"HISTORICAL PERSPECTIVES ON INVENTION & CREATIVITY"

THE LEMELSON-MIT PROGRAM
School of Engineering
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FOREWORD

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

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FINDINGS

1) 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.

2) 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, their institutions, values, and incentive structures. Key to the inventiveness of a society is its culture, social priorities, and its public policies. Institutions set the incentive and penalty structure for inventive people.

3) The key to the first industrial revolution, beginning in the middle of the 18th century, is technology. Both knowledge based on discovery and knowledge based on 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).

4) 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 nineteenth 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."

5) 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.

6) Inventions 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.

7) Inventions can be characterized as either “macro-inventions” (or “radical inventions”) on the one hand and “micro-inventions” (or “incremental inventions”) on the other. Macro-inventions are those that change society in a significant way, that 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 industrial 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.

8) Economic forces, including government support of R&D, play a decisive role in the direction inventiveness takes in society.

9) In a society that is capable of generating rapid technical progress, no single invention or innovation is indispensable, since the society can readily generate substitute inventions.

10) The key to sustaining or accelerating the rate of improvement over time lies in the feedback cycle between *what*-knowledge (discovery-type) and *how*-knowledge (invention-type).

11) The provision of flexible learning environments (at home and in school) have repeatedly stimulated and encouraged inventiveness and creativity. Little is known about cultivating such seedbeds -- how they are developed, supported, and maintained.

12) Systematic exclusionary policies and cultural biases prevented blacks and female inventors from contributing to the invention process in fundamental ways throughout history. This has changed only in recent decades.

13) 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.

14) Federal support of individual investigators doing basic research has been effective in expanding discovery-type knowledge.

15) The Federal government has been less effective in finding ways to enhance among individual investigators the creativity that we term invention.

16) The historical record is replete with examples of individuals who, on the basis of personal trust in an inventor, have stimulated and supported that person's inventiveness and commercial success.

WORKSHOP DISCUSSIONS

Introduction

The human race is fundamentally characterized by its proclivity to invent, and the act of invention has usually marked the upward surge of human civilization. Perhaps no other image captures the grand arc of our inventiveness better than the opening sequence of Stanley Kubrick's film *2001: A Space Odyssey*. A group of man-apes on a barren stretch of savannah comes across a skeleton of animal bones. A new thought transpires and an evolutionary leap occurs when a member of the group grasps one large bone and begins using it to smash all the others. By removing an object from its original context and asserting it in another, by conceiving of a remnant as an implement, the man-ape sets his race on a new course. The allegory continues when he triumphantly tosses his new tool into the air. It tumbles toward the sky, soars into space, and dissolves perhaps a hundred thousand years later into a bone-shaped artificial satellite, an invention that was conceived by Arthur C. Clarke, the author of the novel upon which the movie is based. The suggestion is a powerful one: that the saga of human civilization is intimately related to the history of invention.

In between our first hand tools and our visions of space stations is a rich and contentious narrative of inventive activity. To elucidate the lessons from this narrative, the Lemelson-MIT Program, in March 2003, convened a workshop which brought together leading scholars who investigate historical aspects of invention. The mission of this report is not only to organize the perspectives of these scholars but also to illuminate the path inventors have taken throughout history so that we can better understand how our current institutions can best cultivate inventive activity. Throughout the past, new inventions have usually stimulated both short- and long-term economic growth and have often been instrumental in raising living standards, although many inventions have negative side effects and often fail to improve the lives of large population segments. The goal here is not to provide a comprehensive overview of the history of invention, but to focus on critical aspects that enable us to reach a deeper understanding of this complex subject, with the end result being a set of policy considerations that can help foster inventiveness in the future.

Throughout this report, we refer to "invention" and other related terms as they are defined by leading scholars of the subject, several of whom are participating in this workshop.

- *Invention* is the process of devising and producing by independent investigation, experimentation, and mental activity something which is useful and which was not previously known or existing. An invention involves such high order of mental activity that the inventor is usually acclaimed even if the invention is not a commercial success. *Inventiveness* is the form of creativity leading to invention.[1]

- *Creativity* is the ability to solve problems, create products or raise issues in a "domain" (e.g. cooking, engineering, law, music) that is initially novel but is eventually accepted in one or more cultural settings.[2]

- *Innovation*, which may or may not include invention, is the complex process of introducing novel ideas into use or practice and includes entrepreneurship as an integral part. Innovation is usually considered noteworthy only if it is a commercial success. Thus society benefits from innovation, not from invention alone, and often there is a significant lapse of time from invention to innovation.[3]

- *Technology* is the body of knowledge of techniques, methods, and designs that work, and that work in certain ways and with certain consequences, even when one cannot explain exactly why.[4] Technology may also be defined as the effort to organize the world for problem solving so that goods and services can be developed, produced, and used.[5]

- *Propositional knowledge* (discovery-type, or "what" knowledge) takes two forms. One is the observation, classification, measurement, and cataloging of various phenomena. The other is the establishment of regularities, principles, and "natural laws" that govern these phenomena and allow us to make sense of them.. Science is a part of this knowledge, but it includes a great deal more. A *discovery* is any addition to propositional knowledge.[6]

- *Prescriptive knowledge* (invention-type, or "how" knowledge) is techniques. The knowledge consists of designs and instructions for how to adapt means to a well-defined end. An addition to the set of prescriptive knowledge is an "invention" although the vast majority would be small incremental changes, [7] not fully meeting the stricter definition above.

Today, inventions are typically patented, but by no means do they have to be patented to qualify as inventions, nor does every patent represent true invention. Finally, while invention is often an act of creative engineering, one does not have to be an engineer to practice it. Higher levels of education are helpful but not necessary for someone to be an inventor.

With these understandings of the terms in mind, the key questions that our workshop panel addressed and that we consider in this report are as follows: What can history teach us about invention and creativity? What motivations drive inventive activity? How has the process of invention changed over time, and how has it remained the same? What sorts of environments -- physical places as well as social, political, and economic – are most conducive to invention? What are the barriers to invention, and what does history tell us about how to overcome them? How do considerations of gender and racial diversity influence how inventions are developed, marketed, and socialized? What have been the economic, social, and environmental consequences of key inventions? Is it possible and even useful to forecast positive and negative outcomes? What are the public policy implications of our findings? How can we help set a policy agenda for invention, and what kind of public policy changes are required to improve the environment for inventive activity?

Roots of Invention

The term *invent* as we currently understand it came into acceptance in the fifteenth century.[8] The fact that the first instances of the term can be traced to the Renaissance and that usage accelerated during the Enlightenment is probably no coincidence, as invention and the socialization of inventions depend highly on the rapid proliferation of knowledge associated with those intellectual movements. The first patent laws can be traced specifically to Venice in 1474. The rulers of that republic instituted a policy for rewarding people who introduced new technology into society by granting them a 10-year monopoly over the usage of that technology.[9]

However, the historical antecedents to invention have a much deeper past, according to Robert Friedel, professor of history of technology at the University of Maryland. The roots of what Friedel called our "culture of improvement" can be traced back thousands of years. "I call it the culture of improvement and it starts with a premise, which in fact also has been alluded to a little bit already, that human beings have within themselves some kind of capacity -- even, possibly, we could say some kind of proclivity -- to ask whether something can be done better. When you start looking at the language going all the way back to the Middle Ages in the way that people are talking about change, this notion of improvement is, in fact, much more fundamental than the notion of invention."

For the vast majority of human history, this culture of improvement developed haphazardly and unevenly, according to Joel Mokyr, professor of economics and history at Northwestern University. Basic concepts such as the wheel, primitive hand tools, farming implements, weapons, medicines, and improved applications of new materials, were typically narrow advances resulting from trial and error, what Mokyr calls "singleton techniques" that "rarely if ever led to continued and sustained improvements."[10] The epistemic base of knowledge was severely limited, meaning that the conditions for acquiring and socializing knowledge were not broad enough for much further improvement to take place. "Before 1700 or so," he adds, "technology was a world that had engineering without mechanics, iron-making without metallurgy, farming without soil science, mining without geology, dye-making without organic chemistry, and medical practice without microbiology and immunology. Some things could be made to work by trial and error or serendipity, but systematic improvement and extension were much more difficult."

