toward their own work. They are able to embrace failure as a learning experience. Successful inventors are self-critical of their own work. They learn to abandon knowledge that may be too constraining, and they embrace failure as a learning experience. They show an alertness to practical problems and opportunities and an ability to match their talents with the problem using a tool kit of effective ways to conceptualize and break down the problems. Characteristically, inventors are deeply knowledgeable about their

areas of endeavor, on both a theoretical and “hands-on” basis, while they are also comfortable working on the margins of established knowledge.

Many of these traits are characteristic of high performance of almost any sort, and several mark most creative endeavors. A few, such as alertness to practical problems and opportunities as well as a mix of scientific and hands-on knowledge, are fairly specific to technological invention. It is important to emphasize the dispositional side of the inventive mind—the alertness to problems and opportunities, the curiosity, the enthusiasm, the commitment. While many accounts of inventors and inventive thinking place in the foreground knowledge and abilities of various sorts that swing into operation as a problem is solved, it is especially notable that inventiveness is not just a matter of knowledge and ability. The dispositional side of invention is crucial.

To advance their endeavors, inventors commonly need a range of other skills concerned with relating to the constituencies around them. Although inventors focus on invention most centrally, they often must play other roles as well. They need the mindset and skills to promote, persuade, market, marshal financial resources, and so on. In some settings, others may largely play these roles, but in different settings inventors take much of the responsibility themselves; for instance, they often need to function as “intrapreneurs” to advance their missions within an organization.

Popular visions of the inventor often picture him or her as less educated than a technical expert, and indeed several notable inventors left formal education early. However, case studies reveal that effective inventors, whatever their formal education, are almost always profoundly knowledgeable about their areas of work in both theoretical and practical terms. They draw on a wide range of knowledge from varied disciplines, according to the needs of their endeavors, often working on the margins of what is well-established. Studies of expertise and its development argue that this range and depth of knowledge in a specialty typically requires about 10 years of experience before an individual can function at a truly expert level.

Effective inventors are not trapped by what they know or think they know. They are boundary transgressors. They mobilize their knowledge flexibly, selectively, and critically. They often abandon what is “known” in several senses—setting aside previously effective approaches that do not seem helpful in a specific case, bracketing knowledge as not helpful, and challenging prior knowledge as perhaps false or flawed.

Inventors characteristically depend on a mix of deep theoretical understanding of materials and processes and hands-on experiential knowledge of how things work in the physical and social worlds. The former is typically systematic and articulate, the latter often deeply based in experience and hard to express through words or formulas. Of course, particular inventive endeavors vary in the balance of the called-for theoretical and hands-on knowledge.

The development of invention depends on appropriate knowledge resources and access to them. This can take many forms: technical manuals, journals, reports, patent descriptions, libraries that compile such materials, the Internet, the availability of samples and prototypes, the wisdom of peers and more experienced practitioners accessed through conversation and collaboration, and appropriate cross-fertilization between different groups. The ready and appropriate flow of knowledge is crucial to the endeavor of invention.

In many ways, the similarities between technological invention and other creative endeavors are more striking than the contrasts. There is a common trend toward high commitment, effort, and persistence, characteristics found in virtually any enterprise involving high-performance, creative or not. There is the tendency toward independence and flexibility of thought. A variety of boundary transgressions are apparent in many creative endeavors, as are a range of familiar problem-solving heuristics, the importance of problem finding as well as problem solving, and so on.

Inventive thinking is strongly shaped by the inventor's commitment to produce something practical and therefore to deal with a range of practical considerations involved in actually getting something to work in a real physical context and within human society. This includes not only getting something to work physically, but at reasonable price points, without undue risk to users, with the invention operating within reasonable limits of space and time. Often scalability is a key consideration.

A scientist seeks understanding, and he or she proceeds on the assumption that there is an explanation. Nature must be doing something, and it is the job of the scientist to figure out what. An inventor seeks a solution without knowing if one exists or not. He or she may not even know what the problem is. It may be that there is no way to do the job or no way to do the job within reasonable parameters such as cost and time. Thus, the inventor lives with uncertainty in a way that the scientist does not. This may also be a contrast with artists. Artists can usually count on producing something viable as art, even if it is not exceptional. It does not have to “work” in the same sense that an invention has to work.

Invention, the oldest record we have of the creative mind at work, also represents a fresh, exciting, and enormously productive arena of social development. We do not know all we would like to know about invention and the inventive mind, but we know enough to begin to invent the inventive society.

Education

The process of invention and the traits of the inventive mind can be enhanced by education and fostered by appropriate societal support. These same outcomes can also be undercut by the educational system—something that is all too common today. The key question is which role—enabler or barrier—will be the dominant role for education in the years to come?

The cultivation of inventiveness can be pursued at many levels and in different settings. In formal education, every student deserves the opportunity to learn more about the nature of invention and to acquire some simple basic skills and generative attitudes. Students with a particular flair and inclination toward invention merit occasions to learn more and advance further. However, formal education is by no means the only context for the development of inventiveness. In any group—from classrooms to clubs to corporations—patterns of practice and institutional cultures can favor or discourage the development of inventiveness. How can schools, universities, and informal educational settings systematically address the many tensions and dilemmas around fostering inventiveness?

Directed teaching (with pre-defined principles and itemized steps) may not be the best way to convey the craft and spirit of inventive thinking. Equally important might be modeling, mentoring, project-based learning, group participation in an atelier model, and the like. The overall structure of inventive activity—long timeline, purposeful in a flexible way, problem finding as well as solving, and so on—constitutes part of the agenda. The dispositional side of inventiveness recommends attention to curiosity and exploration, confidence and the willingness to take risks, and opportunities for choice and discovery. Equally important is what to avoid: punishing failure, discouraging challenge, and centering learning experiences on the rote and routine. Much of this could be said for cultivating creativity of any sort. However, the specifically inventive side of invention must not be ignored, including the dialogue between abstract thought and hands-on exploration, the role not only of scientific knowledge but operational principles, and the importance of different levels of inventive thought from the overarching system to the smallest components.

To invent in many fields today requires deep technical knowledge, and the modern technical university is well suited to provide that knowledge. There is also, however, the requirement of creativity capability—of inventiveness. Universities (as well as K-12 schools) are less well equipped to foster this important attribute in young people. All too often we see, in both universities and K-12, overemphasis on deductive learning, separation of the learning of principles from their application, inadequate self-discovery, overly-rigid formats, predetermined outcomes, lack of open-ended problems, too little emphasis on learning from failure, and little teaching of visual thinking.

Many of the above “disconnects” have been successfully overcome in isolated cases, leading to “islands of success.” These include individual teachers and courses that represent life-changing experiences for students, community invention centers, invention camps, and other educational innovations. Yet there has been insufficient support to enable the long-term sustainability and diffusion of these innovations. The lack of sufficient mechanisms to help new instructors develop the capability to foster inventiveness, as well as the lack of mechanisms linking together instructors who are innovating in this field,

partly explains the limited 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 inventiveness. Indeed, these institutional arrangements often directly or indirectly discourage these activities.

There are innate tensions that must be dealt with in approaches to fostering inventiveness in education. They include 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 and continually engage the tensions inherent in each dilemma. Simply put, advancing inventiveness in education will involve hard choices.

Despite the popular image of the inventor as a lone agent, invention is a deeply collaborative process. Drawing on our panel discussions and on the report of the National Academy of Engineering Study “The Impact of Academic Research on Industrial Performance” (2003), we note that universities are venues for a greater range of ideas and interdisciplinary perspectives than any other institution in the innovation system. They are the only places where advanced research and education are integrated on a large scale. The constant flow of new students through universities continuously revitalizes the academic research enterprise, challenging the assumptions of faculty and bringing fresh perspectives to research. Industrially supported research and industrial collaborations provide further intellectual challenges. These are potentially conditions favorable to inventiveness and include the bringing together of problem formulation, boundary transgression, focused effort, and open, creative minds.

The increased attention universities have paid in recent years to invention has many positive consequences for both universities and industry, including the teaching of invention “by doing,” providing incentives for invention by students and faculty, and fostering dissemination and commercialization of new technologies. There are many concerns as well, including the undermining of the universities’ broader mission through adherence to narrow disciplinary definitions of excellence, financial constraints, and underlying tensions around how to value faculty effort. At the outset of this report, we indicated that this is a pivotal point in time for society’s overall support of inventiveness. Here we see that educational institutions are also poised at this crossroads.

Intellectual Property

Invention as a human activity is much older than the notion of intellectual property. People had been inventing new tools, techniques, and technologies for thousands of years before legal constructs granted individuals and organizations limited ownership rights for the ideas they produced. Systems of patenting were conceived to motivate and reward people not only for undertaking invention but also for disclosing their ideas to society in order to promote general progress. From the first patent law, in 15th century Venice, to the landmark English patent statute in the 17th century, to the establishment of the United States system of patent protection in the 1790s, to today’s international patent structures, such legal conceptions have changed dramatically over time. In addition, patents have evolved along with the larger web of intellectual property that includes forms such as trade secrets and copyrights. In this study we ask these overarching questions: How well does our current system of intellectual property support the creative process of invention? What are the ways it can be improved?

Society as a whole is the customer of the patent system. High levels of invention are important to our economic welfare, and the patent system supports that invention. Patents serve as an effective incentive for inventors to disclose their know-how to society in return for limited monopolies to exploit their own inventions. This bargain encourages investment in new technologies, prompts corporations to create new products, and gives entrepreneurs the impetus to get new business underway. Of course, the potential financial gain from a patent is an important stimulus to inventors. Other stimuli include altruism, the intrinsic pleasure of inventing, and professional recognition.

In the past 20 years, patent rights have been extended and strengthened through a number of legislative acts and judicial decisions. There are new university patent holders through the Bayh-Dole Act. There is new patentable subject matter in the area of software through *Diamond vs. Diehr* and *AT&T vs. Excel Communications*, genetically modified organisms through *Diamond vs. Chakrabarty*, and business methods through *State Street Bank vs. Signature Financial Group*. Patenting is moving upstream into the realm of fundamental science and products of nature, such as patents on manipulating genes.

Most of the recent growth in the magnitude of patent filings has come from one industrial sector: electronics, computing, and communications. Much of this movement is defensive—to trade portfolios among big players. Software patents have grown enormously in the past 20 years. Software inventions can also be protected by trade secrets, and the source code can be protected by copyright.

Patents vary widely in importance and value. Less than 10% have commercial importance, and less than 1% is of seminal importance. The most valuable

patents are assumed to be the ones that are most highly cited, or referenced, in papers and other patent applications. In the period of 1975-1998, corporations were granted 85% of the highly referenced patents, individuals were granted 9%, universities 4%, and government and nonprofits 2%. In fact, the one-half of 1% of patents granted between 1963 and 1999 that are cited more than five standard deviations above the average for patents granted that year are disproportionately assigned to U.S. corporations (about 70% as opposed to 46% for all patents).

The latency of time between the filing of an application and the issuance of a patent in the United States is 24 months on average. The time increases to up to 36 months for biotech and business method patents. The approval rate for applications to be eventually realized as patents is 75%. Higher yields have been suggested when considering re-filings via continuation or the division of patent applications into numerous claims.

Trade secrets and patents are often complementary and can often dovetail together. Trade secrecy can be used in the early research and development stages, before patents are sought. Trade secrets protect patentable innovations that are not sufficiently novel to patent. Sometimes it is possible to protect the know-how associated with patents as trade secrets, but this strategy can be risky as it may run afoul of patent disclosure requirements. Trade secrets involving early stage research can often discourage the formation of open, creative research environments at universities and in industry.

The U.S. patent system is under great strain; it is not only seeing an increased rate of patent applications, but also the inventions are getting far more complex. Low-quality patents, although a small minority of overall patents issued, place a large cost on the patent system, in terms of money, resources, uncertainty, increased legislation, and a slowing down of innovation. It is more difficult today to perform accurate searches for prior art due to the increased complexity of patents and to the uncoordinated “piecework style” of examination of patent applications in the U.S. Patent and Trademark Office (USPTO). Manpower limitations in the USPTO limit the quality of patents granted. Experimental use of patented technologies is under question, raising the possibility of a chilling effect on innovation being felt everywhere, particularly at universities and startup companies.

There are social costs to patenting as well as benefits. Pooling of patents among different companies can create monopolies. In network industries such as telecom and computing, patents can strengthen already entrenched monopolies and lengthen the duration of monopolies, and patents can create the opportunities for pure rent seeking without taking creative risks, thus impeding the overall level of innovation. Independent inventors and large corporations tend to be concerned about different sets of issues, and sometimes have opposing viewpoints. Any major changes to the patent system will require building a consensus between these two groups.

There is a growing tendency to reward all creativity with protection of intellectual property. Hence what were once islands of protection in an ocean of public domain are now large continents of protection, with only lakes of free access. There is reason to be concerned that there is a growing imbalance of information that is freely available for inventive use compared to information whose use is restricted. The “public domain”, “the scientific commons”, and the “Mertonian ethos” are being threatened by the decline of the public role of the great corporate central research laboratories and by the push at universities to patent their research. What used to be public research is now becoming proprietary.

The creative process of invention is too often separated from the fruits of the patent system by complicated processes including corporate structures and slow and expensive legal processes. Changes to reduce this interference should be made to provide further incentive for invention and hasten the path of inventions to the marketplace.

Sustainable Development

The fruits of human ingenuity have bypassed some three billion people who live on less than \$2 per day. At the same time, several technologies that are central to our quality of life are also now known to cause irreversible harm to the environment. The intersection of invention and sustainability is of central importance to all parts of world. The key question remains—how can the connection between invention and sustainability be encouraged?

Invention and innovation are key to sustainable development—the practice of improving living standards for present and future generations without causing further harm to the environment. Invention and innovation that focus on providing livelihoods and creating enterprises will have a deeper impact on sustainable development, particularly in developing countries.

Invention and innovation in developing countries consist of at least three varieties. The “copy-cat” refers to mimicking, sometimes without authorization, manufacturing techniques developed in richer countries. The “piggy-back” refers to adapting existing technologies to local needs. The “leap-frog” refers to bypassing inappropriate or outdated technologies and adopting more sustainable solutions. It is particularly the final case, the “leap-frog,” that provides the promise of a link between invention and sustainability.

Some countries do not have adequate resources to offer an environment conducive to creative thinking. Rigid and overly formal education systems stifle creativity in all countries but particularly in poorer ones where such educational systems tend to be widespread. Inventors in many countries find it difficult to obtain financial as well as other kinds of assistance, such as mentoring—particularly in developing countries, which also lack appropriate professional networks.

Some countries are more likely to contain patriarchal social systems as well as more authoritarian styles of government. They also lack sufficient role models to inspire invention. Invention and innovation in most poor countries are fairly low as a political priority. All of these contribute to a climate that does not support a culture of creativity.

