INVENTION

Enhancing inventiveness for quality of life, competitiveness, and sustainability

Report of the Committee for Study of Invention, sponsored by the Lemelson-MIT Program and the National Science Foundation

For Release April 23, 2004

Preface

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.

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Report

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 revolutions with their sustained outpouring of inventions, innovations, and

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[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).

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 practice 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

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

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

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.

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.

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 knowledge 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.

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

- 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.

<u>Recommendation 6. Undertake public outreach activities relating to invention and inventiveness</u>.

- 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.

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

- 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!