As defined above, Mokyr refers to two broad categories of practical knowledge that can contribute to gains in human material welfare. The first category, propositional ("what" or "discovery-type") knowledge, includes all beliefs about natural phenomena and scientific regularities. This category includes discoveries, from the isolation of chemicals and elements to knowledge of the structure of DNA. The second category, prescriptive ("how" or "invention-type") knowledge, includes inventions or sets of instructions to form techniques. This category includes everything from mechanics to metallurgy to improvements in aircraft design to techniques for gene therapies and gene sequencing.[11] Such a framework is fundamental to a deeper understanding of invention, and it is more useful than the usual dichotomy of "science" and "techniques," or "theoretical" and "empirical" knowledge.

The process of mapping "what" knowledge into "how" knowledge involves invention. Propositional knowledge "serves as the support for the techniques that are executed when economic production takes place," Mokyr writes. However, he calls this mapping function "one of the more elusive historical phenomena" because of the sometimes strange and unpredictable ways in which the two forms of knowledge interact, or fail to do so. In the past, he notes, the Hellenistic knowledge of optics didn't translate into the invention of eyeglasses or binoculars. Sometimes, of course, our knowledge is wrong (witness the Medieval process of healing by bloodletting) or is incomplete (witness Newton's vision of the universe).

The key to sustaining or accelerating the rate of improvement over time lies in the feedback cycle between what-knowledge and how-knowledge. After 1450, there was a dramatic increase in discovery-type information. Improved ship design had led to a huge gain of propositional knowledge, in the form of maps and access to new materials. But most of the economic gains from this era of geographic exploration can be attributed to a dramatic upsurge in trade, rather than invention. The advent of movable type and the printing press in the 15th century was perhaps the single most important turning point in the history of knowledge diffusion, triggering a revolution in the way information would be standardized and disseminated. But the resulting gains in prescriptive knowledge were still relatively narrow compared to the period that followed the Renaissance and the Age of Discovery, according to Mokyr. The sporadic gains of this era were most often due to "chance discovery, trial and error, good mechanical intuition, or getting something to work without knowing 'why they worked'."[12] For instance, one can make wine and beer without knowing how sugar turns into alcohol, or even that it does. One can also waste time searching for inventions, such as a perpetual motion machine, that aren't scientifically feasible. The epistemic base, in other words, was still too narrow to support a self-sustaining culture of continuous improvement and invention.

The whole notion of improvement also requires further clarification. "I have to emphasize it as a completely contingent idea," says Robert Friedel. "In other words, *your* better may not be *my* better." The invention of gunpowder in China in the early 15th century was welcomed and exploited by European colonialists, for instance, but to Latin American natives on the wrong end of the gun, it was not. "Even my better yesterday may not be my better today," adds Friedel. Think of tobacco processing or asbestos production. "The notion of better, and therefore the notion of improvement itself, is completely contingent on the particular values, on the particular purposes, on the particular aims that you may have at a particular point in time."

Since an improvement to me is not necessarily an improvement to you, Friedel adds, "something else has to happen" for an improvement to prove useful to a wide range of people over a long period of time. "The improvement has to be socialized," he says. "Since the 15th century, we have come up with effective methods for socializing improvement. The processes of writing and publishing, of patenting, of illustration, of education, of professional societies, of promotion, and the like -- all of these are means by which an individual or small group's notion of improvement may then be socialized." During this process, many people may reject a supposed improvement or simply fail to adopt it. "We know that only a small fraction of useful patents, for example, actually make it into the market or are actually judged more generally to be improvements."

What moves a proposed improvement forward? Power, says Friedel. Sometimes this power is intellectual, sometimes economic, sometime military. Sometimes, the power is social standing itself, particularly as it relates to race and gender. "One can, in fact, begin to identify, again from the Middle Ages onward, very different kinds of access between men and women in terms of the mechanisms for socializing knowledge of any kind, but particularly technical knowledge." In most cases, the groups or societies who have adopted powerful new improvements gain advantage over other groups or societies, and sometimes inventions create disruptions, which can translate into economic and social advantage for those who adopt certain improvements first.

Patent laws have always failed to address the subjective values inherent in inventions, says Friedel. "Patents aren't a judge whether it's better, but whether it is new and useful and non-obvious," he adds. Whereas the first patents for technological creativity go back to Venice, the patent laws that are currently in place in much of the world have their direct roots in England's Statute of Monopolies from 1620. "What the British Parliament is doing is telling the Crown that it may not, in fact, grant arbitrary monopolies, except in a few very specific cases. One of the cases that's explicitly set down there is in the case if someone, an individual, brings into the kingdom a new and useful process, invention, or product. In that case, for a limited number of years, the statute goes on to say, the Crown may provide a monopoly to that individual. The limited number of years being defined, initially, in terms of two full apprenticeship terms, which is to say, we give the inventor enough time to train apprentices so that in fact that trade and the product can be spread throughout the realm in some appropriate way." That's the reasoning behind the initial British patent term being set at 14 years.

The modern notion of intellectual property stems from these laws, and that notion soon made its way across the ocean. Many of America's Founding Fathers were inventors and great admirers of the inventive spirit, and so these men embedded such protection into the U.S. Constitution, which calls for a limited patent monopoly for "the first and true inventor" of any new product, process, or machine. With protections for inventions being codified into the laws of a brand new country, our entire notion of improvement became more rigidly defined. Friedel argues that invention became more of a legal construction rather than a purely intellectual one.

The very language of invention seems to have great consequence, as evidenced by the contrast between the English and the French notions of patents. "In the English terminology, patents are always labeled in terms of improvement," Friedel adds. "If you look at the language of French patents, things are worthy of patenting not because they're improvements but because they bring the product closer to perfection, which is intellectually a fascinating contrast to the rather open-ended Anglo-American idea that you can improve something. You can improve something ad infinitum, whereas the French notion is that there is some kind of Platonic ideal, and the patent is bringing the product to some kind of perfection." Perhaps this distinction between French idealism and British practicality helps, in some small way, to explain why the fires of the Industrial Revolution were ignited in England, and not in France. The French, notes Mokyr, were leaders of 18th century science, but it was the British who famously exploited French knowledge for commercial gain. "To simplify to the point of absurdity," writes Mokyr, "one could say that France's strength was in what-knowledge, Britain's in how-knowledge, and that the mapping function bridged the Channel." [13] No doubt, this is an exaggeration, as both Britain and France were leaders in developing both classes of knowledge during this period.

It is, however, no exaggeration to say that the process of mapping what-knowledge to how-knowledge suddenly and permanently accelerated in the middle of the 18th century.

The "virtuous cycle," as Mokyr terms it, kicked in around 1750, leading to a fantastic upheaval. More than a century earlier, Francis Bacon had proclaimed that applied science is "the servant of invention and commercial and manufacturing interests." Now, his vision was becoming a reality. "The key to the Industrial Revolution is technology, and technology is knowledge," says Mokyr. New techniques of managing the technologies of transportation and production also played a pivotal role.[14] For these reasons, Mokyr prefers calling this period the Industrial Enlightenment, emphasizing how integral pure knowledge was to creating virtually every process and machine inside the manufacturing factory. In turn, the hallmarks of the era -- the industrial factory and the steam engine -- produced knowledge channeled right back into the process of science-based discovery.

The men who embodied the Industrial Enlightenment were all great students and producers of knowledge. Scotsman James Watt's steam engine was based on his studies of pressure, evaporation, and condensation, and his invention, in turn, led others, notably Frenchman Sadi Carnot, to formulate the basis for the second law of thermodynamics, which led to further invention. Humphry Davy led the legendary Royal Institution on its mission both to develop and absorb scientific knowledge, and it became the place where an untrained bookbinder named Michael Faraday was able to invent the electrical generator and formulate basic principals of electricity that were studied by virtually every electrical inventor thereafter. Pottery artisan Josiah Wedgwood, was a "compulsive quantifier, an obsessive experimenter, and an avid reader of scientific literature," notes Mokyr. Benjamin Franklin studied Newton, and his own inventions and theories were, in turn, scrutinized in England and France. The virtuous cycle was now in full swing, and it triggered a culture of sustained improvement that continues today.

But even though we have thus far explained the workings of the knowledge diffusion process, many questions remain. Chief among them is the question of what drives the spirit of invention in the first place. What is it that triggers in certain individuals the will as well as the ability to invent?