Many inventors in poorer countries are compelled to become social entrepreneurs. Their goals are not just to develop innovative products; they also carry out an important social function in helping to see their products adopted by communities, creating livelihoods in the process. This produces a greater set of hurdles for inventors in these contexts.

Banks and venture funds do not like lending to social entrepreneurs because of concern that they lack business experience and also because social entrepreneurs tend to be less interested in protecting their inventions; some encourage replication if it means a product will reach more people. Such practices, however, prevent social entrepreneurs from raising the appropriate level of finance needed for mass production and marketing.

Modern forms of intellectual property protection can get in the way of inventiveness in poor countries. Patents are expensive to apply for. They have the potential of impeding the sharing of knowledge on sustainable development. In addition, trade barriers that protect industries in developed countries can also damage or destroy the development of livelihoods in developing countries

There are only limited incentives in the developed world for inventing products or processes for the developing world, because final rewards of such inventing are typically small. Effective sustainable development will require new mechanisms for innovation that encourage invention as well as manufacturing and marketing systems, which are specifically designed to create sustainable solutions.

III. SUMMARY FINDINGS AND RECOMMENDATIONS

The following findings and recommendations represent a synthesis of those from five workshops conducted in the course of this study. Some of the recommendations are for “add on” activities that would be relatively easy to accommodate, while others would involve fundamental institutional change.

Summary Finding 1. We have many valuable insights about how invention has developed historically and how the inventive mind works, with much more work still to be done.

Recommendation 1. Leverage existing knowledge on how the inventive mind works on behalf of a more inventive society to address key challenges of today’s world.

- Emphasize adventure, excitement, and mystery as much as the analytical and technical side of invention. Inventive thinking as displayed by the finest inventors is not just an analytical, but also a passionate, undertaking.
- Encourage the inventive thinking that involves recurrent cycles of “boundary transgression,” i.e., crossing boundaries of convention, expectation, and disciplines.
- Anticipate that there will be unanticipated consequences of invention, an enduring lesson from history.

Summary Finding 2. Education is key to fostering and sustaining an inventive society.

Recommendation 2. Strengthen those aspects of the education process that enhance creativity in general, and technological inventiveness in particular.

- The creative mind should be cultivated in schools and colleges through curriculum content, style of activities, the overall culture of the school and classroom, and through activities associated with schools and colleges, including clubs and contests. Inventiveness should be made an explicit goal of education at all levels and be so stated in the U.S. National Standards for Education (K-12) and in the engineering accreditation standards.
- Open-ended, problem solving type problems and examples should occupy a larger position in college curricula.
- Historical study of the social and political implications of inventions and new technologies should figure more prominently in curricula.
- Appropriate supporting infrastructure should be fostered to enable teachers to utilize new teaching methods and materials.

- Colleges should offer courses on invention and the inventive process, including hands-on activities, visual thinking experiences, historical case studies, and “how things work” exercises for all students, not just engineering or science majors.
- Engineering schools should examine their tenure and promotion policies to determine how greater weight might be given to invention and to the teaching of inventiveness.

Summary Finding 3. The best way to learn to invent is to invent.

Recommendation 3. Initiate, strengthen, and expand initiatives to involve young people directly in the invention process.

- Government, industry, and foundations should build on and expand efforts to support teams in high schools and colleges that work collaboratively with the private or local government sectors to invent useful products or processes.
- Design-oriented activities and realistic, open-ended applications should be infused into university engineering courses, the primary aim being to teach the important principles of a field in ways that will promote inventive creativity in the application of these principles.
- Engineering schools in research universities should seek research projects and external collaborations, and maintain policies that promote inventive creativity of students and faculty.
- A network of community centers, “invention homes,” or “free workshops” should be created that would provide access to the tools, materials, and flexible space so important to invention; these centers could be based in schools, museums, or other locations.
- Workshops should be instituted allowing teachers to learn by experience how to effectively lead a project-based classroom.
- Networks of innovators and social entrepreneurs should be established and supported both domestically and internationally.

Summary Finding 4. Patents serve as an effective incentive for inventors and investors in technology, but the complicated processes involved in patenting too often hinder the creative process of invention.

Recommendation 4. Review patent law and the patenting process on a continuing basis and make necessary changes to enhance their positive impact on invention and inventive creativity.

- Ways should be sought to speed the legal processes involved in patenting and to reduce the cost of patenting.

- Study should be made of the balance of information that should belong in the public domain as well as that which becomes intellectual property. This includes the appropriateness of patentable subject matter and the allowance of exemptions for basic research.
- The government should provide better facilities and databases for searches of prior art at minimal cost to the inventors.
- A post grant review or opposition should be instituted in order to strengthen the quality of patents by resolving questions of validity. Such a process also allows knowledgeable third parties to supply and argue the relevance of prior art.

Summary Finding 5. In areas including global sustainability and global poverty, the incentives for invention and innovation are low, and barriers are high.

Recommendation 5. Seek ways to help create and enhance suitable environments that foster inventiveness which contributes to sustainable development.

- In developing countries, special attention should be given to education reform to stimulate inventive creativity, interdisciplinary research, and original thinking at all levels. Intergovernmental organizations, including UNESCO, could play a lead.
- More attention should be directed to investing in local invention and innovation, particularly that which helps create employment and enterprises in poor countries. USAID and other bilateral donors should encourage and support more social entrepreneurship in such countries and stimulate counterpart agencies to do the same.
- Corporations and banks should do more to promote sustainable development by understanding the specific needs of social entrepreneurs and providing them with access to finance, investment, mentoring, and technical support. The benefits to corporations would include providing key entry points to new markets.
- New models of intellectual property protection should be considered that would stimulate creativity as well as technology and healthcare product diffusion to all areas of the world. Inventors and innovators everywhere should be given incentives to share their knowledge and market their products as widely as possible, in order to globalize the best ideas for sustainable development.
- Efforts to promote inventive creativity should include assistance with human rights, freedom of speech, justice, and the rule of law, since these are the environments in which inventive creativity can best flourish.

Summary Finding 6. Public awareness helps promote inventive creativity.

Recommendation 6. Undertake public outreach activities relating to invention and inventiveness.

- The public should be better informed of the basic profile, characteristics, and roles of inventors, through books, television programs, etcetera that display and celebrate the inventive mind and the societal benefits that result. Specific examples could include educational television and radio special series on invention, source books on invention, historical vignettes, and other resources for teachers.
- Foster public events, including competitions, public displays, traveling exhibitions, and other ways to increase the public profile of inventors and inventiveness
- Additional awards and prizes should be established honoring inventors. New prizes could have the objective of stimulating invention in specific needed areas (e.g., global sustainability) as well as of raising the stature of inventors and invention in the eyes of young people.

Summary Finding 7. Although much is known, we need a deeper understanding of inventive creativity to serve education and social development most effectively.

Recommendation 7. Substantially increase engineering and social science research on the process of invention and the teaching of inventiveness.

- Research should be aimed at a deeper understanding of the creative mind and creative environment, the measurement of inventiveness, diffusion of teaching of inventive creativity, and rapid learning as part of the boundary transgression that is at the heart of invention.
- Research should include study of the influence of flexible learning environment and role of parents, teachers, mentors, and broader social institutions.
- Study should be made of the impact on inventive creativity of past major programs of federal and state support of K-12 and higher education.
- Study should be undertaken of the role of each societal sector (individual, small corporations, universities, etcetera) in major inventions and innovations of the recent past, the importance of inter-sector interactions, and the impact of patent and other relevant law.
- Assessment should be undertaken of how invention could make a difference to the sustainable development needs of the poorest regions and nations. This could include research to understand and promote social enterprise, cultivation of creativity on a local level, surveys of key technology gaps, and surveys of available financial resources.

IV. A VISION: A COMMUNITY OF INVENTION

We began with a sense of the historical moment. Opportunities have been created by today's research-based understanding of invention, by modern communications, and by our emerging knowledge of society. Challenges have been generated by the environmental impact of industry, overpopulation, and the uneven distribution of wealth and health. These conspire today to make the cultivation of an inventive society both a feasible and a needed agenda.

We commissioned five working groups and asked five core questions, addressing the role of invention and inventiveness in human history; the workings of the inventive mind in individuals and groups; the contributions (present and potential) of education to the fostering of inventiveness; the impact of intellectual property law on inventive endeavor; and the links between invention and sustainable health and development around the world. From these deliberations, we have synthesized a range of findings, reflections, and recommendations.

Now let us take a step a few decades into the future. Suppose that many of the recommendations in this report will then have been pursued by groups that have a deep and thriving interest in invention and its impact on the human condition. Let us envision a much greater public awareness of invention and the inventive frame of mind. Let us posit various constituencies loosely networked into a "community of invention" including individual inventors, corporate stakeholders, government agencies, educational institutions, community leaders, and user and citizen groups. Let us ask what success might look like, not with any claim to a detailed forecast, but in the spirit of inviting creative dialogue.

This "community of invention" will in those few decades represent a systems-level initiative comparable in scale and scope to the enabling societal initiatives that helped to transform society a century or more earlier: the establishment of general public education, land grant universities, and free public libraries. Achievements of the community will include new insights into the nature of inventive capability; a strong public awareness and valuing of inventive skills, of the spirit of inventiveness, and of spiritual aspects of invention; and a clear understanding of the limits of technological invention.

The "community of invention" will have been able to forge a consensus about intellectual property practices and thus will have brought such practices into better balance with respect to the incentives to invent for small-scale inventors. More broadly, societal barriers to invention will have been examined and addressed systematically, including issues of access to resources, concerns with liability, and collaboration across cultures and distance. In a similar way, tight integration of educational institutions with distributed invention processes will have been achieved, helping to introduce and sustain

important changes in curricula and teaching styles. This community will have cultivated widespread development of work environments that are more flexible and attuned to fostering and valuing invention and creativity.

A pattern of broad participation will have developed in legal, social, economic, and cultural decisions concerning invention and inventiveness. Society at large will have learned to take the long view around matters of technological choice, proactively anticipating challenges and establishing mechanisms to deal with both predicted and unintended consequences. The community of invention, together with other committed groups, will have stimulated substantial progress on a range of challenging issues, advancing toward:

- A world in which high levels of health and prosperity are uniformly distributed;
- Solutions to fundamental environmental challenges, particularly those related to industrial development;
- A stable and sustainable world population with good quality of life;
- Workable approaches to fundamental ethical dilemmas associated with bio- and other technologies;
- A clearer appreciation for the appropriate role of the United States and other leading nations in the global context with respect to invention and inventiveness.

Perhaps most fundamentally, people in general will not be just beneficiaries but participants in ways small and large in a culture of inventiveness. Schooling at all levels will incorporate engaging and energizing aspects of invention in particular and creativity in general. Key concepts and skills associated with creativity will be common knowledge and commonly practiced. Social stereotypes and social barriers concerning engineers, artists, entrepreneurs, and other notably creative roles will have diminished, and people of diverse backgrounds, ethnicities, and faiths will participate vigorously. Raw acquisitiveness will be on the wane, national and international conflicts in decline, and people will generally find that small is better and less is more, all as a result of human inventiveness.

Is this vision utopian? Certainly. Is it attainable with intelligence, collaboration, and hard work, like the next generation of microchips? Or is it as out of reach as cold fusion? We believe that it can be attained at least in part.

Our specific recommendations are summarized in Section III. We do not claim that these represent a full and sufficient set to achieve the vision laid out above. However, we hope a start can be made, and we aim to be part of a long-term collaboration, a community of invention, that would work toward the goal of an inventive society. Taken together, these recommendations provide a foundation for a future community of invention—in the United States

and potentially on a global basis. It is no news that the future is hard to predict. It is certainly true that the vision outlined here is as subject to the winds of change as any human enterprise. However, prediction in its usual form leaves out the element of sustained human will and intelligence. A better framing of the challenge of prediction for the present moment comes from technology guru Alan Kay, who quipped, “The best way to predict the future is to invent it.” We can hardly think of a more apt principle for a community of invention. If we can invent our future, rather than just let it happen, it is far more likely to be a future we would like!

Merritt Roe Smith

The history of the United States provides telling examples of the role of invention in human history. One can see special pressures for change in the vast wilderness that confronted European colonists and their descendants from the 17th century on. Against substantial resistance from the harsh environment and Native Americans, white settlers kept migrating further and further from the Atlantic coast, swarming from towns where land was becoming expensive to cheaper acreage on the frontier. Determined to escape limitations imposed by land shortages, class structures, and religious persecution, these people needed tools of survival—guns, axes, knives, ploughs, pots. They could obtain such items only by trading the wood they cut, the furs they trapped, and the grain they harvested with local merchants who, in turn, looked to distant towns on the eastern seaboard and to Europe for their supply. There was so much to do, and the inventive were constantly looking for ways to lighten their labors by improving tools, refining methods, and automating machinery. Stoves or fireplaces more economical of wood, a mechanized grain sorter, and steamboats and railroads to carry goods and people more swiftly were all desirable inventions. As inventiveness grew, the country grew. At a time when George Washington was being hailed as “the father of his country,” inventors were being saluted as “the artists of their country.” Invention instilled national pride, giving currency to the expression “Yankee ingenuity.”

The significance of invention in American history has led many at home and abroad to call the United States a “technological society.” Inventiveness has manifested itself from the earliest voyages of discovery to the present day. However, such creativity has not been restricted to technology. It is political and cultural as well.