Drivers of Invention

Analyzing the critical factors that drive inventive activity, our workshop participants stressed both economic and non-economic incentives, plus motivations inherent to basic human nature. The most common explanation as to what drives inventive activity is the age-old maxim that “necessity is the mother of invention.” But that aphorism explains very little and is wrong in many or most instances. Since new possibilities often give rise to new desires, it may even be more correct to say that “invention is the mother of necessity.” “The crucial question is why some groups respond in a particular way to needs or wants which in some other groups remain unfulfilled,” writes technology historian Carlo Cipolla.[15] Why do certain individuals take on a life of invention, some to the point of obsession, while others don’t even consider it? What motivates inventions, and why are some people and some societies more inventive than others?

Focusing on the pivotal period of the Industrial Enlightenment, several of our participants noted that many of the key figures of that age were surprisingly unmotivated by patents. So what besides altruism drove these inventors? Adam Smith, in “The Theory of Moral Sentiments,” posits that such men are motivated to engage in such enterprise with the aim of garnering “the esteem of their peers.”[16] In 18th and 19th century Britain, in particular, men of science and discovery formed tight-knit “creative communities,” says Mokyr. Early gentlemen’s communities included the Lunar Society, the small but disproportionately influential handful of men that included Josiah Wedgwood and Erasmus Darwin, grandfather of Charles Darwin.

Esteem certainly seems to have been the coin of the realm at the most famous association of the age. Many of the fellows of Britain’s Royal Society were already of the landed class, with ample time to devote to inventive activities, and they seem not to have been motivated principally by financial gain. Humphry Davy, for one, didn’t patent many of his own inventions, such as the mining safety lamp, as he believed invention was for the common good. Yet he did express outrage when his ideas were appropriated by others, notes Mokyr. In the American colony of Pennsylvania, the largely self-taught Benjamin Franklin also aspired to this tradition. He did not seek patent protection for inventions such as the bifocals and the Franklin stove. His famous “electrical kite” experiment of June 1752 won him not only membership to the Royal Society but also garnered its prestigious Copley Medal. Franklin even went so far as to form his own association, the American Philosophical Society, to foster inventiveness and bring together “virtuosi or ingenious men residing in the several colonies” and maintain correspondence about "new mechanical inventions for saving labor" and other innovations, all for the benefit of "mankind in general."[17]

These elite networks soon widened, and the masses became more and more educated in scientific matters over the ensuing decades. Wrote one English observer in 1828: "In every town, nay almost every village, there are learned persons running to and fro with electrical machines, galvanic throughs, retorts, crucibles, and geologist hammers."[18] By 1850, there were 1,020 associations for technical and scientific knowledge in Britain alone, with a total membership of around 200,000.[19] Laurels of many kinds were bestowed upon those who came up with the most clever inventions, and so standing among elite or tight-knit groups of peers seems to have been a principal motivator driving inventive activity at this time.

The notion that one could make vast sums of money via intellectual property had only begun to take root. In the 1740s, John Harrison was after a British Parliament prize of £20,000 when he embarked on his "inventive odyssey" to develop an accurate chronometer with which he could then calculate a ship's longitudinal position. But he wasn't able to collect most of the prize money until years later, and his chronometer itself was too expensive to become a profitable product at the outset. In the meantime, the Royal Society awarded him the Copley Medal.[20] Only after the Revolutionary War, with an urgent need for the newly independent United States to develop its own industry and its own manufacturing did financial gain become a principal driver of invention. "Assured that he would make a fortune" from his cotton gin, Eli Whitney secured a federal patent in 1794. He never did make much money on it, however, as imitators soon produced similar machines despite Whitney's expensive efforts to protect his rights.[21] Still, his motivation was evident.

The esteem-driven system of invention established in England was indeed trampled by the forces of the marketplace, especially in the United States. Among early 19th century American inventors, raw financial gain did emerge as a principal motivating factor. Among the first Americans whose inventions led to great fame, and sometimes fortune, were Robert Fulton (steamboat), Samuel Morse (telegraphy), Oliver Evans (automated grain mill), John Deere (steel plow), Cyrus McCormick (reaping machine), Charles Goodyear (vulcanized rubber), Simeon North (flintlock pistol), Samuel Colt (revolving pistol), and Thomas Blanchard (eccentric woodworking lathe). At a time when the U.S. population was roughly doubling every twenty years[22], the demand for food and consumer goods was exploding, spurring the need for new technologies and improvements. Francis Cabot Lowell and his Boston Manufacturing Company, founded in 1813, demonstrated how immensely profitable it could be if one exploited the inventions of others and organized machines and labor in efficient new ways. By 1839, the twenty-nine textile mills of Lowell, Massachusetts were churning out more than 1 million yards of cloth every week, surpassing the venerable mills of Manchester, England.[23]

But this is where the economic drivers of invention come up against powerful social forces. The spindles of Lowell, after all, were able to make cotton cloth that was so cheap and plentiful due to the fact that the raw material was being gathered by slave labor in the South and the fabric was being manufactured by machines operated by powerless young women in the Northeast. Racial issues were particularly underestimated. “It's a time when there's tremendous racial tension in the United States,” says Rayvon Fouché, assistant professor of science and technology studies at Rensselaer Polytechnic Institute. “So, how can we have this society where race is so high on the national agenda, but in that other realm, technology, we don't have any discussion or issues or any connections between the two?” Fouché addresses this scarcity of attention being paid to the intersection of technology and race by focusing on black inventors.

Before emancipation and the Civil War, black inventors had no intellectual property rights. “Machines invented by slaves were not patentable,” says Fouché. Afterwards, they struggled against the politics of segregation. For African Americans, he says, the popular notion that patents equaled success was generally not true. One of the most prolific black inventors, Granville T. Woods, held 48 patents, many of them on electrical railroad devices. Yet even he had a hard time asserting his inventions. One of his patents, on the hay rake, was challenged in patent court, notes Fouché. After the white lawyer disputed the invention on the merits of the case and failed to impress the court, the lawyer went with a racist argument: “It's a well known fact that the horse hay rake was first invented by a lazy Negro who had a big hay field to rake and didn't want to do it by hand.” Despite such attacks, blacks continued to invent.

Very few of the most successful black inventors were mythologized. The popular legends surrounding George Washington Carver are one such example. “Heroes are very important for oppressed people,” says Fouché. “ In times of distress, communities often rely on and construct heroes to meet their needs. They create positive images around which communities can unite.” But the mythology surrounding black inventors was often of a different nature, according to Fouché. Blacks during Reconstruction needed to prove the point that they could innovate and contribute to American society. Their myths, he adds, “supported multiple ideological agendas. You had black leaders at the time, like Booker T. Washington, whose agenda was assimilationist -- pull yourself up by your boot straps. And of course, the inventor mythology was very much [about] succeeding in often adversarial conditions. On the other hand, you had W. E. B. Du Bois who was very much on the opposite end of the spectrum. But black inventors fit Du Bois' agenda equally as well because these black inventors showed a high level of intellectual sophistication and skill, and were also competitive in a larger racial market.”

However, Fouché adds that it was also “a myth that black inventors did it to uplift their race and create a stronger African-American community.” He suggests that blacks invented for the same reasons as whites: for esteem, money, and to better the human condition in general. Nevertheless, their stories are often used as evidence that blacks could contribute to the larger culture. This helps explain why the mythology surrounding black inventors is of a different nature. While white inventors were made into icons, “black inventors were reduced to patent numbers and artifacts.” During Black History Month, for instance, education associations often produce posters containing things invented by blacks – an ice cream scoop, for instance. “The ice cream scoop was invented by a black man,” Fouché says. “You have a patent number. But the underlying implication is that, of course, if you didn't have this ice cream scoop, no one could ever experience ice cream in any way.” This kind of portrayal, he suggests, unintentionally reduces and trivializes the inventive genius of the individuals.

In the postbellum culture at large, meanwhile, there was a new explosion of inventive activity. Large-scale networks of government- and privately-financed canals, railroads and telegraph lines brought about new management techniques and a culture of continuous, relentless improvement, which greatly accelerated the patent rate. Whereas there were typically only a few dozen U.S. patents granted each year at the beginning of the 19th century, by the end of the century the U.S. Patent Office was granting more than 20,000 annually.[24] The most revolutionary products of this golden age of inventors soon led to industrial empires on a scale never before seen. The inventions of Samuel Morse, Isaac Singer, George Westinghouse, and Charles Goodyear all sparked new industries during this period, although most of the riches from Goodyear's invention of vulcanized rubber came after the inventor's death.