We need look no further than to the writing of various state constitutions during and after the American Revolution and to the U.S. Constitution itself to appreciate the political inventiveness of the founders of our democratic republic. Nothing like these documents had existed before. What is more, in the 1780s these documents became models for the issuance of corporate charters, themselves innovations that served as fundamental guidelines in the development of modern financial and industrial enterprises. Corporate

⁵ This paper is based on the findings of a two-day workshop involving historians and others, brought together to discuss the history of invention and implications it has for the present day. Workshop participants were: Merritt Roe Smith, Chair; Merton C. Flemings, Vice Chair; Evan I. Schwartz, Rapporteur; Claire Calcagno, Rayvon Fouché, Robert Friedel, Lillian Hoddeson, Thomas P. Hughes, Victor K. McElheny, David A. Mindell, Joel Mokyr, Arthur P. Molella, Mark B. Myers, Nathan Rosenberg, and Rosalind H. Williams. The full report of the workshop, “Historical Perspectives on Invention & Creativity,” is available on the Lemelson-MIT Program Web site, (<http://web.mit.edu/invent/>). The author wishes to acknowledge Evan Schwartz’s excellent work as rapporteur as well as Victor McElheny’s valuable editorial suggestions.

charters were, in effect, mini-constitutions that governed large sectors of the emerging business system in the United States. As a British visitor noted in 1854, “the joint stock system” (and limited liability that accompanied it) represented a unique feature of the “American system of manufactures.”⁶

The history of the United States is replete with the names of world famous inventors and innovators. The list runs from Benjamin Franklin, Oliver Evans, and Robert Fulton to Thomas Edison, Henry Ford, and Bill Gates. One has only to peruse a magazine like the *American Heritage of Invention and Technology* to get a sense of the pervasiveness of invention in U.S. history and how it has changed American lives (and lives throughout the world) during the past two-plus centuries. Much has been written about inventors and invention and the impact they have had on the U.S. economy and society—both good and bad. Much is known about both individual and group styles of invention, from the classic Edisonian approach to the large corporate research operations that came to the fore and dominated much of the twentieth century.⁷

Thanks to historical inquiry, we know that most technologies, like the steam engine and the computer (and the larger technological systems of which they are part), are the result of incremental steps and improvements rather than revolutionary discoveries. To be sure, breakthrough inventions (like the transistor) occur, but they are few and far between. By and large, technology development is evolutionary rather than revolutionary in nature. Equally important, history shows that invention, indeed the inventiveness of a society, is a contingent phenomenon. Much depends not only on talented individuals but also institutional, political, economic, and cultural factors that, depending on their disposition, can help or hinder inventiveness. An example is the federal patent system, begun in 1790 and elaborated in 1836, and the incentives and protections it provides inventors. Yet even the patent system is subject to the contingent influences of political, economic, and social forces. A salient example is the 1980 Supreme Court decision to allow patenting of artificial organisms. Many other examples could be cited. The one constant is change itself.⁸

Of all our findings, none is more important than the statement that “invention always occurs in context—social, economic, institutional, cultural—and must be understood in terms of those contexts.”⁹ We must never lose sight of the fact that the inventiveness of society depends on the constant interaction

of individual and institutional players working within the parameters established by society and its politically determined public policies. Such interactions are often messy, frustrating, and unpredictable, but they exist, and any effort to encourage and cultivate inventiveness in the 21st century must take them into account or suffer the consequences.

Another important finding is the centrality of society’s knowledge resources to invention. Recent studies of the eighteenth-century Industrial Revolution and its aftermath reveal not only that technology was a key factor, but also that invention itself, as in textile machinery or chemicals, became sustained for the first time in history.¹⁰ Such sustained creativity owed much to widening public access to knowledge embodied in cheaper and cheaper mass-produced print materials (books, journals, etc.)¹¹; the expansion of learned societies and libraries; and the debut of new, more rigorous institutions of engineering and science education (like the *École Polytechnique* of Revolutionary France and its American counterpart, the U.S. Military Academy at West Point, founded in 1802 by expatriate French military engineers). At the same time, discovery-type knowledge associated with science became more accessible to inventors, thereby facilitating closer interaction between the two and, in the long term, fostering the development of new science-based technologies. Unlike any era before it, the age of the Industrial Revolution (c. 1750-1850) and the unprecedented knowledge production that accompanied it led to sustained invention. Sustainability was key. Indeed, sustained invention became an earmark of the modern era.

Time does not permit a close examination of all the economic, political, and social factors that influenced the advent of sustained invention during the age of the Industrial Revolution. A brief look at public education in the United States will have to suffice by way of illustration.

Great Britain’s Parliament, in response to America’s impressive showing at the 1851 London Crystal Palace Exhibition, commissioned educator George Wallis and manufacturer Joseph Whitworth to visit the United States and report on its “remarkable industrial progress.” Both concluded that the key to American progress lay in the “widespread intelligence which prevails amongst the factory operatives of the United States.” Indeed, Wallis noted, “there is not a working boy of average ability in the New England states, at least, who has not an idea of some mechanical invention or improvement in manufactures, by which . . . he hopes to better his position, or rise to fortune or social distinction.” Wallis attributed such “inventive disposition” to “the attention paid to the education of the whole people by the public school

6 Quote from Nathan Rosenberg, ed., *The American System of Manufactures* (Edinburgh: Edinburg University Press, 1969), p. 205.

7 See, for example, Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Viking, 1989).

8 For entry to the literature on invention, see Judith A. McGaw, ed., *Early American Technology Making and Doing Things from the Colonial Era to 1850* (Chapel Hill: University of North Carolina Press for the Institute of Early American History & Culture, 1994); Brooke Hindle, *Emulation and Invention* (New York: W. W. Norton, 1981); Hughes, *American Genesis*; David F. Noble, *America by Design* (New York: Knopf, 1979); Philip Scranton, *Endless Novelty* (Princeton: Princeton University Press, 1997); David E. Brown, *Inventing Modern America* (Cambridge: MIT Press, 2002).

9 See “Findings,” p. 12 (in this volume).

10 A persuasive exposition of the knowledge/sustained invention thesis is Joel Moykr’s *The Gifts of Athena: Historical Origins of the Knowledge Economy* (New York: Oxford University Press, 2002).

11 Evald Rink’s extensive bibliography of technical publications in America before 1831, entitled *Technical Americana* (Greenville, DE: Eleutherian Mills Historical Library, 1980), documents the explosive growth of printed materials on technology during the late 18th and early 19th centuries.

systems” of the United States, particularly those in New England and Pennsylvania. America’s state mandated public schools contrasted sharply with European practices. In Wallis’s judgment, “the adaptive versatility of an educated people” gave the United States a significant competitive advantage and in large part explained its rapid advance as an industrial nation. Compared with the United States, Britain’s educational system was sorely lacking.¹²

What state legislatures and local communities did for secondary education, the U.S. government did for technical education at the collegiate level. A determined Vermont congressman, Justin Morrill, pushed the key piece of legislation, establishing land-grant colleges, through Congress in July 1862—a dark moment in the Civil War. President Abraham Lincoln enthusiastically signed it into law. Under the Morrill Act, each state in the union received 30,000 acres of land for each member of its congressional delegation. The recipient state, in turn, was to sell the land, establish an endowment, and use the income to establish at least one agriculture and mechanic college devoted to promoting “the liberal and practical education of the industrial classes in the several pursuits and professions of life.”¹³

Thanks largely to the Morrill Act, technical education took a giant leap forward after the Civil War. Although agriculture and science benefited from the legislation, engineering gained most. Between 1862 and 1872, according to one study, “the number of engineering schools jumped from six to 70. By 1880 there were 85, and by 1917 there were 126 engineering schools of college grade in the United States. Between 1870 and the outbreak of the First World War, the annual number of graduates from engineering colleges grew from 100 to 4300; the relative number of engineers in the whole population had multiplied by fifteen.”¹⁴ Interestingly this period of engineering expansion coincides exactly with the great burst of industrialization and economic growth that took place in the United States after the Civil War.

In terms of impact and significance, there is no twentieth-century analog to the Morrill Act. To be sure, there is the GI Bill, enacted in 1944, which permitted upwards of 2.2 million World War II veterans to receive a college education. It is often said that the GI Bill educated a generation of engineers (450,000), teachers (238,000), scientists (91,000), doctors (67,000), and

other professionals. Schooled by war and an education many could not have afforded on their own, the GI Bill generation carried out a managerial revolution and provided many inventors for new fields such as electronics. A famous example is Douglas Engelbart, the pioneer of the computer mouse and graphic interface software for computer applications.¹⁵ From an institutional standpoint, however, nothing compares to the long-term impact of the Morrill Act. Among other things, it enabled the United States to build a higher education infrastructure (particularly in engineering and science) that penetrated every corner of the country and made college affordable to those who previously could not afford it.

America’s land-grant colleges graduated untold thousands of engineers and scientists who went on to successful careers as inventors, researchers, educators, and businessmen. They played key roles in building modern industrial America. In the process, land-grant schools not only helped to place engineering and science on a firm professional footing but also played a central role in wedding science to the so-called “useful arts.” This last point is particularly noteworthy because it had a lot to do with the expansion of knowledge so critical to sustained invention and development associated with the growing momentum of technological change in late nineteenth-century America. These and other implications of the Morrill Act led the distinguished British historian Arnold Toynbee to conclude that “the land-grant idea” was “the one original contribution of American higher education to the universe of institutional systems around the globe.”¹⁶

This brief foray into the history of public education—an object of particular veneration in the United States—is instructive. For one thing, it reveals that in the past, enlightened public policies have stimulated academic environments and made them economically viable as fountains of knowledge production and invention. In short, history clearly shows that federal, state, and local governments—especially the federal government after the Civil War—have stimulated inventiveness through their funding of public education at the secondary, collegiate, and graduate levels. Second, history reveals that great inventors (and inventive institutions) are almost always surrounded and supported by research associates and staffs that, themselves, make important contributions to the process of discovery and invention. Many of these individuals are products of the land-grant system and comprise an invaluable national resource. Indeed, significant inventive talent has emerged from their ranks. Finally, none of this would have happened without the initial vision of a Vermont congressman named Justin Morrill and the financial support of the

¹² The quotes in this paragraph are drawn from Rosenberg, *American System*, pp. 203-4, 305-6, which reprints the original Wallis and Whitworth reports along with a third report on “The Machinery of the United States of America.”

¹³ U.S. Statutes at Large 12 (1862): 503. On the Morrill Act and its significance, see Heather Coxe Richardson, *The Greatest Nation of the Earth: Republican Economic Policies During the Civil War* (Cambridge, MA: Harvard University Press, 1997), esp. pp. 155-60; James McPherson, *Battle Cry of Freedom* (New York: Oxford University Press, 1989), esp. pp. 450-53; Allan Nevins, *The Origins of the Land Grant Colleges and State Universities* (Urbana: University of Illinois Press, 1962); Ray V. Herren and M. Craig Edwards, “Whence We Came: The Land-Grant Tradition – Origin, Evolution, and Implications for the 21st Century,” *Journal of Agricultural Education* 43 (No. 4; 2002): 88-98.

¹⁴ David F. Noble, *America by Design* (New York: Knopf, 1977), p. 24.

¹⁵ On the GI Bill, see Keith W. Olson, *The GI Bill, The Veterans and the Colleges* (Louisville: University Press of Kentucky, 1974); Michael J. Bennett, *When Dreams Came True: The GI Bill and the Making of Modern America* (Washington: Brassey’s, 1996); Michael D. Haydock, “The G.I. Bill,” *American History* 31 (No. 4; 1996): 52-56, 68-70. For a more guarded assessment, see John Bound and Sarah Turner, “Going to War and Going to College: Did World War II and the G.I. Bill Increase Educational Attainment for Returning Veterans?” (Cambridge, MA: Bureau of Economic Research, Working Paper 7452, Dec. 1999).

¹⁶ Herren and Edwards, “Whence We Came,” p. 94.

Federal government. At a time when state universities and other educational institutions are facing severe budgetary constraints and escalating costs threaten to close college education to the children of middle and lower income families, now is the hour for the U.S. government to reaffirm its support not only of higher education but education at all levels. Nearly 150 years have elapsed since the passage of the Morrill Act. Its payoffs in terms of invention, social capital, and socioeconomic welfare have been incalculable. At a time when our educational system is severely pressed, if not in crisis, we need something akin to the Morrill Act's boldness and vision for the 21st century. Particularly urgent is the expansion of vocational and continuing education, along with better integration of computers and the Internet into both formal and self-directed instruction.

With these observations in mind, it's worth asking how we, as a society, should be thinking about the ongoing need to encourage and cultivate inventive talent. What can history tell us about this all-important question? For starters, it is clear that government policies, however enlightened, are only part of the solution. When we speak of the continuing need to foster inventiveness in our society, we are talking about a multi-layered subject. Clearing paths for invention and innovation is a constant struggle. We must be sure to provide supportive environments—at home, at school, at work—in which people of all backgrounds (some with inventive ability) can grow and flourish. In retrospect, education comprises but one part of the larger environment in which inventors are formed.

The cases of John Bardeen (two-time winner of the Nobel Prize in physics for his work on the transistor and superconductivity) and James Watson (Nobel Laureate for his work on the structure of DNA) are instructive in this context. Both had parents who recognized their special abilities and nurtured them. Both went to excellent secondary schools with excellent teachers. Both had challenging mentors in college and graduate school who excited them, demonstrated critical thinking skills, and showed them what it was like to be at the cutting edge of a field. Like other inventive people, Bardeen and Watson learned as much from failures as successes. Both had access to good libraries and worked in flexible research environments in which interdisciplinary collaboration and information sharing proved crucial.¹⁷ Indeed, deeply collaborative flexible learning environments have repeatedly stimulated inventiveness and creativity in engineering and science. They are the incubators of invention and need to be encouraged at all levels by government, business, and educational institutions. We must also support informal education, through museums, science clubs, and science contests for pre-college students.

17 On Bardeen, see Lillian Hoddeson and Vicki Daitch, *True Genius: The Life and Science of John Bardeen* (New York: W. W. Norton & Co., 1997); on Watson, see Victor K. McElheny, *Watson and DNA: The Making of a Scientific Revolution* (Cambridge, MA: Perseus Books, 2003). Also see McElheny, *Insisting on the Impossible: The Life of Edwin Land* (Reading, MA: Perseus Books, 1998); For other examples, see Schwartz, "Historical Perspectives," pp. 31-38.

Maintaining an open door is also important. I recently read a letter to the editor of *American Heritage Magazine* of Invention and Technology about the Wright brothers and the 100th anniversary of their famous flight. In it the writer mentions that "the Wright brothers were highly intelligent and well-read young men." "However," he continued, "I would venture that if they had been processed through our modern public school system, they would have been just about as marginally literate as all too many of today's high school graduates."¹⁸ Overstatement or not, this observation strikes a chord. Wide variances exist in our school systems and the quality of education that young people receive these days. How many kids with creative/inventive ability fall through the cracks because they lack either parental support or do not have access to good teachers and educational programs? This question probably cannot be answered with exactitude, but it is certainly worth thinking about how we, as a society, might close this gap.

Likewise, in the past, systematic exclusionary policies and cultural biases have prevented women, blacks, and other minorities from contributing to the invention process in fundamental ways.¹⁹ Although the situation has changed in recent decades, we must remain vigilant to insure that access to careers in science and invention remains open to all who demonstrate promise and want to enter.

In addition to openness, tolerance is essential in a modern inventive society. Creative people, whether artists or engineers, are often nonconformists and rebels. Indeed, invention itself can be perceived as an act of rebellion against the status quo. We need to become more cognizant of this factor to insure that educational institutions and society foster truly creative students, not just those that perform best on graded tests and on similar standard measures of accomplishment.

As a society, the United States has compiled an enviable record of scientific discovery and engineering invention. However, it has been far less effective in anticipating the long-term effects and larger implications of new discoveries and inventions. We tend to be reactive rather than proactive when it comes to studying the problems (and promises) that new technologies generate. As one MIT colleague put it, "we often adopt new tools without considering the ramifications."²⁰ We need to get better at anticipating the unanticipated. Living, as we do, in a contingent world, we cannot keep generating inventions without devoting more attention to our ability to live with the changes we generate. In order to mitigate the negative effects of new technologies and, in effect, sustain creativity, there needs to be a broad-based discussion and investigation of how new technologies affect our life-world.