Alexander Graham Bell and Thomas Edison, born just weeks apart in 1847, became the hallmark inventors of the era, and their inventions spawned new myths and new expectations for invention. Inventors were no longer just motivated by esteem or by money alone, but by the unique opportunity to transform the world. "Every invention is invariably always an act of rebellion and an act of disrespect toward existing knowledge, in the very sense that you look at something that exists out there and you say, look, I can do better," says Joel Mokyr. "But we also have to keep in mind, however, that out of every hundred people who think that they can improve on something, probably ninety-nine are wrong." Rare successes such as Bell and Edison were demonstrating for others how to systematize the process, to learn from their mistakes and the mistakes of others, and by doing so, they popularized an altogether new style of invention. That leads us to explore the next major question: How has the process of invention itself changed over time? Can we identify and characterize the major styles of invention in order to understand what methods can work in the present and in the future?

The Changing Styles of Invention

The latter part of the 19th century saw the rise of the archetypal style of invention. Whereas the inventors of the pre-Renaissance were often forgotten people who made random and often unsustained discoveries, and the inventors of the Industrial Enlightenment were often philosophical men who also dabbled in science and politics, the inventors who emerged in this new era were deliberate in their career-long efforts, and they believed that world-changing innovations were always possible and desirable, and so they sought to systematize their methods like never before, so it could be done again and again. As Alfred North Whitehead put it: "The greatest invention of the 19th century was the invention of the method of invention."[25]

The independent inventors of the Edisonian period "persuaded us that we were involved in a second creation of the world,"[26] writes Thomas P. Hughes, Mellon Professor Emeritus, at the University of Pennsylvania and Distinguished Visiting Professor at MIT. The "Edisonian style," as Hughes calls it, is centered around the "invention factory," a laboratory commanded by a master inventor who envisions big ideas and defines new directions but where the day-to-day experimentation and innovation is performed by a staff of young, well-trained, hard-driving craft persons and engineers. According to Hughes, the Edisonian period began in 1876, the year Edison opened his Menlo Park laboratory and Bell first demonstrated his telephone. The era lasted until about 1920, when industrial labs became the major site of invention. Inventors during this time "were consciously modeling their style upon the Edisonian style," says Hughes. "[Edison's] style was so well known because of newspaper coverage that [other inventors] could imitate the way he organized his inventive activity in his laboratory, first in Menlo Park, then in West Orange, New Jersey."

One of the common customs from the Edisonian period onward is that laboratories kept detailed notebooks that documented their activities. The notebooks provide a remarkable window, enabling scholars to study how new ideas developed, from conception to reality. In the case of Edison, ideas such as the inspiration that became the phonograph can be traced from the very first drawing of the "talking machine" in November 1877 to a series of more finished products over the following years. In the case of his electric light, progress can be tracked from the first successful experiment with the carbon filament in 1879 to his vast system of delivering electric power to urban areas over the ten years following that seminal breakthrough. The drawings and the documentation were also of great use in patent offices, courthouses, and in the press for sorting out who first demonstrated disputed inventions.

One prolific Edisonian inventor from this period, Elmer Sperry, made his mark experimenting with electrically-powered gyroscopes, focusing on their potential to stabilize automobiles, ships, and airplanes. Conceived by a Frenchman in the 1850s, the gyroscope started as a heavy wheel that spun inside a frame. Around 1907, Sperry sought to refine and adapt the invention, which led to entirely new inventions. Thomas Hughes read through forty years of Sperry's notebooks, which documents Sperry's 350 patented inventions and improvements, as well as his false starts and blunders. "One can follow the path of his creation," says Hughes. In his notebooks, Sperry would typically cite leading technical journals that documented what competitors were doing. At one point, "he cites two articles . . . about gyro-stabilizers for ships. Then a few pages later, I find a mathematical formula. I don't know where he picked it up, but he's analyzing with this mathematical formula the anti-rolling power of a gyro-stabilizer of a certain weight."

What Hughes describes is central to the very process that independent inventors and corporate laboratories would put in place for the rest of the century and beyond, a system of scanning technical journals and searching existing patents in the hunt for new patents clustering around large problems and unaddressed opportunities. "Sperry decides that he can improve upon the patented device. He finds that this gyro-stabilizer the Englishman has invented is a heavy, heavy beast -- as he calls it. It doesn't react quickly to the roll of a ship. So, Sperry finds an inadequacy in the existing device and so he says, 'What we need to do is correct the sluggishness of this beast.' So, he invents -- yes, he invents -- this arrangement. He couples a small, light gyro with this heavy gyro and the light gyro senses the roll of the ship long before the heavy one senses it and the light one, when it senses the roll -- the incipient roll, as Sperry calls it -- it sends an electrical message to the large gyro to begin to respond to the roll and to dampen the roll. So, Sperry realizes that this is a patentable idea and he then goes into the next phase, which is to make notes in his notebook of the various claims that he will make."

By studying the deficiencies of existing technology and by surveying technical literature and previous patents, Sperry and many others were contributing to larger and larger systems. A natural outgrowth of hundreds of individual inventions, the complex engineering system became the centerpiece of the inventor's world. By the early 20th century, large-scale systems were being constructed everywhere: Edison's inventions led to a vast power-and-light system that transformed daily life. Bell's invention led to the Bell telephone system, which soon became the world's largest private employer. Henry Ford's assembly line, first installed in 1913, grew into a mass-production system that revolutionized business. The Wright Brothers and Glenn Curtiss spawned a far-flung aviation system. "These systems were the work of the systems builders, whose creative drive surpassed in scope and magnitude that of the inventors," writes Hughes.[27]

The advent of complex engineering systems required different models for understanding invention, and it gave rise to a new style of invention. Hughes provides a vivid analogy for observing the way these systems evolve. While invention sometimes involves great leaps and discontinuous change, often it does not. Comparing the advance of complex engineering systems to military battle lines, specifically those in World War I, Hughes details the concept of the "salient," which is an isolated advance forward in one part of the front, as well as the "reverse salient," which is a lagging element in the same front. "In other words," he says, "the components in a large engineering system that are lagging behind need to be corrected so the entire system can continue to develop." As a result, "reverse salients" are places where inventors congregate, where patents congregate. A classic example, cited by Hughes, is the Westinghouse system of alternating current electrical power. In 1886, the literature showed a need for a good polyphase AC motor that could drive the system properly. Inventors flocked to the problem, and five inventors in different places came up with similar technologies almost simultaneously.

Conversely, a salient is an invention that is ahead of its time and requires the rest of the system to be created or to catch up. As an example, Hughes cites the turbo-generator, which around 1905 began replacing the reciprocating steam engine in electrical power plants. "The advanced component stimulates invention in order to bring the rest of the system in line," he says. "So, what resulted was that a number of inventors went into high-voltage electrical transmission so one could extend the area of supply and use the capacity of the turbo-generator to increase output with the same footprint."

The rise of this kind of systems engineering, in large part, triggered the next major era of invention: the corporate style of research and development. The corporate R&D lab was the brainchild of a few German chemical companies of the late 19th century.[28] But American companies were the ones that built the world's biggest and the most famous laboratories. In the year 1900, fearing that Edison's expiring patents would open up the electric lighting industry to outsiders, General Electric, the company originally formed by Edison, opened its Schenectady laboratory. Following on GE's heels were Westinghouse, DuPont, Eastman Kodak, General Motors, AT&T's Bell Laboratories, and RCA. By the 1920s, corporate labs were eclipsing the Edisonian inventors. By 1931, U.S. corporations received more patents than U.S. individual inventors for the first time, and corporations would keep widening that lead for the remainder of the century.[29] By 1940, the U.S. Census Bureau eliminated the occupation of inventor as a separate job category.[30] Those who worked in corporate labs were called staff engineers, or simply "researchers."