18 AHMIT (Winter 2004): 5.

19 On exclusionary practices toward black Americans, see Raavon Fouche, *Black Inventors in the Age of Segregation* (Baltimore: Johns Hopkins University Press, 2003).

20 Rosilind Williams. See Schwartz, "Historical Perspectives," p. 56.

Last but certainly not least, it is important to know how crucial decisions get made in our society with its strong bias toward the simple and concrete. Who decides, for example, what problems get targeted for invention and who allocates the resources accordingly? In short, who sets the agenda and, equally important, why do some agendas fail to find their way to the top of the list? We need a clearer understanding of how these processes work and why they work the way they do. As an eminent sociologist of science puts it, “innovation without representation is tyranny.”²¹ Are we, as a democratic society, satisfied with the way agendas are set and actions taken?

²¹ Bruno Latour, quoted by Schwartz, p. 57.

VI. MAPPING THE INVENTIVE MIND²²

David Perkins

The products of human invention pervade our lives, from the digital revolution to medical miracles, from the alarm clock that wakes us up to the sedative that helps us sleep. They make life longer, more comfortable, more informed, more engaging, for the most part safer from disease and violence, and more productive in innumerable ways. To be sure, the advance of technology also creates problems, such as nuclear proliferation and damage to the environment. Such challenges demand serious attention and underscore the need for greater social responsibility, sustainable growth, and more inventiveness. That acknowledged, only the most ardent romantics would care to swap their lives today for ones of 500 years ago, and much of the difference stems directly and indirectly from technological invention.

Indeed, inventions offer us the oldest record we have of the creative mind at work. The stone axe, the prehistoric hearth, and ancient ceramic vessels all demonstrate the ingenuity of our ancestors far before any written records recount their thoughts and endeavors and even further before anything like formal science existed. Old as it is, invention may also represent one of the newest frontiers in extending the reach of human endeavor. If we can understand deeply the thought processes and the social context of invention, we may be able to leverage our ingenuity in systematic ways that will address the most fundamental problems of our times and accelerate the advance of civilization. Today, with effort and insight, we may be able to reinvent invention in more powerful forms.

Accordingly, let us put a key question on the table: *What makes the inventive mind inventive, and how can we get more of it?* To ask such a question is to look under the hood of invention and ask how the engine works. We do not lift the hood as often as we should. For a theme of such fundamental importance to human civilization, technological invention is substantially under-investigated. That acknowledged, cognitive science is one among several disciplines that has illuminated important aspects of the inventive mind. In August 2003, I convened a workshop called “The Architecture of Invention” in collaboration with Merton Flemings and with the support of the Lemelson-MIT Program to synthesize what cognitive science had to say about invention. The picture of the inventive mind offered here draws extensively on the deliberations and findings of that workshop and the official report. It is my effort to articulate some central ideas about *what makes the inventive mind inventive, and how we can get more of it.*

²² This paper is based on the findings of a two-day workshop involving cognitive scientists, psychologists and others, brought together to discuss the inventive mind. Workshop participants were: David Perkins, Chair; Merton C. Flemings, Vice Chair; Evan I. Schwartz, Rapporteur; W. Bernard Carlson, Vera John-Steiner, Lillian Hoddeson, Christopher L. Magee, William P. Murphy, Jr., Mark B. Myers, Raymond Nickerson, Stellan Ohlsson, Linda Stone, Thomas B. Ward, Robert Weber. The author wishes to thank Evan I. Schwartz for his excellent assistance as rapporteur. The full report of the workshop, “The Architecture of Invention,” is available on the Lemelson-MIT Program Web site (<http://web.mit.edu/invent/>).

Invention from 20,000 Feet

If we want to peer inside the inventive mind, we had better know what it looks like on the outside. What kind of activity is invention? While such a question can be pursued in rich detail, for present purposes a few key points will suffice.

Invention by definition is a creative activity, bringing into being what was not there before. It is also an activity with a functional emphasis. While the creative arts engage our thoughts and senses, and creative science probes the way the universe works, invention produces ways and means of doing things: bottle openers for opening bottles; microscopes, optical and electronic, for seeing the very small; cell phones for handy communication; supercomputers for predicting the weather. Although in principle invention encompasses more than technological invention—for instance, the invention of political systems or organizational structures—the comments here focus on technological invention. However, technological invention must be understood as more than a matter of devising gizmos. It includes creating materials (as with paper for writing and publishing), processes (as for a chemical refinery), algorithms (as for various computer tasks), databases (as of fingerprints), and more. It's also important to note that invention often reaches beyond solving recognized problems to open up previously unrecognized opportunities such as, for example, the flood of applications flowing from the development of the laser.²³

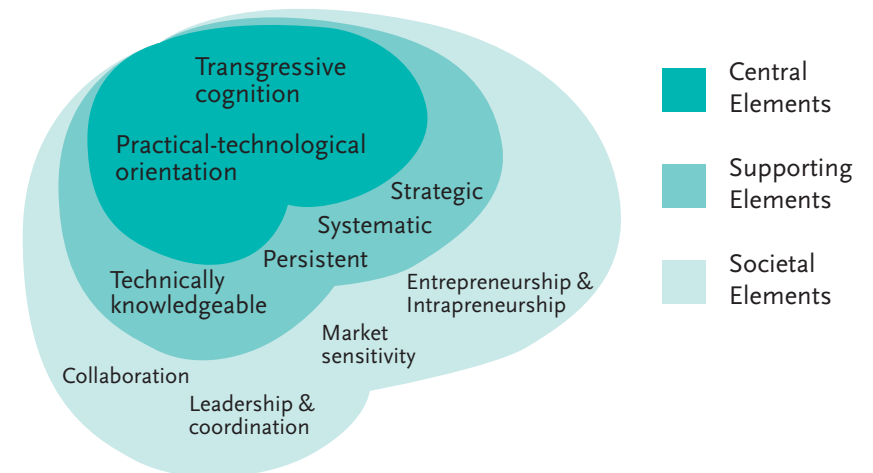
In keeping with this, invention is a highly intentional and sustained activity, and a complex one. It involves identifying, defining, and redefining problems and opportunities (often called *problem finding*), pursuing them with ingenuity and persistence, negotiating relationships with a range of social entities such as sponsors, manufacturing groups, and more. The clear lesson of case studies is that no significant inventions today are the consequence of a single “Eureka” moment. Such moments occur, but they are dramatic highlights in a long saga, involving much thought and many trials. Indeed, many notable inventions required several years, even decades, to come to fully fruitful form—for instance, the electron microscope or ultrasound technology.

As the necessity for sustained focus suggests, invention is not a detached activity but a passionate one, demanding the right sort of disposition or character. Inventors care about what they are doing, often showing dedication to the point of compulsion and curiosity to the point of distraction from ordinary affairs. While many are driven by financial incentives, they are also very much caught up in the quest for a deeper understanding of how things can be made to work for a better world.

All this holds when we consider big-time invention and its giants such as Thomas Edison or Edwin Land. However, it is important to remember that everyday invention makes up an important part of practical life, as people reach for a better way to organize their messy files, adapt a bookcase to hold a sound system, make a temporary repair of a leaky roof with whatever is handy, or figure out a more efficient office routine. These, too, benefit from focus, persistence, and flexible thinking, but of course in smaller measure. When we speak of understanding the inventive mind and fostering it, we are not just speaking of big-time invention but everyday invention as well. Indeed, arguably, one of the best ways to get more big-time invention is to create learning experiences and settings that foster general everyday inventiveness.

Mapping Invention

With all that as backdrop, *what makes the inventive mind inventive?* Studies in cognitive science disclose that highly inventive people consistently display a range of abilities and character traits. While this pattern can be organized in several ways, one way of representing it is as a kind of map (see diagram) with a central region representing the essence of inventive thinking, a surrounding region of characteristics that directly support inventive thinking, and an outer region representing important social aspects of inventive enterprise that the inventor needs to function effectively. In particular, at the core, the inventive mind displays *transgressive cognition*, meaning a tendency to cross boundaries in various ways, and a *practical-technological orientation*. Both of these characteristics receive support from *technical knowledge*, dogged persistence, and a systematic and strategic frame of mind, and further depend on socially oriented capabilities concerning *collaboration, leadership and coordination, market sensitivity, and entrepreneurship and intrapreneurship*.



²³ The technical points about invention are drawn principally from the “Architecture of Invention” workshop, the writings of the participants, and a collection of articles on technological invention including articles by contemporary inventors, historians, and cognitive scientists: Weber, R. J., & Perkins, D. N. *Inventive minds: Creativity in technology*. (New York: Oxford University Press, 1992)

Central elements: transgressive cognition / practical-technological orientation

Transgressive cognition. Perhaps the most fundamental question we can ask about invention is where does the “newness” come from? A broad answer is that the cognitive processes of inventive thinking are full of boundary transgressions—they cross boundaries all the time in various ways. Case studies of invention repeatedly show patterns of questioning received wisdom, borrowing ideas from one area to serve another, conducting basic inquiry to provide a foundation for practical invention, pulling back from an approach that is not working very well to strike off in a new direction, and so on. Thus, inventive thought transgresses boundaries of convention and expectation, boundaries between fields and areas of practice, the boundary between the known and the unknown, the self-made boundaries formed by premature commitment to a particular approach, and more. Through skepticism, questioning, analogy, brainstorming, trial and error, exhaustive search, and in many other ways, inventors transgress boundaries to devise fundamentally fresh and more powerful ways of doing things.

Practical-technological orientation. Besides its transgressive character, inventive thinking adopts a particular target: practical-technological innovation. It is this mission that distinguishes invention from other notable areas of creative endeavor in the arts, the sciences, and elsewhere. One fundamental criterion imposed by the practical-technological orientation is that the invention must work, not just on the laboratory bench, but in society. Innovation just to be clever and fresh and stimulating will not do.

As emphasized earlier, all this is more than a matter of knowledge, skill, and imagination; it also involves a distinctive profile of passion and commitment. Operating in a transgressive way calls for a strong spirit of restlessness and adventure, a willingness to step out of the mainstream and beyond prior solutions, a readiness to question one’s own previous ideas and toss half-baked solutions into the trash can after learning what one can from them. Likewise, the practical-technological orientation of the inventor is more than a particular specialization. It is a passion to make things work and a passion to solve this or that problem in an effective technology-based way.

Supporting elements: technically knowledgeable / persistent / systematic / strategic

Technically knowledgeable. The inventor who leaves school early and, liberated from conventional knowledge, accomplishes remarkable things, is a favorite in the folklore of invention. It is true that some notable inventors left formal education early, and it is equally true that most did not. More importantly, the spirit here is profoundly wrong. Whether through formal education or other means, inventors are almost always deeply technically knowledgeable in their specialties, a finding that holds for virtually all areas of great accomplishment in the arts, sciences, and elsewhere. Invention rarely benefits from naïveté,

although one can know a lot and still not be inventive. Besides extensive mastery of engineering, inventors typically gain from sophisticated understanding of science. Far from “applied science,” invention maintains a complex and generally fruitful marriage with science, both drawing on the various sciences for models and theories and giving back methods and instruments.

Persistent. It’s already been emphasized that invention at the professional level characteristically is the pursuit of years or decades. Indeed, the most common experience of the inventor is not success but failure: failure and retreat to try another approach, failure and experiment to understand what went wrong, failure and repair to take a step forward. Virtually all significant inventions sit at the top of a tower of failures. Would-be inventors need to be psychologically ready for failure and ready to learn from it, and the social structures that support their endeavors need to be in it for the rough climb and the long haul.

Systematic. Another favorite in the folklore of invention concerns the accidental discovery—the sudden recognition of a connection between A and B that solves the problem. As with the previous favorite, something superficially like this happens from time to time. But again, the story ill serves the reality. Sudden recognition virtually always rests on a long history of engagement with the problem at hand; as noted in Louis Pasteur’s well-known phrase, “chance favors the prepared mind.” Moreover, a single sudden recognition rarely solves the problem, but more likely it makes up just one of many episodes of discovery along the way to a mature invention. On the whole, invention is a strikingly systematic pursuit, despite the occasional opportunistic moment. It involves enumerating possibilities, careful testing of prototypes, targeting particular questions for investigation to inform the next step forward, seeking information from technical sources and colleagues, and so on. As just noted, it involves repeated cycles of learning from failure. It is an extended logistically sophisticated endeavor rather than the lucky break in the basement on Saturday morning.

Strategic. In keeping with this, invention is also characteristically a highly strategic pursuit. Inventors use a number of strategies intuitively or deliberately for their problem finding and problem solving, for instance: subgoaling, defining and pursuing subgoals to systematize the development of an invention; repurposing, seeking new purposes for existing artifacts; and analogy, drawing on analogies to suggest approaches to the problem at hand. There are many more.

In summary, the technically knowledgeable, persistent, systematic, and strategic character of invention contributes tremendously to success. Why then, it is natural to ask, are these not part of the central region of our map along with transgressive cognition and the practical-technological orientation? Simply because they are less distinctive to invention per se, although no less important to its success. Many other endeavors besides invention call for technical knowledge, persistence, systematization, and strategic thinking—for instance,

the work of a skilled portrait painter or construction engineer. It is the combined central elements of transgressive cognition and practical-technical orientation that make the endeavor specifically inventive, and the technical knowledge, persistence, systematization, and strategies that equip it for success, or at least, equip it in part, for there is yet another region to recognize in this map of invention.

Societal Elements: Collaboration / Leadership and Coordination / Market Sensitivity / Entrepreneurship and Intrapreneurship

The lone inventor is yet another icon from the folklore of invention, and, like those mentioned earlier, its worship is misplaced. An inventor today, and by and large in the past as well, is very much not an island but part of a complex system with which the inventor needs to negotiate effectively in a number of ways. The inventor needs to function well in multiple roles within a complex social, organizational, and economic network. This is less true for the ordinary moments of everyday invention that contribute so much to getting on in life, but it is overwhelmingly true for invention as a professional enterprise. In particular:

Collaboration. Especially in today's world, invention is characteristically a team endeavor, dependent on collaborative skills. The time scale, the complexity, and the costs of meaningful contemporary invention virtually compel this.

Leadership and coordination. Accordingly, functioning as an inventor typically involves a range of social-organizational skills. Inventors lead teams that need to engage effectively with other organizational units such as finance, manufacturing, and marketing.

Market sensitivity. Inventors invent not just for themselves but for markets, both responding to the markets' needs and helping to lead those markets. Market sensitivity does not necessarily mean pandering to what is most marketable. Many inventors focus on specialized ecological, medical, and other endeavors where the wealth of a company such as Microsoft is unlikely. Nonetheless, they must deal in practical terms with what can find a place in the world and pay its way, or their endeavors will come to nothing.