The R&D labs of the world's biggest industrial corporations focused on the process of constantly improving the large-scale systems that drove profits in their industries. These labs were, for most any measure, extraordinarily successful. But they were also quite exclusionary. Not only did the big R&D labs often keep independent inventors from marketing their inventions on their own, but these labs were also the exclusive domain of white males. Black inventors and other minorities were kept "on the fringe," says Rayvon Fouché. "They were not working for GE and Westinghouse." In the most extreme cases, these corporate-controlled engineering systems were powerful instruments of social change or social cohesion. "Take Henry Ford and the assembly line," says Arthur Molella, director of the Lemelson Center at the Smithsonian Institution "He clearly had a goal in mind -- to control people." His rigid social engineering and management techniques were subsequently codified around the world, with the ideology referred to by scholars as "Fordism" or "Taylorism," after Frederick Winslow Taylor, the father of scientific management. "Ford, like Taylor, saw [workers] as components in the machine system of production," writes Hughes.[31]

There remained isolated cases of independent inventors, from the 1930s onward. Notable examples include Philo T. Farnsworth and electronic television, Edwin Land and polarized materials and instant photography, and the numerous electronic inventions of Jerome Lemelson. Small numbers of lone inventors persisted in inventing, licensing their patents, and in the case of Land, forming large companies, but the newer corporate style of invention was dominant. "A century ago," says Joel Mokyr, "we had the inventor as the hero of the modern age." Inventors were "the main actors who brought on the Industrial Revolution. Such heroic interpretations were discarded in favor of views that emphasized deeper economic and social factors, such as institutions, incentives, demand, and factor prices. It seems, however, that the crucial elements were neither brilliant individuals nor the impersonal forces governing the masses, but a small group of at most a few thousand people who formed a creative community based on the exchange of knowledge."

Prime examples of creative communities coming together to accomplish something momentous include the Tennessee Valley Authority and rural electrification during the Great Depression, and the Manhattan Project and the atomic bomb during the Second World War. These were such large-scale and complex projects that no one person could assume the role of primary systems builder, says Hughes. "The Manhattan Project, like a committee, tended to probe its way to decisions, trying first one solution, then another, or even several simultaneously, and reaching its goal by gathering momentum through the enrollment of human and material resources," Hughes writes. Taylor and Ford, he adds, "would have been appalled by the inefficiency."[32] In other words, the Manhattan Project was far more like a creative R&D lab than it was a methodical industrial factory.

In the post-World War II period, the corporate R&D labs drew on lessons learned at the Manhattan Project, and those labs dominated invention like never before. One breakthrough in particular typified both the prestige and transformative powers of the corporate lab. "In 1948, a trio of scientists at the Bell Telephone Laboratories had devised the transistor, a technology that would revolutionize electronics. They discovered that an arrangement of small wires and a semiconducting material such as germanium could be made to control the flow of energy in electrical circuits."[33] Smaller, more reliable, and less consumptive of power than the clunky vacuum tube, the transistor would become the "nerve cell" of what later would be called the Information Age.[34]

The main actor behind the transistor was physicist John Bardeen. Working under the supervision of William Shockley, Bardeen served as "the head" behind the project, while colleague Walter Brattain served as "the hands."[35] Their collaborative style of corporate invention broke the molded image of the fabled lone inventor, says Lillian Hoddeson, professor of history and physics at the University of Illinois at Urbana-Champaign. Inventors and geniuses over the past two centuries had been portrayed in the media as "off balance" and "weird" people who "work alone," or "don't need extensive schooling," or "whose ideas come to them instantly in a brilliant flash," or "don't quite follow the social rules," the most well-known example being the fictional mad scientist Dr.

Frankenstein. “Well,” says Hoddeson, “Bardeen was absolutely nothing like that.” Drawing on her original research for her recent biography of Bardeen, Hoddeson describes her subject as a “kind, gentle, social and uncharismatic” man who attended the best schools, worked in the most favorable institutions, toiled for years on problems and “loved working in collaboration” with other engineers and researchers and as someone who was “very much grounded in the real world.” He was so quiet that colleagues called him “Whispering” John.[36] He was naturally drawn to interesting engineering problems and was persistent in solving them.

Funded by the AT&T telephone monopoly, Bell Labs thrived, growing to a research staff of tens of thousands. By the time Shockley, Bardeen, and Brattain shared the Nobel Prize for their discovery in 1957, the corporate lab was in the midst of a golden age. Enormous facilities at corporations -- ranging from IBM to Xerox to Hewlett-Packard, from Siemens in Germany to NEC in Japan -- all flourished. Soon, however, entrepreneurs and less research-intensive companies were also capitalizing on the lengthy time differential between when these labs invented something and when a resulting product could be ready for market. Other companies brought out small, cheap transistor radios, for instance, before AT&T found substantial commercial applications for transistors. In the burgeoning world of computing, radical inventions developed beginning in the late 1960s at Xerox’s Palo Alto Research Center (PARC) ended up being brought to market brilliantly by startups such as Apple Computer. Fueled by massive infusions of private venture capital, entrepreneurs were capitalizing on innovations before the actual inventors had the chance.

This Silicon Valley style of invention was, in a sense, a hybrid of independent Edisonian invention and corporate R&D. Edisonian inventors and the capitalists who backed them, would divide the company stock between themselves, says Hughes. Usually the inventors would then move on to new patents and new companies, with professional managers running the existing operations. That is true of many modern tech startups as well. Meanwhile, modern academic labs bridge all these different models. “Many of the Silicon Valley types were working in an academic environment when they came up with a major software or hardware improvement,” says Thomas Hughes. Professors at Stanford University in particular were kept on a tenure track while taking leave of teaching and starting new companies, thus eliminating the disincentive for taking risks on new ideas. These different styles of invention blended together in the complex new world of microelectronics and computer software. Thus, it becomes less useful to discuss distinct styles of invention than it does to discuss the best environments for creative engineering. This is the category of questions many of our workshop participants focused on most intently: What kind of places foster originality? What kind of spaces and intellectual, social and economic structures lead to both incremental and breakthrough invention?

Building Creative Environments

To answer these crucial questions, several of our participants highlighted principles for building environments that best foster inventiveness. These principles derive from deep biographical case studies that show how certain individuals responded to various environments in which they were placed, and sometimes how they created their own inventive environments from the elements available to them. “Historians of technology really need to spend a lot more time and give much more attention to the impact of the spaces in which creative people work,” says Lillian Hoddeson. “I'm using the word ‘space’ in the broadest possible sense to include physical space, but also economic factors, social factors, political factors, institutional factors -- the whole schmeer.”[37]

The first key environment, of course, is a nurturing home. In one story told by Hoddeson, John Bardeen was a young child in want of a piece of cake on the top shelf of a pantry. His mom not only let him make the difficult climb to get the cake, but she still supported and encouraged the boy even when everything came crashing down to the floor. Witnessing his talent for math, Bardeen’s mom skipped him ahead three grades in that subject. “The math teacher let him sit in the back of the room and solve problems that were ahead of the class,” says Hoddeson. Socially, she adds, Bardeen felt different from the other kids, but he ended up “intrinsically motivated” to solve problems.

Exposure to top minds is also a hugely influential environmental factor. Attending the University of Wisconsin in the mid-1920s, Bardeen only received average grades, but he attended the lectures of and interacted with three guest professors who went on to win Nobel Prizes. “It was very, very important for Bardeen to work with some of the top people. Even though he was a young man, I think in some uncanny way, it gave him a message about what being at the forefront means – [seeing] what kind of research, what kinds of questions people like that get excited about." Working as an engineer for an oil exploration company after college, Bardeen grew frustrated because he didn't fully understand the geological problems at the heart of the work, and he wasn't very interested in geology. So he went back to school. At Princeton, he found professors and advisors who demonstrated critical thinking skills. "He learned how to break down problems, how to de-compose them -- in two different ways. One was just to simply break them into their parts, their sub-problems. But the other way of de-composing a problem is to break it down into model problems where only the essentials were left and then to eventually add on more aspects of the new problem later." Mentors, therefore, are a crucial element of an inventive environment.

At Harvard, where he was a junior fellow, Bardeen enjoyed largely unconstrained freedom to explore new ideas, another key criterion for fostering inventiveness. Yet another principle is finding the right kind of collaborators. Also at Harvard, "he had his first experience collaborating with an outstanding experimentalist -- and this was Percy Bridgeman. Thereafter, Bardeen always sought and often found that kind of collaboration and teamwork with experimentalists – engineers who had actually worked there in the lab. Bardeen himself hardly ever picked up even a pliers. At home, his wife, Jane, had to fix everything. But in his work, he was very, very close to the data. For that, he needed to be in a place where he could collaborate with experimentalists."