Entrepreneurship and intrapreneurship. Besides inventing, inventors often have to raise funds and "sell" projects externally and internally. The intricacies of raising venture capital for a new enterprise are familiar today. However, research on industrial laboratories reveals over and over again how innovative individuals within established organizations have needed to hustle their visions in-house and often advance projects between the cracks before the projects gain general support and have a chance of reaching outside the organization to contribute to society at large.

Inventing the Inventive Society

Our map of the inventive mind is a broad sketch of the factors underlying invention. Contemporary cognitive science has much detail to add about all the zones of the map, although much remains to explore as well. Recalling the central question, "what makes the inventive mind inventive and how can we get more of it," the map can also help us navigate toward a more inventive society by cultivating the capabilities and dispositions that it charts. Imagine that you and the people around you were significantly more inventive than is the case today. What a difference that would make—in education, in business, in government, and indeed in the many small maneuvers of life!

Unfortunately, such a vision lies more than an arm's length away. Despite the importance of invention, in many ways our culture is not one that honors and cultivates the inventive turn of mind. Schools pay little attention to fostering creativity in general and invention in particular. Curricula do not include much specifically technological content, although they do provide a fair measure of science content. Worse, with some notable exceptions, school style and culture are commonly antagonistic to creativity. Looking beyond schools, many organizational settings in industry and government are highly risk-averse and not friendly to the inventive mind. Finally, even in the occasional pocket cultures that welcome creativity, systematic approaches to training and mentoring of the inventive mind are few and far between. What, then, can be done?

Reasonable Goals

One simple point is what the goal is not: to create Edisons by the millions. When people speak of educating invention, this often sounds like an effort to produce inventive geniuses on a large scale. Such an enterprise seems neither possible nor desirable. We certainly lack the understanding to manufacture Edisons as though they were light bulbs!

Realistically viewed, the cultivation of invention and inventiveness is not very different from the cultivation of other complex activities, such as artistry or skill at sports. With time, effort, and informed guidance, almost everyone can improve substantially. To be sure, only a few will come to function at an expert level. However there are many levels of useful activity in a society. Just as some basic skills of financial management are enormously valuable, even if one is not an accountant or a chief financial officer, so are some basic skills of invention.

What then would constitute reasonable goals toward inventing the inventive society? At a very general level, these three seem appropriate:

- A population more informed about invention, inventors, and inventiveness. Everyday conceptions about invention, inventors, and inventiveness are often naïve and misdirected, standing in the way of appreciating both how the mind works and how society works.
- A population generally more inventive in an everyday sense. Invention is a very useful skill and mindset that enhances one's effectiveness in all sorts of contexts.
- A greater number of people functioning inventively at a professional level in a range of occupations.

One might ask how this agenda relates to the cultivation of creativity in other domains, such as literature or business management. In the quest for the inventive society, there is no reason to draw a sharp boundary between invention and other forms of creativity, particularly concerning the goals for the general population. To be sure, technological invention by definition involves a practical-technological focus. However, the transgressive character of invention is common to all forms of creativity, as are dispositional traits like persistence and curiosity, along with cognitive strategies like analogy and repurposing. Given the relatively meager attention creativity receives in current educational systems, there is far more common cause than rivalry to be sought across the range of creative disciplines and endeavors.

Appropriate Means

With these broad goals in view, how might one approach inventing the inventive society? In very general terms, the following actions seem appropriate:

- *Informing.* Informing people about the basic profile, characteristics, roles, and so on of invention and inventors such as transgressive cognition, the tremendous importance of dispositions alongside skills, and the highly social nature of invention.
- *Training and mentoring.* Direct training and mentoring in relevant knowledge, skills, strategies, and attitudes, with special weight given to the central elements of transgressive thinking for all contexts and the practical-technological focus as appropriate.
- *Social restructuring.* Shaping community and organizational contexts for cultures and structures friendly to the inventive mind.

Such a mission can play out on several fronts in different ways. In schools, the mission may play out through curriculum content, style of activities, the overall culture of the school and classroom—which is largely determined by

the teacher—and through activities associated with schools, such as clubs and contests. In the world of corporations and government, it may play out through thoughtful programs of training and mentoring, and through cultural and structural styles that foster the inventive mind. In the media world, this may occur through books, television programs, and so on, that display and celebrate the inventive mind and its ways of working, undermining the myths, sharpening the reality, and encouraging the practice.

To be sure, such general ideas are far from a blueprint, indeed hardly even a sketch. Still, they point a helpful direction. It was noted at the beginning that invention, the oldest record we have of the creative mind at work, could also represent a fresh, exciting, and enormously productive arena of social development. We certainly do not know all we would like to know about invention and the inventive mind, but we know plenty to begin to invent the inventive society.

VII. HOW SHOULD EDUCATION CHANGE TO IMPROVE OUR CULTURE OF INVENTIVENESS?²⁴

Christopher L. Magee (Chair)
Sheri Sheppard
Joel Cutcher-Gershenfeld

Educational institutions have a special role when it comes to inventiveness—the potential to serve either as enablers or barriers. Too often, the experience in schools, at all levels, undercuts inventiveness due to highly directed approaches to learning. Yet, there are numerous “islands of success” that illustrate the many ways that innovative, interactive teaching can reinforce and expand inventiveness. In this chapter, we review the limits of the current systems, as well as explore what is possible. First, however, it is important to set the larger context.

Basic broad-scale shifts are currently occurring in human society that are potentially as significant as major previous historical shifts—first from hunting/gathering to farming, and then from farming to industrial production. As with 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.”²⁵ Whatever term is used, the creative use of knowledge is the essence of what is needed to succeed as an individual or nation in the modern world. In this chapter, we make the connection between educational institutions and the particular kinds of knowledge associated with what can be termed “inventive work” and technological invention.²⁶

Our examination of education will address the full spectrum from K-12 through university education, as well as related community activities, with a primary focus on technological invention in university-level engineering education. Technological invention is inextricably linked to other aspects of engineering education. Routine problem-solving and invention represent opposite ends of a design continuum, with increasing specification and predictability associated 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 what can be termed “inventive creativity.”

Current State of Educational Systems

In the spring of 2004, approximately 3.2 million students will graduate from high school in the United States. Roughly 60% will have completed mathematics through Algebra II, 60% will have completed coursework in chemistry, and 28% will have completed coursework in physics.²⁷ Because mathematics and natural science are among the major knowledge bases that technological inventors tap into in their work, these percentages are significant because they reflect the number of students who are potentially exposed to knowledge relevant to inventive work, and the number of students who potentially will go on to study engineering or physical sciences at the university level, where (ideally) inventive thinking would be emphasized.

The mathematics and science coursework that these students are engaged in is generally organized around national frameworks²⁸ that emphasize students’ developing understandings and competencies along both content and process dimensions. Among the newest of these frameworks is one on Technology Literacy²⁹ (completed in 2000), which has an explicit standard focused on innovation and invention. Individual states are free to select which aspects of the national frameworks to emphasize in educating their students—some take a traditional approach, while others introduce collaborative and project-based learning as a means of achieving educational goals. Knowledge competency and achievement levels are measured through a series of national³⁰ and state tests.

A small percentage (7%) of these high school graduates will have taken a course in engineering²⁹, or in industrial or visual arts, where creativity, use of materials, design, and the making of physical artifacts are emphasized. An even smaller percentage will have been involved in, for example, the FIRST Robotics Competition³¹, a multinational co-curricular competition involving teams of young people and professionals in solving an engineering design problem in an intense and competitive way. They may have also participated in “Camp Invention,” a weeklong summer enrichment day camp offered in local elementary school for children in the second through sixth grades. This program invites children to let their imaginations run wild through teamwork, creative problem solving, and inventive thinking.

Of the high school class of 2004, less than 2% will go on to receive a bachelor’s degree in science in an engineering field and less than 2.5% in natural sciences (2% in biological sciences and 0.5% in physical sciences). Another

²⁴ This paper is based on the findings of a two-day workshop involving educators, inventors and others, brought together to discuss education and inventiveness. Workshop participants were: Christopher Magee, Chair; Merton C. Flemings, Vice Chair; Joel Cutcher-Gershenfeld, Rapporteur; William P. Murphy, Jr., David Perkins, Henry Petroski, Mitchel Resnick, Sheri Sheppard, J. Kim Vandiver, Decker F. Walker. The full report of the workshop, “Advancing Inventive Creativity through Education,” is available on the Lemelson-MIT Program Web site (<http://web.mit.edu/invent/>).

²⁵ See, for example: Michael Piore and Charles Sabel, *The Second Industrial Divide* (New York: Basic Books, 1984)

²⁶ See for example, Richard Florida, *The Rise of the Creative Class*, (New York: Basic Books, 2002)

²⁷ up from 53% (algebra II), 49% (chemistry) and 22% (physics) in 1990.

²⁸ Mathematics standards (<http://standards.nctm.org/document/>), Science standards (<http://books.nap.edu/books/0309053269/html/index.html>)

²⁹ <http://www.iteawww.org/>

³⁰ For example, the National Assessment of Educational Progress assessment measures students’ performance in a number of subjects, including mathematics and sciences, in the 4th, 8th, and 12th grades. It uses up-to-date subject frameworks and the latest in assessment methodology.

³¹ FIRST stands for “For Inspiration and Recognition of Science and Technology,” <http://www.usfirst.org/>

0.8% will get a bachelor's degree in computer science. For those studying engineering, over half of their coursework will focus on the engineering sciences—the use of science principles to analyze and describe technological systems and applications. Most of the teaching in these courses is lecture-based, with the principles presented in a deductive manner, while students turn in weekly problem-sets with single right answers. Occasionally engineering science classes are accompanied by hands-on laboratory assignments that emphasize the use of principles to solve open-ended problems. In these laboratory settings the teaching staff acts as guides or mentors, and students work in teams of two or three. The best laboratory experiences have students learning to work with uncertainty, exercise judgment, and express findings in written form. It is common to hear students say that their laboratory assignments are among their most time consuming and that some of these assignments are among the most valuable in their education, and yet students generally get very little course credit for laboratories.

There is also a complicated international overlay to this situation. While 85% of doctoral degrees awarded by U.S. universities in 2002 went to U.S. citizens and permanent residents studying the humanities, this was only true of 55% of doctoral degrees in the physical sciences and 39% of doctoral degrees in engineering. Four of the top five countries whose students earned science and engineering doctoral degrees feature education systems that emphasize highly directed approaches to learning: China, South Korea, India and Taiwan—with the fifth being Canada. Thus, the majority of future educators in science and technology will not necessarily be oriented around challenging traditional educational methods. Further, innovation in education may be essential to attracting more U.S. citizens to these fields.

A growing number of engineering programs include courses in learning how to design. These are not only “capstone” senior level courses, but also freshmen level courses and seminars. In these classes students (generally working in teams of three to six students) solve open-ended design problems. They learn that there is a design process with stages and underlying principles, such as the value of initially generating a widening set of design options that can be winnowed down and refined through the use of prototypes. Students also learn that communications (visual, written, oral) and a combination of creativity and resourcefulness are essential to successful design. The product of students' work may be a written report, oral presentation and/or working prototype hardware. Industrial sponsored design projects are becoming more common at the senior level, whereas at the freshmen level the instructor generally authors the design problem. Faculty frequently serves as consultants or mentors to the student design teams. Few design experiences engage students in basic need finding (i.e., discovering and defining an arena ripe for technological innovation). Similarly, much more could be done around building experience with prototype development. Still, these are valuable experiences that also illustrate the value and limits of engineering science principles.

Inventive Qualities and Enduring Dilemmas

In the preceding chapters it was noted that invention, design, and creativity are defining features of human existence. The characteristics of inventors and the extended nature of the inventive process described in the previous chapter form our guiding assumptions as we examine the influence of education on inventiveness. Building on these guiding assumptions, the education workshop participants identified a set of enduring dilemmas that surround inventive activity.³² The dilemmas are particularly relevant to the educational experience, but also are at play in industrial settings where invention is practiced. Effective engagement of the tensions associated with these dilemmas is the essence of recasting education in order to advance inventiveness.

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

Disciplined vs. open-ended exploration: Inventive activity involves disciplined (convergent) and open-ended (divergent) thinking. They have 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 undercut or reinforced by competitive dynamics. Competitive pressures and cooperative partnership are both essential to innovation in the “real world.”

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 by 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 forms of feedback given to students.

³² 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.

Outcome focused vs. process focused: The aims to produce a final product and the importance of having a successful learning experience are frequently in tension—particularly because there are time constraints on the learning experience.

There is no right or wrong way to resolve these tensions—these all involve hard choices. We highlight the tensions here so that the choices can be intentional on the part of instructors and learners. Indeed, effective learning about invention and inventiveness may involve a balance between both aspects of a particular dilemma during the course of the educational experience.

Disconnects of Current Educational Systems with Invention

In current education practice, the tensions listed above are too often resolved in simplistic ways that work to the detriment of the fostering of inventiveness. Education at the university level in engineering and other fields, and in K-12 settings, rarely has inventiveness as a goal. Perhaps this is to be explained by beliefs that creativity and inventiveness cannot be taught, or by reference to the previous era where education and socialization of industrial workers did not require or even desire fostering inventiveness. Instead, students and workers were to complete structured tasks that had been set forth by experts. Symptoms of a lack of focus on invention include the following:

- An overemphasis on deductive learning and underemphasis on experimental and inductive learning—principles separated from their context, use, and application.
- Curricula that provide 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.
- Learning formats that are highly structured, constraining the expression of ideas; too rapid a pace of learning (such as endless problem sets) undermining the open-ended reflection and self-assessment necessary for invention.
- Inadequate balance between building a body of knowledge and the creative use of the knowledge (e.g., insufficient use of open-ended problems).
- Insufficient attention and appreciation given to the important role of failure and learning from failure.
- Faculty appointments, promotion, and tenure requirements that do not emphasize invention or the teaching of inventiveness and may even discourage these activities; inadequate appreciation given to the importance of individuals developing and constructively channeling their personal passions that are crucial enablers of invention in society.

Among broader problems associated with inventiveness in education is the fact that, although there are identifiable “islands of success” where the teaching of invention and design has been done well, broad diffusion has not occurred. Insufficient mechanisms exist today to help instructors develop the capability to foster interactive, self-directed learning. Insufficient mechanisms link together instructors who are innovating in the way that they teach about design, engineering, and creativity. While the culture of the engineering and design professions that host invention has been changing, there are still barriers encountered by women and minorities.

Where We Would Like to Be

Our workshop developed a vision of what we would like the educational process to become, with technological inventiveness as a key goal. Here are elements of an educational vision in which inventiveness is strongly advanced:

Widely shared value placed on invention. Educators would see the development of capability in inventiveness as being at the core of education at all levels: primary, secondary, undergraduate, graduate, and continuing education. Citizens would be aware of basic design principles and appreciate the importance of creativity, invention, and design in society.