After his unhappy war years working in a highly constraining environment as a military engineer, Bardeen joined Bell Laboratories, an ideal environment that was both unconstrained and filled with vast resources of every kind. He was able to choose problems that were interesting and important to him, despite the fact that some didn't seem to have immediate bearing on AT&T. He was also paired up with an outstanding experimentalist in Walter Brattain. They bounced ideas off of one another, considered small adjustments, and created a series of models that built up to their big breakthrough in December of 1947.

After that crucial invention, however, their boss William Shockley became resentful and jealous that he had missed having a direct hand in the seminal invention of the transistor. Shockley poisoned the environment for Bardeen, assigning him to uninteresting projects that were divorced from the next commercial stage of the transistor. After two years of trying to fix this situation, Bardeen left for the University of Illinois, "where everything was positive for him again." His subsequent work on superconductivity led to a second Nobel Prize for physics, making Bardeen the only person ever to win the physics prize twice.

Among the intellectual resources that many successful inventors consider essential is the library. "Bardeen would visit the library almost every day to keep up with the literature," says Hoddeson, "That was very, very important to him." This was also true of a young Edwin Land in the 1920s, says Victor McElheny, visiting scholar at MIT's Program in Science, Technology, and Society. Land was obsessed with self-directed learning to the point that he dropped out of Harvard, in 1926, gravitating instead to the vast reading room of the New York Public Library, spending eight to ten hours per day ransacking the shelves for knowledge, "swallowing the world of optics" and everything about the subject of light polarization. McElheny describes the library as a subversive environment in many ways. "Libraries are the tool of self-education," he says. "They're the thing which allows you to get around these god-damn teachers and around your parents. To find it out for yourself, and to go fast -- which is what I think any bright person wants to do." Time spent in the library is also liberating in more ways than one, because intense, autonomous learning can make one realize that authority figures know so little. "The world does not belong to bright people," McElheny says. "The world is actually a rather alien place for bright people. Bright people are not in charge."

This obsession for libraries was also a trait of a young James Watson, the co-discoverer in 1953 of the DNA structure and the subject of McElheny's latest biographical study. Growing up in Chicago during the Depression, "every week, Watson would be walking to the Public Library with his father," notes McElheny. While suffering the isolation of a kid who rarely talked or socialized with people his own age, "this incredible geek" learned how to learn and think for himself.

Occasionally, creative environments must be custom-made for certain people or certain projects. Returning to college at Harvard after three years in New York, Edwin Land projected an air of inevitability. He was considered "the genuine article," says

McElheny, “and you are supposed to help such a person.” An impressed chairman of the physics department granted Land his own research space to work on his concept of a light polarizer. “As far as I know,” he adds, “that's the only time an undergraduate in physics at Harvard has ever been given his own laboratory.” Land labored there day and night, totally immersed, often neglecting completion of his college assignments until the last moment. More than Watson or Bardeen, Land was focused less on abstract ideas and more on physical materials – chiefly a cheap plastic light polarizer -- and his demonstrations impressed an iconoclastic and wealthy Harvard physics instructor, George Wheelwright III, as well as a loyal patent attorney and a slew of Wall Street wizards. Based on his early demonstrations, Land and Wheelwright formed the company that in 1937 became Polaroid, where Land created an environment where invention happened in the intense, persistent mold of its founder.

In Edisonian style, the big ideas in Polaroid’s laboratory often came from the top. One day in 1943, while on a wartime vacation in Santa Fe, Land took a photo of his daughter, Jennifer, who asked why she couldn’t see the picture right away. The question immediately set Land off into a furious brainstorm, and during an hour-long walk, he worked out the specifications for the instant camera, almost right away envisioning the final product. He inspired a small group of scientists and engineers and made that product come to life over the next four years. The force of his inventive personality held the company together for five decades. But when Land was forced to give up the company’s leadership in 1980 – after the commercial failure of an instant-movie system – Polaroid lost its innovative lead and started falling apart, eventually collapsing completely.

Watson, by contrast, was a spark plug who focused on his role as the catalyst for building self-sustaining environments. The Cavendish Laboratory in Cambridge, England, where he worked in the early 1950s, was “an incredibly favoring environment” because it stood at the nexus of biological brainstorming happening in a cluster of laboratories in England, France, and the U.S. “Watson is constantly saying that this was the only place that this [double-helix discovery with Francis Crick] could have come together,” says McElheny. Watson constantly stressed the “principle of sharing information. You've got to talk to your opponents. You’ve got to share information. You cannot hide your cards all the time for fear that somebody else will steal them. You've got to open up.”

After his key role in discovering a structure for DNA that specified how it could be the molecule of heredity, Watson dedicated the rest of his career to the creation of stimulating scientific environments. “In the 50 years since then, Watson was building institutions, building places, building environments. He builds this very, very hot lab at Harvard. He was brought to Harvard in 1956 for the express purpose of being the spark plug of change from traditional biology to modern biology. He makes an enormous pest of himself, showing up in the lab at all times of the day and night, asking annoying questions. But, the basic message he was giving, over and over again is, ‘Have you read this? Have you seen that? Have you heard this? What about that?’ This is not somebody who was a boss or an emperor surrounded by acolytes. He was a spark plug, an irritating factor, an instigator.”

Just as the field of biology was reaching a new boiling point in the late 1960s, Watson yearned to build a different, more independent environment. At Harvard, “they have formed a department around him so as to keep him -- and Poof! -- he goes to Coldspring Harbor [to a laboratory] which is falling down and bankrupt. He has this passionate commitment to that as an environment. He's determined that this place shall not disappear. He then spends the next 25 years building, re-building, fixing up. It doesn't matter whether you're talking about the shrubbery or the lawns, or the vines or the trees, or the adaptive re-use of the buildings, or whatever -- he's constantly trying to build an environment.”

Watson’s great achievement in the final decades of the century was the creation of a far-flung environment for biological discovery, fighting for the resources necessary to launch the new Human Genome Project. “At the end of his career, he builds this empire of labs,” McElheny continues. “Even though it wasn't his idea, he becomes the inevitable start up guy. And he does it by recruiting the right people to work in the program, by shouting down opponents, by calling them idiots and so on. And also by winning the loyalty of the small-scale scientists.” Bringing this life-long effort full circle, McElheny argues that Watson would probably never had done all this if it wasn’t for the environment he had at home and at the library as a youth. “Any program to sponsor creativity is going to have to work very hard on opportunities for self-education. That, to me, is the bottom line. You have just got to bust open pathways somehow for these masterful mold-breaking people to learn on their own."

"What kind of social environment seems to be most likely to generate inventions?" asks Joel Mokyr. "It's tolerance for people who are in this sense not conformist, people who are crackpots or, you know, in a generalized sense, deviants, will-not-conformists, people like that. The key to creativity is a willingness to put up with nonconformism above all, and that the more conformist a society is, by and large, the less creative it will be in all dimensions of human activity, but particularly in technology. I think that is one lesson that we probably can take away from the totalitarian experiments of the twentieth century," in which individual deviation was suppressed, to society's disadvantage.

A debate among our participants centered around what kind of environments produce the breakthroughs, the radical inventions, as opposed to the incremental ones. Thomas Hughes argues that corporate R&D labs tend to focus on research that applies to their existing product lines, which constrains the problem choices their researchers have and that "inventors in academic environments tend to come up with radical inventions because the university is not as constraining of their problem choice."

Robert Friedel disagrees with that assessment, arguing that there have been many breakthroughs at corporate labs, even since the invention of the transistor at Bell Labs. Friedel cites much of the rest of the micro-electronic industry, including seminal semiconductor and computer hardware inventions, that were developed by industry. Friedel stresses the whimsical notion of serendipity, and how industrial environments sometimes produce accidental discoveries. He points to a staff engineer at DuPont named Roy Plunkett, a non-genius "who did not fit into the category, for example, of a Watson or a Bardeen" who "was trying to produce an alternative refrigerant" and how he "happened to see in the course of carrying out the fairly routine reactions . . . that the material that he was working with had basically disappeared." In 1938, Plunkett discovered that there is a smooth material that is coating the canister, and he broke it open and started looking at it and testing it. His discovery led to the invention of Teflon. "My real point is that at Dupont, he was in an environment, in a situation, where he was able to walk down the hall and say 'What is this? Let's take a look at it.' His boss didn't tell him to stick (no pun intended) to his original problem of refrigerants. He could actually pursue this other path with the same resources around him."