Integration into curricula. There would exist a robust combination of courses throughout the curriculum specifically on design and invention. Problem solving, invention, and design would comprise the key organizing framework for courses teaching fundamental principles in engineering and other domains, including the sciences, social sciences and humanities. Thus, direct connections would be made between specific principles and personally meaningful application contexts. There would be systematic building of the capability to explore the question of, “Why is this the way it is?”

Balanced individual and group development. Curricula would provide opportunities for individuals to develop their own personal “voice” or “style” as designers, inventors and engineers, as well as an understanding of their own strengths and weaknesses. Curricula would provide opportunities to develop the social and technical competencies needed to be a successful member and leader of a design team.

Balance between academic discipline and creativity. Appropriate attention would be given to the way that disciplined capability can enable pushing at boundaries and thinking “outside the box.” Discipline-focused courses would also stress the importance of boundary transgression.

Appropriate attention to initiative, expression, and pace. Curricula would give support to individual initiative and self-discovery without always specifying in

advance expected learning outcomes and answers. There would be 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 would have strong incentives for teachers and professors to devote the time and energy needed to advance invention in the curriculum. Educational organizations and institutions would 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 ideas and learning materials, and other related enablers. There would be facilitated exchange across primary, secondary, university, and industry settings.

No barriers to entry in the profession. The profession would be appropriately reflective of societal demographics; for example, half of engineers and inventors would be women. The community of engineers and inventors would be characterized by mutual respect, dignity, and appreciation of diversity in perspectives, background, and other dimensions. “Free workshops” and “local invention homes” would be widespread, thriving, and connecting students at all levels with one another and inventors, operating so as to minimize barriers to entry to the invention profession.

Getting from Here to Where We Want to Be

We are today far from an educational utopia with respect to technologically creative inventiveness. Perhaps this is a result of the original purpose of education as implemented over the past 200 years. In any case, we conclude that changes must be deep and broad—to advance the principles of inventiveness and to do so in a way that is inclusive. Fundamental structural changes will be needed. As Boston community activist Mel King observed, “The rear wheels of the train don’t catch up with the front wheels unless something dramatic happens.” Our recommendations in this section are in the spirit of “necessary first steps,” but we believe there is urgency to getting started on this journey.

Policy Implications and Recommendations

Inventiveness should be made an explicit goal of education at all levels. Sustainable inventiveness should be explicitly embodied in the National Standards for Education for K-12 and in the ABET criteria, which is a university-level engineering accreditation. Inventive output should be explicitly considered and heavily weighted in college admission criteria, educational outcome assessment at all levels, university ratings systems, and teacher evaluations including tenure considerations at the university level.

We propose 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 we envision a more intensive and widespread initiative resulting in centers of varying size. The largest of such centers could host or facilitate programs such as science fairs, FIRST contests, InvenTeams, or Camp Invention, while the smaller ones could host individuals and teams preparing for such activities or carrying out independent creative endeavors. We call on industry, foundations, and philanthropists to play a strong role in creating these local centers where invention is practiced, learned, critiqued, and celebrated. The centers would involve accessible materials, tools, and flexible space that are essential to invention. We envision something of the significance and scale of the “free Carnegie libraries” that were so important to educational progress in the United States (and United Kingdom) a century ago.

We encourage 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.

Educational Practice Implications and Recommendations

The policy recommendations above require actions at the working level, including explicit placement of invention on educational agendas. Institutions of higher education, particularly engineering schools should:

- Develop and implement workshops in instruction that utilize interactive modes of pedagogy.
- Lead in development and energetic use of exchange mechanisms for effective teaching and learning of inventiveness 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 as well as engineering and social science 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. In addition, explore the potential for a post-MS degree focused on discipline-focused invention, and explore the role of “teaching practicums” as part of doctoral education.

- Implement tenure and promotion criteria that weigh invention, teaching of invention, and contextual application at least as highly as deductive scientific achievements and the teaching of disembodied principles. Many of these criteria could be founded based on the dimensions of academic scholarship outlined by E. Boyer in his influential report *Scholarship Reconsidered: Priorities of the Professorate*.³³

Universities and foundations should jointly and aggressively pursue a new series of learning materials that would integrate application context and learning of principles. Such learning materials would provide open-ended problems and environments utilizing modern computer-assisted learning tools, complementing (if not replacing) the current set of standard assignments in foundation courses. These materials would provide the basis for uniting the currently separate activities of application and learning basic knowledge. The problems would be designed to cover the spectrum of learning of principles needed for proficiency in given disciplines. An excellent 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.

To execute these recommendations, engineering schools should foster development of courses where the invention process is fully integrated with the learning of fundamental principles. Such problem-based learning could build upon the results of educational developments at Aalborg University in Denmark that have proven effective over the past 25 years.³⁴ Four other recommendations are intended for all institutions of higher education:

- Teaching of creative problem solving through Visual Thinking, as pioneered by R. H. McKim of Stanford 30 years ago, should be widespread.³⁵ Increased emphasis on visual thinking as a critical component of design and invention is needed to balance the necessary but excessive attention to symbolic manipulation and language skill learning that is currently emphasized in education.
- Early, continuous, and intensive learning about how things work should be instituted—for all students, not just in engineering education. The ability to engage in technological invention requires an appreciation and understanding of how the man-made world around us operates.
- Individual inventive learning courses as well as team invention learning courses should be instituted throughout all curricula.

³³ Ernest L. Boyer, *Scholarship Reconsidered: Priorities of the Professorate*. (The Carnegie Foundation for the Advancement of Teaching, 1990).

³⁴ Finn Kjersdam and Sig Enemark, *Project Innovation in University Education* (Aalborg: Aalborg University Press, 1994)

³⁵ Robert McKim *Experiences in Visual Thinking* (Brooks-Cole, 1972)

- Easy access should be provided to hands-on and individually-driven inventive activities that extend beyond courses.

To effect these needed policy changes at the K-12 levels, an important step would be to develop and implement workshops to help teachers learn how to manage, survive, and enjoy a chaotic, project-based classroom in which students pursue projects based on their personal passions. Effective models for allowing teachers to acquire such skills have been demonstrated in the Carlson and Sullivan initiatives throughout the state of Colorado³⁶ 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.

We recommend continued pursuit of sharing and cooperation mechanisms for best-practice teaching such as those established and funded through NSF.³⁷ We also recommend strengthening and extending programs that foster and support the doing of design and invention in schools and colleges in innovative ways. These include FIRST, the National Collegiate Inventors and Innovators Alliance (NCIIA),³⁸ and the Lemelson-MIT Program’s high school InvenTeams. These consortia should consciously focus on invention and the successful teaching of inventive skills to the greatest extent possible.

Research Implications and Recommendations

An ambitious but important area of research would be to develop a design-oriented view, rather than a naturalistic view, of knowledge, with the aim of transforming much of the way knowledge is thought about and taught. A second key area for research would be development of metrics to assess the impact of different educational programs on inventive capability.

A further area of useful research would be study of the educational backgrounds of large numbers of successful inventors. The study of “quick learning” techniques used by such inventors would be of significant use in achieving a deeper understanding of these techniques so important in invention. Studies of the diffusion of invention-related educational innovations would be useful in determining the factors important to successful diffusion.

A further important research question would involve the effect an educational process that emphasizes self-learning, pursuit of personal passions, and invention would have on attraction and retention of students to the technical fields. Particularly significant would be attracting and retaining women and

³⁶ See for example <http://itll.colorado.edu/ITLL/>

³⁷ See for example <http://www.wcer.wisc.edu/cirtl/>

³⁸ <http://www.nciia.org/>

minorities to these fields. Although many workshop participants believe that focusing on invention in education can significantly contribute to the solution to some of the barriers-to-entry problems, we are not aware of firm evidence. In this respect, we know that disconnects in education can stifle inventiveness, but we still have to demonstrate that effective education can transform and extend the role of inventiveness in society.

VIII. IN SUPPORT OF INVENTION – INTELLECTUAL PROPERTY ³⁹

Mark B. Myers

The intellectual property system in the United States is held both in high respect and with some degree of caution across the world. The United States is currently going through unprecedented growth in the strength of intellectual property protection for the many varied forms of creative work. Intellectual property rights are being extended, vigorously asserted, and aggressively enforced. There is a general sense that the intellectual property system, patents, copyrights, and trade secrets are working well and contributing to the social welfare. This period of increased intellectual property protection coincides with an historical period of rapid technological advance in telecommunications, computing, biotechnology, and emerging areas such as nanotechnology. It coincides as well with a period of revival in United States' productivity, from about 1.4% to greater than 3%. There is a sense that in high technology industry there has been a restoration in the country's competitiveness.

However, like any set of laws and practices, these forms of protection sometimes are misinterpreted and misapplied, and they sometimes yield inconsistencies, loopholes, and unintended consequences. Because these rules and laws exist to support and stimulate the human activities that gave rise to them in the first place, we ask these overarching questions: How well does our current system of intellectual property support the creative process of invention? What are the ways it can be improved?

To answer those and related questions, in September 2003 the Lemelson-MIT Program convened the distinguished group of experts in the area of intellectual property listed at the beginning of this report. Our participants included professors of law, economics, engineering, and management, as well as patent attorneys, intellectual property researchers, a university patent office director, a former director of the U.S. Patent and Trademark Office, inventors, and entrepreneurs, with many of our participants taking on more than one of these roles over the course of their careers. The goals of this report are to summarize the discussion of the critical aspects of intellectual property and to reach conclusions about how to change the system to better support and stimulate invention.

³⁹ This paper is based on the findings of a two-day workshop involving attorneys, legal scholars and others, brought together to discuss intellectual property and invention. Workshop participants were: Mark B. Myers, Chair; Merton C. Flemings, Vice Chair; Evan I. Schwartz, Rapporteur; Anthony Breitzman, Q. Todd Dickinson, Rochelle Cooper Dreyfuss, Robert Gundlach, Bronwyn H. Hall, Karl F. Jorda, Stephen A. Merrill, Lita F. Nelsen, David H. Staelin, Sidney G. Winter. The author wishes to thank Evan I. Schwartz for his excellent work as rapporteur. The full report of the workshop, "How Does Intellectual Property Support the Creative Process of Invention," is available on the Lemelson-MIT Program Web site (<http://web.mit.edu/invent>).

Contrasting Different Forms of Intellectual Property

All forms of intellectual property protection represent bargains between creators and society. They are a series of trade-offs in which creators are granted limited rights in return for the benefits their creation provides to the rest of us. But each of the different forms of intellectual property possesses a different set of these trade-offs. These bargains must be viewed in the larger context of success in business. Companies need to create new products or improve their current ones. When individuals or teams traverse the path toward those goals, what sorts of intellectual roadblocks arise?

To answer these questions, consider the three different forms of intellectual property and contrast their costs and benefits. Those three forms are copyrights, patents, and trade secrets. Three questions can be asked about them:

- First, can you go there? In other words, can you acquire the knowledge that is represented by that particular piece of intellectual property?
- Second, can you stay there? Can you use that piece of intellectual property as part of your own solution to your problem without making a deal for it?
- Third, can you do it yourself? Can you acquire an equivalent result?

	Copyrights	Patents	Trade secrets
Can you go there?	YES – except for software’s hidden “source code”	YES – upon publication	NO
Can you stay there?	NO – except for “fair use” of short quotes	NO – not without licensing	NO
Can you do it yourself?	YES – express the ideas differently	NO – the basic ideas are protected	YES – come up with the ideas on your own

With copyrights, anyone can go there for the price of admission. Anyone can read or see or hear copyrighted works such as books, articles, movies, or music. The exception is the source code for software—the lines of computer language—which are not disclosed beyond the confines of the company that distributes the executable version.

With copyrights, though, you cannot stay there. The law clearly says that you cannot plagiarize a copyrighted work. Under the “fair use” provision, you can quote a small snippet or a few bars of a tune without making a deal for the rights, but you cannot appropriate more than that. You can, however, work around copyrights. Copyright does not bar you from absorbing the content and using its ideas for your own purposes. So when you are trying to make your way in the creative process through a space occupied by copyrighted

intellectual property, this is not a very serious problem because you have easy access to the texts, and you can absorb the knowledge and express it in a new way.

In this sense, patents provide a stronger form of protection. Upon publication, typically 18 months after filing, anyone can access patents, but you cannot stay there or appropriate the ideas without negotiating for a license. In contrast to the copyright case, you can infringe the patent without doing anything that the patent holder is actually doing. That is what creates the greater blockage effect of the patent.

By comparison, trade secrets are much simpler. Typically, such secrets are bound by employment contracts. The recipe for Coca-Cola is a famous example of a trade secret. If you have not signed a non-disclosure agreement with Coca-Cola, you are not prevented from trying to duplicate the recipe and market it under a different brand. Unlike patents, trade secrets enable others to mimic what you have done, provided they do not violate a specific secrecy agreement. Companies do not often let outsiders visit their factories where they practice the ideas that are protected by trade secrets.

Different forms of protection overlap in many ways and often dovetail together. The greatest synergies can be found between patents and trade secrets. Trade secrets often protect a set of associated know-how that can make patents more valuable. Trade secrets can be licensed along with patents, under hybrid licenses, and they can triple the value of the technology license. Some regard a patent as little more than an advertisement for the sale of the company know-how. You can integrate patents and trade secrets for optimal, synergistic protection of innovation. That is because trade secrets often include the best mode of practicing the invention, which often gets developed after the associated patent is filed.

Incentives and Rewards for Invention

Understanding what causes people to invent and to disclose their ideas is critical to the understanding of intellectual property. A primary motivation for invention is the satisfaction in solving a socially important problem. A prolific inventor remarked, “I was not motivated to pile up patents. I enjoyed opportunities to figure out how things worked and how to make them work better.”

Other primary motivators for stimulating invention in individuals include:

- Professional reputation, recognition, and advancement
- Altruism
- Financial gain
- Intellectual “currency” within organizations

The experience of the group suggests that patents are secondary motivators for invention. The statistics of patents would bear this out, with only about 10% of U.S. patents becoming economically important, and less than 1% becoming of seminal value. Many useful inventions are openly shared, such as open source software, or held as trade secrets, such as the source code for the original implementation of page description languages.

Patents unquestionably protect entrepreneurs who are striving to commercialize new ideas. Patents signal to venture capitalists that you are a firm that is worth investing in. Of course, that does not mean that the venture capitalist actually reads or understands the patents. But even the general public has a sense that a product is better because it is patented. An historical example is patent medicines; they were patented so that people would think that the medicines did not contain just narcotics or alcohol, and that these medicines really were making you better for some scientific reason.

The experience of a MIT venture-mentoring program, which currently has about 50 startups in its portfolio, finds that in about 95% of cases, the founders or the mentors are worried about protecting their intellectual property and thus seek patents. Having patents not only helps these startups raise money, but it also provides the perception that their innovations will not be stolen when the company is ramping up its business. The motivation of these students is not royalties but the opportunity to start their companies.

When the companies start to grow and mature and become profitable, their patents play a more substantial role. If the company does not have the proper protection at that point, they can be sued by a rival startup or by a big company, and such a lawsuit would be damaging if it came at a critical moment, such as during a marketing campaign or an initial public offering.

In this respect, patents can be considered insurance. Only about 10% of patents or patent applications in the United States and 8% in Europe are challenged by third parties at some point in their lifecycle. And only about 2% of patents in the United States and about 1% in Europe become the subject of litigation. But like insurance, the cost of not having patents can be extremely high, and businesses and their investors do not want to carry that risk.

Patents can eventually lead to wider economic and social benefits and rewards. However, there is not necessarily a direct connection between patents and financial gain, or between increased patenting and increased motivation to invent. Other things need to happen in order for intellectual property to pay off. Patents typically have an indirect effect on the creative process of invention.

The Impact of the Patent System on Invention

The patent system has been transformed over the past 25 years by an unusually large number of significant changes. Some of these changes are legislative, and even more of these changes are from the courts, applying the law to new circumstances. Collectively, the impact on invention has been dramatic. The largest of these changes can be summarized as follows:

1980: The Bayh-Dole Act creates a new category of patent holders, namely universities and non-profit research institutions

1980: Genetically modified organisms patentable through *Diamond vs. Chakrabarty*

1981: Software is patentable through *Diamond vs. Diehr* and *AT&T vs. Excel* (1999)

1982: The Court of Appeals for the Federal Circuit is established to consolidate appeals of federal patent cases, establishing uniform guidelines for patent enforcement and resulting in higher rates of patent validity

1988: Process patents granted by the USPTO

1991: *Polaroid vs. Kodak*; \$1 billion in damages awarded for first time

1994: TRIPS agreement for international intellectual property recognition

1998: Business methods are patentable through *State Street vs. Signature Financial*

These and other developments have contributed to a general expansion of rights and benefits for patent holders. It is much easier and more common in intellectual property (IP) law to expand rights rather than take them away. Intellectual property protections tend to be a one-way ratchet.

This expansion of rights may have contributed to the simultaneous surge in patents applied for and issued. The United States issued between 60,000 and 70,000 patents per year from 1965 through 1983. Then there was a sharp spike upward, leaping to about 170,000 per year by the late 1990s. During this time, we have also seen higher renewal rates and a more frequent asserting of patent rights. Since 1988, the number of patent lawsuits filed in U.S. District Court have doubled, and overall patent litigation rates have increased tenfold over the past two decades.

CHI Research has found that the increased rate of patenting has naturally favored large multinational corporations who can best afford to file and assert large numbers of patents. About 41% are now assigned to U.S. corporations. Foreign corporations now receive nearly half of U.S. patents, up from about 40% in 1980. Individually owned patents have declined slightly over this period, to about 9%. Only about 2% of patents are university owned, and government owns 1%.

Not surprisingly, patenting is highly correlated with R&D spending. About 100 companies account for 70% of the R&D in the United States, and about 20 universities represent a very substantial portion of academic R&D, according to CHI. But we are also seeing increased patent productivity among big firms. The number of patents yielded on dollars of R&D spent is increasing within large firms. This concentration is spreading to large government and university laboratories as well.

In terms of high-impact inventions, there is still a substantial amount of independent and small company invention. Many of the individual inventors are small companies, and so small companies are very significant. Where do small companies patent? The data show real barriers to entry in aerospace, motor vehicles, oil and gas, computing, and plastics. More than 97% of the patents in each of those areas are being issued to large corporations. Small companies, meanwhile, are showing strength in biotechnology, pharmaceuticals, and medical electronics. About 25% of patents in these industries are being issued to small companies and individuals.

Numbers, of course, only tell a part of the story. Numbers of patents correlate with money spent on R&D. Because only a small number of patents—an estimated 1%—turn out to be of high value or have a high impact on the marketplace, the sheer numbers do not reveal where these high-impact patents are being generated. To find these kinds of patents in its database, CHI Research looks for patents that are highly cited by writers of other patents. Universities and small companies tend to have a disproportionate share of highly cited patents.

Historically, high-impact inventions have tended to come from individuals. Historians look back at inventions and divide them into two different categories: macro-inventions and micro-inventions. As defined in previous workshops, macro-inventions are the pioneering creations that change the world in a significant way. Examples include the light bulb, the photocopier, the laser, and the airplane. They are also inventions that lead to hundreds or thousands of follow-on inventions and improvements, which are the so-called micro-inventions.

That trend is still alive. Pioneering patents are disproportionately created outside big corporations, by individuals or universities. As an example, in the encryption software industry, all the important players are small firms, startups, or new entrants. Big firms have patented in that area a great deal, but they are not big players in the industry. By far, the most highly cited patent in that class is held by MIT, namely the patent from Professor Ronald L. Rivest that formed the basis of RSA Data Security. Another example, previously mentioned, is the Cohen-Boyer patent, developed at Stanford, which formed the basis of Genentech and the biotech industry.

However, there are also many instances of high-impact corporate patents. Hewlett-Packard's inkjet patent was cited 450 times over a 12-year period, for example. This is the patent that made inkjets ubiquitous and has dramatically changed the home printing and photo-finishing marketplace. Inkjet printers had been around since 1970, but were complicated and expensive. In 1979, a Hewlett Packard engineer named John Vaught had the idea of doing away with inkjets that work by vibrating the cartridge. Inspired by watching a coffee percolator, Vaught got the idea of making the process work by rapidly heating the ink and shooting it out a tiny nozzle.

High-impact patents often have the most dramatic effect on the company that holds that patent, as the owner has the unique chance to build on its own innovation. Every patent creates the opportunity to create more patents. Robert Gundlach says that his 155 patents would not have happened if Chet Carlson had not had his seminal xerographic invention and patent. He is referring to the pioneering patent created by Chester Carlson in the late 1930s; it is the patent that led to further research in xerography at the Battelle Institute and was later sold to the Haloid Corporation, which changed its name to Xerox. Invention, therefore, breeds more invention.

That brings us back to one of our main questions: Do patenting and the patent system increase associated innovative activity? The picture is mixed. Overall, one cannot conclude that patents are uniformly good or bad for invention and innovation but that they have costs and benefits or a set of tradeoffs. The economics of the patent system can be described as follows.

Effects on:	Benefits	Costs
Innovation	<ul style="list-style-type: none"> Creates an incentive for research and new product/process development Encourages the disclosure of inventions 	<ul style="list-style-type: none"> Impedes the combination of new ideas and inventions Raises transaction costs for follow-on innovation Provides an opportunity for rent-seeking
Competition	<ul style="list-style-type: none"> Facilitates the entry of new (small) firms with a limited asset base or difficulties obtaining financing 	<ul style="list-style-type: none"> Creates short-term monopolies that may become long-term network industries May be used to maintain a cartel

The benefits are valuable but the costs can be high. The patent is the granting of a limited monopoly, which is negative for competition. It tends to raise prices on that product. In certain types of industries that reside on standards, such as computing, software, or telecommunications, the patent gives an

advantage in that it may make the monopoly relatively longer-term, because everybody adopts an associated standard. We can point to the rise of venture capital as a benefit, but the pooling of patents between large companies that trade portfolios is a hindrance to competition. Pooling can give rise to a cartel.

Intellectual property rights may have an effect on the organization of industries. Whereas industries in the past may have been dominated by large and centralized R&D labs, innovation is now coming from hundreds of smaller independent firms and individuals. This has been enabled by the vertical disintegration of industry. The transactions across firm boundaries can be enabled by intellectual property rights. It can also be argued, however, that such disintegration is happening regardless of patents. The Internet and other information technologies create the ability to perform projects as ad hoc groups, rather than within a firm. The way that work is done is changing now for reasons that have nothing to do with the patent system. For example, there is much more interdisciplinary work that is being done. For your average medical invention, for example, you need a chemist, a biochemist, a biotechnologist, and a statistician. So there are a lot of different people whose skills are all necessary to bring a product to market.

Many of the participants agreed with the statement that “where you stand depends on where you sit.” In other words, if you are benefiting from patents at the moment, you extol their virtues. If you are on the wrong end of an infringement suit, you curse their faults.

This deep ambivalence may be inherent to the nature of the patent system. A Canadian study concluded that increased innovation leads to increased patenting, but increased patenting does not necessarily lead to increased innovation. Generally, economists have found that patenting does not increase innovative activity broadly, but it tends to redirect innovation. A lot of the innovation tends to be channeled to new areas. New drug discovery and biotechnology, for instance, seem to be currently benefiting from both increased patenting and increased innovation.

Concerns for the Workings of the Patent System

While our participants agree that there is no way to eliminate all of the above-cited “costs” of the patent system while retaining only the “benefits,” they also identified some major concerns that need to be addressed in order to maintain a reasonable balance between the costs and benefits.

Chief among those concerns is that the “experimental use” of patented subject matter—the so-called research exemption—is under fire. This is primarily due to the *Madey vs. Duke University* court ruling denying a research exemption for pure inquiry into subject matter under patent protection. The *Madey vs. Duke* decision seems to have moved or perhaps eliminated the line between non-commercial research and commercial use. As defined by the

ruling, “any conduct that is in keeping with the alleged infringer’s legitimate business, regardless of its commercial implications, is going to be considered infringing.” But how do you define a legitimate business purpose? What is a university’s legitimate business purpose? Educating and enlightening students and faculty is part of Duke’s mission. That increases the status of the institution and lures lucrative research grants. Those grants typically fund research on patented technologies. So it leaves very little room for a university to be doing any work that is going to be utilized within that research exemption.

The issue is trickier than it first seems, because universities do create commercial spin-off companies on a routine basis. Should the students in the MIT entrepreneurship program, who have every intention to make their research become a commercial success, receive a research exemption? How about the MIT professor before he or she spins out a new company as an entrepreneur? Yet a primary objective of the patent system is to encourage people to improve the prior art. If you cannot practice and test the prior art in a non-economic environment in order to improve it, that runs absolutely counter to the purpose of the patent system.

It can be argued that these cases concerning the research exemption are rare and will continue to be. As a practical matter, a commercial enterprise would be foolish to launch a lawsuit against a university conducting experimental use. With such lawsuits costing anywhere between \$1 million and \$10 million, it would not be worth the time and money to sue an academic user.

The question, though, is whether researchers feel they are being impeded and whether universities will effectively self-censor themselves in order to avoid risk. That is the chilling effect that many non-commercial institutions are worried about. When corporations feel their intellectual property is threatened, they will threaten to sue, no matter how non-threatening the alleged infringer might seem. Look at the music industry suing young people over copyright infringement. Even if you do not get sued, a letter from a large company can have a chilling effect. You take it very seriously, and it is worrisome, and it starts influencing you or your directions.

Looking at the larger picture, the participants see a major threat to the “public domain” of research, a base of common resources that have been responsible for so many innovations in the past—from the space program to the semiconductor industry to the Internet to biotech. If research universities get treated the same as corporations, in the eyes of the law, will they respond by acting more and more like corporations? Public research is already becoming more and more proprietary. Will it become more so? What were once islands of protection in an ocean of public domain are now large continents of protection, with only lakes of free access. There is reason to be concerned that there is a growing dearth of information that is freely available for inventive use.

Another significant concern over the health of the patent system is the current proliferation of low-quality patents. The participants agree that this is one of the biggest problems plaguing the patent system specifically and the overall environment for innovation in general. Patent offices around the world are overwhelmed by the growth of patent applications. There is a concern that examiners are letting a lot of patents that should be non-enforceable slip by into issuance.

There are three systems in place for judging patent quality. One is litigation over validity. This, of course, is an extremely expensive way to determine whether a patent should be considered valid or not. The second way is the re-examination process. And the third is the USPTO's own quality review process, in which they take a sample of about-to-issue patents and judge whether the decisions made by examiners were correct. These are all deficient in various ways. Most importantly, they are deficient in that they touch a very, very small number of patents.

The consequences of low-quality patents are numerous, according to our participants. Those consequences include the following:

- Low-quality patents clog the entire patent office process, leading to time delays for all patents.
- R&D areas are avoided because of thickets of obvious technologies that are patented.
- New investment slows.
- The slowing of new investment slows the advance of cumulative technologies that require building on existing ideas.
- Uncertainty increases, due to the chance that someone will appear trying to enforce rights to something that is obvious.

The increasing complexity of applications and the jump in the number of claims associated with each patent are contributing to the rise in low-quality patents. Faced with such complexity and limited examination time, examiners may be approving questionable patents, as it is much less work to approve a patent than to reject one. An observation of that National Academies study is that overall approval rates are in the range of 75 to 80%, which is higher than the traditional claim of a 67% approval rate.

To help weed out low-quality patents, a more robust opposition system could be considered. The European patent system includes more provisions for third party challenging of patent applications. Under the European system, about one-third of the opposition cases result in an overturning or blocking of the patent, and another third result in some restrictions. The benefits of

improving patent quality are clear. First, it results in more valuable patents once they are issued. Second, it eliminates many costly lawsuits. Third, it increases the overall reputation and confidence in the patent system.

Improving the Patent System to Better Support Invention

When it comes to making change to intellectual property laws and practices, especially the patent system, it first helps to keep in mind how difficult it is to bring about wholesale change.

There are several reasons, the first of which is success itself. The U.S. patent system has been around for 220 years. There is a huge mythology about patents. If you polled the average person on the street about patents—and they do this sometimes with juries—you find that people have a huge respect for what they believe the system to be. They think the system is good and working well, and that it serves the purpose of not only advancing the technological interests but also the economic interests of the United States and has for a long time. It provides that one great opportunity—which is the greatest of all American myths—for the little person with the great idea to take it and run with it, build a business, and become wealthy. And that mythology is very hard to overcome.

The other roadblock is the conservative nature of the system. Corporations by their very nature are risk averse. Most attorneys do not like the rules to change because of the complexity created for their practice. Finally, there is the highly influential independent inventor community that has proven that it can mobilize its forces when it feels threatened. Even if you could get all of these major constituencies to agree on something, to get the Congress to focus on this issue of patent reform is very challenging.

That said, the system could be changed if it is done in a highly targeted and disciplined way. The areas of change to improve quality that our participants have targeted are:

- New standards for searchability, making it easier to search the patent applications themselves as well as databases of prior art that include technical journals and other sources outside the patent office. Additional research into search tools would be an appropriate area of funding for the National Science Foundation.
- Better compliance and incentives for full disclosure of searches, so that prior art is uncovered during the search and examination process. The government should provide better facility and databases for searches at little or no additional costs to inventors.
- Higher standards of non-obviousness so that inventions that are clearly obvious do not find their way into patents that may have to be litigated or invalidated later.