In more recent years, the distinction between corporate labs and academic environments have blurred, says Lillian Hoddeson, and the same goes for the distinction between basic research and applied research. She cites the major breakthroughs in biotechnology that have happened in academic labs but were transferred quickly to corporations, and the fact that the researchers themselves often bridge both worlds. This is true in the computing world too, especially at MIT, at Stanford, and at Hoddeson's home institution, the University of Illinois at Urbana-Champaign, which all incubated innovations that led to the Internet era's hot tech startups, a few of which still exist.

From time to time, enlightened public policies have stimulated academic environments and made them economically viable as fountains of invention, says Nathan Rosenberg**,** senior fellow at the Stanford Institute for Economic Policy Research. Most significantly, the Bayh-Dole Act of 1980 enabled universities to license patents to companies and collect royalties on sales, even when the original projects were funded, in whole or in part, by government grants. "The Bayh-Dole Act really set a lot of this into motion," Rosenberg says, "so that today we have more than 400 universities that have offices of technology licensing." These universities collected about $1.7 billion in patent royalties last year, about the same figure as IBM, the world's foremost licensor of corporate patents.[38]

Underscoring these points, Claire Calcagno, a visiting scholar at MIT's Program in Science, Technology and Society, cites her extensive study of the creative spirit of Harold "Doc" Edgerton, the MIT professor of electrical engineering and measurement who invented many devices for corporations but also established a creative environment at his own university-based laboratory. Edgerton's work bridged several fields, including archaeology, oceanography, and photography, as well as electrical engineering. Relying on Edgerton's own writings, some of which are unpublished, Calcagno paints a portrait of how Edgerton's "creative mischief" led to archaeological discoveries and inventions such as the modern stroboscope, high-speed photography, underwater cameras, and sonar improvements. Edgerton, who died in 1990, "has been called the dean of ocean engineering," Calcagno says. "Why was he successful in all these ways?"

Edgerton pioneered the creation of the interdisciplinary, collaborative environment devoted to pure research, which he himself defined as when "the investigator does not have the haziest idea of what he is doing" and when "he doesn't know where a certain project will lead." Calcagno also notes a back-and-forth tension, or interaction, between this free and open-ended environment and what seems to be the opposite, a purposefulness that drove Edgerton to develop concrete inventions that could be licensed to such corporations as General Electric. He stressed working hard so that his students and researchers would be in a position where serendipitous discovery could happen. By this, he meant that careful awareness and unconventional thinking is required to recognize good luck when it happens. He also believed in learning from failures. "When you're working on something new, ninety percent of your efforts are failures," Edgerton once said. "And I think that's good for students to see. It's a terrible blow for a student to go out with me and I fall flat on my face and get a whole lot of nothing. [But] it's a tremendous experience for them."

David Mindell, the Dibner associate professor of the history of engineering and manufacturing, explores the paradoxes inherent in modern engineering cultures. Mindell cites his own experience building an improved sonar navigation device for DeepArch, the MIT deep sea technology and archaeology project that he leads. He notes how computing and communications tools make creative work more isolating and more connected at the same time. "My own intellectual history corresponds roughly to the history of the personal computer, and so I've always had a computer on my benchtop," he says. "But the things that you can do with it today are fundamentally different from what one did with it in the past. First of all, you simulate it before you build it. Then, as you build it, you constantly tweak the simulation so that you have a material instantiation and a simulation running in parallel."

"Having the Web on one's benchtop completely changes the whole nature of what a little workshop is. Electrical engineers used to have walls full of data books about hundreds and thousands of chips. I have almost none of those in my lab right now, because you can get them all on the Web instantly. You literally go to Google and you type in a number like 2N6550, and, you can get the data sheet like that. Ditto for ordering from catalogs and Federal Express." With just-in-time delivery, "I don't need to keep lots and lots of chips and this huge collection of components in my lab, because if I can get onto Digikey's website by eight o'clock at night, I can have it at ten o'clock the next morning. And that's a staggering level of infrastructure. It makes an individual person able to move forward like that in a way that would be extremely difficult [otherwise].”

These tools enable inventors to accomplish an unprecedented amount of work on their own. This ability is central to Mindell’s own process. “I don't want to learn all the hard problems from other people,” he says. “I want to stumble on them myself, struggle with them, and if I can then get through them, I will have learned it much better. The more times it breaks, the happier I am, because then if I can fix it, the more intimately I know how it works and how it doesn't work. I have a kind of almost arrogant myopia about what I'm designing. I don't want other people to tell me how it should go. I need to learn it on my own, because I need to be able to constantly recreate the process of going from the principle to the thing.”

However, Mindell also realizes that he is not alone in his process, and he questions the mythology of whether any inventor has ever truly accomplished something great on his or her own. “On the one hand, I work in a fairly local, physically isolated environment, and on the other hand, I'm well aware of the resources that it takes to create that environment, both time, space, equipment, and how much connectedness is required in order to actually even get to the point where you're face to face with what you consider the real problem. So there's this sort of paradox of lone work but only work that can possibly exist if one works for a big institution that gives one the time to do this, it's supported by a federal grant, and it's tied into what that particular government agencies want.”

Mindell also realizes that he is only creating a small piece of a large puzzle. “With this invention particularly, almost everything I build is only useful as part of a larger system that's a very, very specialized system of undersea robots and all the infrastructure required to support it. All of the products are deeply collaborative. We each do little pieces of it, but it's all part of a larger group.”

That’s why even a lone inventor must hand off his or her creation and have others contribute to it before it can be released into the broader world. “The success of a technology really depends on it existing independent of its inventor,” says Mindell. “And this is actually a problem I see with a lot of the students at MIT. There's a great emphasis on project-oriented, hands-on learning, but the students adopt this sort of, make-it-work-for-the-demo [approach]. The professor gives you the grade, and then it all falls apart, and they consider that their measure of success." To borrow a phrase from Doc Edgerton, all successful, socialized inventions must go through "the trauma of using it."

Finally, our participants focused on the broader physical environments in which invention flourishes. "In the book that I just finished, on the history of control systems and computing," says Mindell, "one of the really dominant themes was this notion of local engineering cultures and how deeply people are influenced by their local environments in ways that they may not always realize." Several of our participants stressed the urban environment that forms a contextual space for the laboratory and the creative process. Indeed, the Nobel Museum in Stockholm has an exhibit on this subject, showing how vibrant urban environments gave rise to individuals who eventually won the prize. Focusing on urban spaces such as Paris in the 1920s, pre-war Budapest, and post-war Cambridge, England, the exhibit shows how diverse environments created a context in which invention and artistic creativity could grow. Today, says Victor McElheny, "we can name the places in the world" that embody what he calls "the diversity of a broader sense that sponsor creativity." Lillian Hoddeson concludes that "places reflect values." Therefore, if an individual, a group, or an entire society values creativity and inventiveness, then they will gravitate towards and build great collaborative environments.

Consequences of Invention

Until this point, we have been focusing on the roots of the inventive process, what drives inventive activity, the different styles of invention, and how to build creative environments. But we have thus far left open one of the biggest questions: What are the consequences of invention? Or as Stanford economist Nathan Rosenberg puts it: "What happens to major inventions after their technological feasibilities have already been established? What comes after the eureka?"

History is full of examples of people completely misunderstanding and miscalculating the implications of major inventions. The people who were wrong include not only the so-called experts but the inventors themselves, and they weren't wrong on just the minor details but on just about everything. Of course, they were wrong for a good reason. Rosenberg cites an old saying: it's easier to invent the future than to forecast it. "When major inventions are first achieved, their performance is typically quite primitive," he says. "Think of the airplane in December 1903, or the mobile phone in 1984. Forecasts of their future significance are almost inevitably dominated by the preoccupation with the primitive features of the prototypes. But what is also true, and this brings me to my second perspective, is that many technological breakthroughs . . . first emerge with no obvious domain of application." Indeed, Rosenberg compares early inventions to unmolded clay or mere building blocks.