- The implementation of a post-grant review process appears to be a useful way to strengthen the quality of patents by resolving earlier the questions of validity.

Fixing this problem of low-quality patents is going to take time and money. Whether the solution lies in hiring more examiners, in paying more to retain them as they gain experience, or instituting a new post-grant review process, the solution is going to require investment. Under the current director James Rogan, the USPTO has published its “21st Century Strategic Plan.” Among the most important issues it addresses is funding for the USPTO. For several years Congress and the Executive Branch have looked upon fees as an additional source of general revenue as opposed to financing a specific activity, so the patent office has to negotiate separately with Congress on its funding, independently of the fee structure. On the current patent application fee basis, there should be adequate funding to support the improvements that the intellectual property system requires.

IX. INVENTING A SUSTAINABLE FUTURE ⁴⁰

Julia Marton-Lefèvre (Chair)
Ehsan Masood

“A global human society characterized by islands of wealth, surrounded by a sea of poverty, is unsustainable.”

This is how Thabo Mbeki, South Africa’s president, opened the World Summit on Sustainable Development in Johannesburg in the summer of 2002. The Summit was the largest gathering of its kind in more than a decade. Its aim was to provide a commitment at the highest level to reversing the poverty and environmental degradation that continues to blight our planet.

As the overview section of this report states, invention and innovation have helped many attain a standard of living that would be the envy of even the most privileged citizens of earlier centuries. Nonetheless, the fruits of human ingenuity have completely bypassed more than two billion people—the world’s poorest. Moreover, several technologies that have been central to the gains in our quality of life—including the internal combustion engine and Green Revolution agriculture—are now known to cause potentially irreversible harm to the global environment in the form of human-induced global warming and the unprecedented loss of biodiversity that we are currently witnessing.

Sustainable development is an attempt to resolve this paradox. It is the quest to find models of development that allow all of the world’s people to enjoy a better quality of life, without compromising the ability of future generations to do the same. It is, without a doubt, perhaps the most difficult challenge of our times, but one that all the nations of the world know they must tackle, whether through meetings like the Johannesburg Summit; the many United Nations agreements to protect the environment; or the recent Millennium Development Goals, a plan by world leaders to reduce poverty and help the environment to recover, complete with targets and timetables.

Creative Thinkers Wanted: Invention in Sustainable Development

What, then, is the role of invention and innovation in the transition to sustainable development? Human creativity thrives when challenged to find solutions to real problems. And sustainable development is already testing

⁴⁰ This paper is based on the findings of a two-day workshop involving social entrepreneurs, inventors and others, brought together to discuss invention and sustainable development. Workshop participants were: Julia Marton-Lefevre, Chair; Merton C. Flemings, Vice Chair; Evan I. Schwartz, Rapporteur; Shereen El Feki, David Grimshaw, Pamela Hartigan, Ashok Khosla, Zhang Lubiao, Penelope Mawson, Nick Moon, Adil Najam, Julia Novy-Hildesley, Anna Richell, Ammon Salter, Eugenio Singer, Rory Stear. The author wishes to thank Evan I. Schwartz for his excellent work as rapporteur. The full report of the workshop, “Invention and Innovation for Sustainable Development,” is available on the Lemelson-MIT Program Web site (<http://web.mit.edu/invent>).

the brightest minds and the most creative intellects. Innovation, according to Civic Entrepreneurs, a seven-volume survey of 100 global projects in sustainable development, is common to all of those that have been shown to work. The study's co-authors, Adil Najam of Tufts University and Tariq Banuri of the Stockholm Environment Institute, write in the first volume:

Sustainable development is more likely to come from innovative responses than from the replication of routine solutions: since business-as-usual got us into this mess in the first place, investing in more business-as-usual is likely to only worsen the mess. The domain of sustainable development is the domain of bold thinkers and innovators.

Ashok Khosla is founder and president of Development Alternatives, a New Delhi-based not-for-profit organization that invents technology products for India's rural poor. He suggested at our Workshop that there are essentially three types of invention in developing countries: The first is the "copycat." This refers to the fairly widespread and often unauthorized replication of ideas, technologies, and techniques that originate in developed countries. The second is the "piggyback." This refers to those companies in developing countries that provide manufacturing and service-based operations for richer countries but at much lower costs. The third is the "leapfrog." This refers to the ability of poor countries to bypass inappropriate technologies on the road to more sustainable ones. For example, many parts of Africa that do not have landline telephones could soon adopt wireless networks without the need to first install fixed-line connections.

Promoting invention for sustainable development in many ways is no different from promoting invention in its conventional sense. All of the recommendations of this study would apply to invention for sustainable development in both rich and poor countries. These include: supportive public policies; professional and social environments that pick out and encourage creative individuals; education systems that develop and reward free-thinkers; systems of intellectual property protection that reward creativity, without acting as a brake on the creative process; and collaborative networks of inventors and scientists to exchange ideas and feedback.

The Challenge for Inventors in Poor Countries

Inventors in poor countries face additional constraints not always found in the developed world. For example, the state mostly cannot be relied upon to provide assistance to inventors; nor can it be expected to enact supportive legislation. This is largely because invention and innovation are not considered high political priorities. In most developing countries, public sector institutions suffer from low levels of trust and high levels of cynicism among ordinary citizens—people mostly do not believe that a government's role should be to improve the lives of its citizens.

This report concludes that education systems worldwide are currently not set up to encourage or reward creativity in pupils. This is particularly the case in the poorest developing countries, where rote learning and outdated syllabuses dominate the curricula of state-run schools.

But unlike their colleagues in developed countries, inventors from some of the world's poorest regions suffer from additional challenges: First, they have few formal ways of obtaining finance for research and development, production, and marketing of their products. Second, inventors have few avenues to network with fellow inventors, share ideas, and receive feedback. Third, the ability to encourage and develop a culture of invention is made more difficult in countries with a strong tradition of patriarchy or those that have authoritarian systems of government. And fourth is the virtual absence of role models—far fewer than in developed countries. China and India could be seen as an exception to this. In China, for example, the government has taken the unusual step of publicly handing over the task of developing a new generation of high-yielding rice to a single prominent scientist, Yuan Longping.

A Social Role for Inventors?

Inventors from the poorest countries often have to shoulder a much larger burden of responsibility compared to their peers in richer countries. Not only do they develop their ideas in a less favorable environment, but they also have to work that much harder to raise finances for research, as well as the mass-production and marketing of their products and ideas. Many find themselves doing three jobs, instead of one: that of the government, entrepreneur, and inventor. In the research literature, inventors who take on this broader role are becoming known as "social entrepreneurs."

Ashok Khosla, referred to earlier, is an excellent example of a social entrepreneur. His organization, Development Alternatives, develops technology-based products intended for India's 700 million rural poor—some 70% of the population. In most rich countries, the state assists its poorest citizens by providing them with a minimum standard of housing, healthcare and education. It also provides schemes and incentives to those looking for employment. This is not the case in the poorest countries, including India. In the United States, Khosla—who trained in physics and lectured at Harvard University—might have been a brilliant inventor. But in India, he has to be an effective social entrepreneur too, if he wants to see his ideas take root in society.

Over the past two decades, Development Alternatives' 500 strong staff has invented many new products aimed both at making lives easier for the poorest and creating jobs at the same time. These products include: a hand-operated press that converts mud into low-cost bricks for housing; a low-energy, low-emissions brick kiln; a machine that makes inexpensive roofing tiles out of industrial waste; a process that turns weeds into diesel-engine fuel; cleaner wood stoves that emit fewer noxious fumes—a major source of deaths in the developing world; hand-powered looms; and papermaking machines.

The list of products is long and impressive, but Khosla knows that great difficulties exist in having his products reach those who need them most. What this means is that he has had to develop the distribution channels himself. For example, one of Khosla's most significant innovations is a system of franchised dealerships where entrepreneurs set up their own businesses distributing his products and training people in using them.

Nick Moon, also a Workshop participant, is another example of an inventor-turned-social-entrepreneur. He is the co-founder—with Martin Fisher—of Kenya-based ApproTEC, a not-for-profit organization that also specializes in technology-based products for the rural poor—products that both improve lives, and provide a means of employment. In Kenya, 85% of adults do not have jobs that pay a regular salary—most of them work on the land. ApproTEC's most famous product is its "Money Maker" foot-powered water pump that can irrigate two acres of land. It allows subsistence farmers in East Africa to increase their productivity and begin selling their crops on a larger scale. This and ApproTEC's other products, such as its manually-operated oilseed press and its concrete pit-latrine toilet slabs, have created more than 30,000 new businesses in Kenya and Tanzania—900 new businesses every month—and 35,000 new jobs.

Development Alternatives and ApproTEC may be located in different continents, and developing different products, but their experiences and the challenges they face are similar. Creating 35,000 jobs is admirable, but it represents a tiny dent in Kenya's unemployment situation. Both ApproTEC and Development Alternatives want to do more—much more. But in some ways, this extra step is proving the hardest. Despite their many successful products, ApproTEC generates revenue of only \$1.2 million per year, and Development Alternatives generates just \$2.3 million. Both also still rely heavily on aid donations—33% of income in the case of Development Alternatives. The scale of the challenge is summed up by Khosla, who says that 15 million new jobs are needed in India every year. On its own, Development Alternatives has generated 300,000 in two decades.

Finance and Intellectual Property: Roadblocks to Success

Two hurdles block the road to bigger things; one is finance, the second concerns intellectual property, and both are related. An organization that wants to raise its turnover from \$2 million to \$200 million will need an injection of new finance that is of a similar order of magnitude. This means knocking on the doors of banks and financial institutions. Khosla and Moon both work in countries where the practice of venture capital is less developed than in richer countries. Their predicament is made worse by the fact that those with the keys to the safe do not like lending to not-for-profits—often out of a justified concern that charities are not very good at running large and complex businesses. On the other hand, donor governments and philanthropic foundations are reluctant to give money to organizations with avowedly commercial aims.

Similarly, banks and venture funds want to be reassured that their investments have the maximum protection against potential competition. Often this means insisting that products are covered by patents and other forms of intellectual property protection. But social entrepreneurs like Moon and Khosla have yet to be convinced of the value of intellectual property systems. Patents and trademarks, in particular, are expensive to apply for in Europe and the United States. Moreover, social entrepreneurs want as many people to copy their designs as possible so that more people benefit from their products. This is a disconnect between the reality on the ground in many developing societies and the larger, global institutions that may even seek to foster inventiveness.

When Invention Meets Enterprise

One social entrepreneur who has successfully made the leap from small-scale to big-time is Rory Stear, founder of the South Africa-based Freeplay Energy Group. Stear talked to us about Freeplay's principal product, which is a wind-up radio that does not need batteries, or any other external power source except for human energy. A few minutes of hand cranking provide up to 40 minutes of listening time. The radios are manufactured in Asia, and profits come from sales to wealthier consumers in the United Kingdom and the United States. The radio is proving particularly attractive in the United States as an essential household item in case of a power-cut caused by a possible terrorist attack. A part of these profits is used to give away radios to the poorest, at low—or no—cost. Some 150,000 have been distributed so far, providing continuous access to information for more than 2.5 million people in Afghanistan, Africa, and Kosovo. Moreover, the patented wind-up technology is used in other Freeplay products such as water purifiers, flashlights, and cell phone chargers.

What is different about Stear, as compared with Nick Moon and Ashok Khosla, is that he is not an inventor, but rather a business professional. Indeed, the radio was not even his idea. Stear was working in corporate finance when his business partner watched the radio being described on a BBC television program. Stear and his partner bought the patent and marketing rights from the inventor and set up the Freeplay Group. Stear's financial background undoubtedly helped him to raise the several million dollars needed to manufacture and market the radios on a truly global scale, and to attract big-name shareholders including General Electric, Ben and Jerry's, and Anita Roddick, co-founder of the Body Shop.

However, Freeplay is also different in another respect. Development Alternatives and ApproTEC are concentrating on products that create and provide opportunities for a new generation of entrepreneurs. Freeplay's products, on the other hand, are of more immediate use to individuals.

Inventors and innovators—like any other type of professional—need professional networks. Networks are critical to exchanging ideas and contacts and receiving mentoring, as well as providing much-needed encouragement and critical feedback. Good ideas without the possibility of implementing them remain only good ideas. Networks play a crucial role in moving from ideas to implementation. Ashok Khosla, Nick Moon, and Rory Stear are fortunate in that they are part of one of the few such networks that has members from all parts of the world—the Schwab Foundation for Social Entrepreneurship, set up just five years ago by Klaus Schwab, founder of the World Economic Forum in Davos, and his wife Hilde. The foundation aims to build a global community of social entrepreneurs and help set standards of excellence in social enterprise. Other global networks that specifically cater for social entrepreneurs include the Ashoka Foundation and Leadership for Environment and Development (LEAD).

Not Just Business as Usual

This study begins by mentioning two important technological inventions—the internal combustion engine and Green Revolution agriculture—which have had both positive and negative consequences for people and the global environment. The challenge for the next generation of inventors is to develop technologies whose impacts are as positive as possible.

For that to happen, these new technologies are unlikely to follow a traditional path. Sustainable development is a concept that is rooted in the idea of consultation, dialogue, and research. Decisions are made after weighing the impacts they will have on people and on the environment. In the past, technological inventions have not followed such a process. Technologies have been mostly adopted according to the needs of the market with often retrospective attention paid to social and environmental impacts. More sustainable technologies will require a greater degree of consultation and evaluation than has happened in the past. Convincing ourselves of the value of this new approach to problem solving will in many ways be as challenging as finding the solution itself. But it is a challenge that all of us—inventors, innovators, and ordinary citizens—must rise to. It was no less than Albert Einstein who once said, “Today’s problems cannot be solved if we still think the way we thought when we created them.”

This report summarizes findings and recommendations of a year-long study of invention and inventiveness. We have aimed, through an interdisciplinary approach to the subject, to shed new light on invention and on the special kind of creativity involved in inventing. We have also aimed to formulate specific recommendations to foster inventiveness, and with it, quality of life, competitiveness, and sustainability. A total of 56 individuals from a wide range of academic disciplines, including history, economics, cognitive science, psychology, engineering, medicine, and law participated in the study. The study has had primarily a domestic (United States) focus, although the portion addressing sustainable development took a more international perspective due to the global nature of that challenge.

The study was carried out under the auspices of the Lemelson-MIT Program at Massachusetts Institute of Technology, with additional support from the National Science Foundation. It was released at an “Invention Assembly” hosted by the National Academy of Engineering in April, 2004. It represents, in the mind of many participants, the first phase of their continuing effort to better understand and enhance inventiveness in the United States and globally.