One overriding consequence of invention is that it triggers the need for more invention, or more precisely, "identifying specific possible categories of application," Rosenberg says. These opportunities call for a "different set of skills." Often, inventions have powerful applications in "totally unanticipated contexts" or in different sectors of the economy, and the process of mapping inventions to applications in different domains involves what Rosenberg calls "intersectoral flows."

He cites the steam engine, which was conceived as a device for pumping water out of flooded mines. "It was a pump," he says. "It was, in fact, for a long time referred to as a pump." Only after a "succession of improvements in the late eighteenth century" did it become a "source of power for the textile factories, iron mills, an expanding array of industrial establishments." By the early nineteenth century, it became the engine of transportation, "a generalizable source of power" for railroads, steamboats, and ocean-going steamships. After the Civil War, it was used to produce "a new and even more generalizable source of power, electricity." Rosenberg concludes that "Thomas Newcomen and James Watt should surely be forgiven for having failed to foresee the far-flung applications of their ingenious inventive efforts."

Major new technologies, or "macro-inventions"[39] not only "induce further inventions and investments over a much wider technological frontier" but "often constitute entirely new technological systems." These vast systems require a rethinking of the way the world works, an often inconceivable expansion of imagination. "If you go back to eighteen-thirties and forties," he says, "you find people thinking about railroads merely as feeders into the existing canal system." As late as 1919, radio was seen as a wireless telegraph used for naval communication, not a medium for broadcasting. The British still call the radio the 'wireless.' In the same vein, the telephone was "originally conceptualized as a business instrument, like the telegraph, to be used primarily to exchange very specific messages such as the terms of a contractual agreement," not for chatting. "Western Union was offered, at one point, the opportunity to purchase Bell's 1876 telephone patent for a mere one hundred thousand dollars. They rejected the offer. In fact, Western Union stated in 1879 that it was willing to withdraw from the telephone field in exchange for Bell's promise to stay out of telegraphy."

In the same way, says Rosenberg, almost everyone ignored "the Wright brothers' remarkable achievement" back in December 1903, which isn't surprising since "the first flight extended roughly the length of a football field. I strongly suspect that if any of us had been at Kitty Hawk during that fateful morning, none of us would have driven home with visions of airplanes crossing the Atlantic in six hours. It was fully one third of a century, remember, before airplanes became an invention of real commercial significance, with the availability of the DC-3 in 1936. That one third of a century was filled with literally thousands of technological developments that finally rendered the regularly scheduled airplane flights relatively safe, reliable, and capable of operating at a very low cost per seat-mile."

Predictions about computers were equally off base. The ENIAC, developed in part at the University of Pennsylvania in 1946, "weighed thirty tons, had nearly eighteen thousand vacuum tubes, and was notoriously unreliable." The president of IBM back then made his infamous proclamation that IBM should stay out of the computer business "because his marketing people were telling him that the world demand for computers could probably be satisfied by one or two dozen machines." The co-inventor of Harvard's Mark I, Mark II, and Mark III computers, the brilliant physicist Howard Aiken, told Congress in 1956: "If it should ever turn out that the basic logics of a machine designed for the numerical solution of differential equations coincide with the logics of a machine intended to make bills for a department store, I would regard this as the most amazing coincidence that I had ever encountered."

Still, the early forecasts and predictions continued. Early mobile phones were installed in cars and typically cost about a quarter of the price of a new car. "When AT&T was undergoing divestment in 1983-'84, it was important to the senior AT&T decision-makers to know what the financial future was likely to be for different sectors of AT&T's huge telephone empire. It was not yet clear whether the cellular spectrum that the FCC had granted to AT&T would remain with AT&T or go to the Bell operating companies. AT&T therefore paid a considerable fee to one of America's best-known consulting firms to forecast what the subscription level for cellular phones would be likely to be in 1999." The forecast stated that the likely subscribership might be as much as one million." The real number turned out to be more than 70 million.

An invention with perhaps even more mind-boggling consequences is the discovery of the laser, which led not only to a Nobel Prize but a protracted patent lawsuit to determine the first true inventor. No one predicted the range of applications upon its invention in the 1950s. "The laser has become a primary instrument of scientific and engineering research, due to its ability to perform operations and measurements with a degree of precision that was previously impossible," says Rosenberg. The laser became such a key tool in biology, chemistry, physics, and all fields of engineering that "several Nobel Prizes in science have already been won for basic research that made extensive use of lasers." The laser is indispensable for a wide range of surgical procedures, from removing tumors to delicate eye operations. "Lasers have also received FDA approval for the removal of unwanted body hair, and much more important, as a substitute for the dentist's drill." There are five journals in the U.S. that "focus exclusively on the application of lasers in medicine." Lasers are used to cut textiles, metallurgical materials, plywood, and plastics. Lasers are being tested for spotting contaminated meat. "During the Super Bowl, the supply of water in the big pipe going into the Qualcomm Stadium was monitored by a laser beam to detect the presence of noxious substances in the water supply. So the laser is now an anti-terrorist weapon." This is not to mention checkout scanners, computer printers, laser-guided bombs, missiles and other weaponry, and the ubiquitous use of lasers in electronics for digitally decoding music and movies. Lasers are now being tested for removing graffiti from walls.

“Which of the eventual uses of a laser that I've just enumerated do you think you would have forecast if you had been around at the time [of its invention]?” Rosenberg asks. “What was missing was not scientific knowledge. What was most missing was imagination.” Inventions cause us to look at the world anew and re-imagine the implications and applications for each fundamental new technology. Or to put it another way: one of the biggest consequences of invention is more invention. Apply this perspective to a current invention now first coming to market -- Dean Kamen’s Segway human transporter, for instance -- and one can imagine that both the hype and the widespread ridicule being directed at the invention may seem quite silly in about twenty years. Or maybe not. Again, it may be easier to invent the future than to forecast it.

Indeed, inventors over the past three centuries have achieved such remarkable success in transforming the world in so many unexpected ways that the forces they have unleashed may be bringing about a reinvention of invention itself. Rosalind Williams, the Robert M. Metcalfe Professor of Writing at MIT’s Science, Technology, and Society Program, concentrates the broad question of the consequences of invention on one particular institution, the Massachusetts Institute of Technology, where she served as dean of students in the late 1990s. “MIT, of course, thinks of itself and is in many ways an invention factory . . . a stronghold of Edisonian inventiveness and engineering-based design,” she says. “It's a place that strongly and justly is identified with inventiveness and creativity. But it is struggling to maintain itself as such a center.”

One of the consequences with which MIT is grappling is “the dispersal of inventive activity beyond the engineering profession,” which Williams calls “one of the most striking features at contemporary MIT.” Who is inventive, she asks? “It's sure not the engineers only anymore,” she says. Engineers are up against competition from a number of professional groupings. “The word techno-science says a lot,” she explains. “Scientists have long been claiming, ever since the Manhattan Project, that they're the best engineers. You can believe it or you can not believe it, but that kind of statement is pretty provocative. When it works well, techno-science really works beautifully because the scientists and engineers have a back and forth using a lingua franca of information technology to work together in really exciting ways. But the point is, the boundaries are gone or very nearly gone.” Engineers are also in competition with design professionals, who are expert in the aesthetics and human factors that engineers are sometimes known for ignoring. "So, in many ways the engineers just find themselves having a lot of competition in being inventors," says Williams.

This struggle, she suggests, is reflected in the assumptions implicit in our language. In 20th century industry, we've moved from a world where "efficiency" was the supreme term to the current era where "innovation" is the reigning buzzword. In this regard, economist Joseph Schumpeter was ahead of his time when he asserted that profit comes from entrepreneurship and innovation. "I think it's only in the past few years that the Schumpeterian model has become a descriptor of the way markets operate and the way people think," says Williams. Even with the dotcom collapse, she argues, this rhetoric remains the dominant and ubiquitous ideology of capitalism. However, "the postmodern celebration of creativity, I think, has opened us up to realizing that there is inventiveness in a much richer and fuller sense than just business plus technology equals profit."

One broad change is that the language of engineering and invention is becoming "feminized" for the first time, "with some really interesting gender cross-dressing in terms of the male and female connotations going on," Williams says. "The language of innovation is very tough guy. It's very competitive and warlike. And it is also a language of male procreation. We create change. We do change. We make things." She cites Neil Gershenfeld, of the MIT Media Lab, and his term "the engineering of life."

But with so many women entering the profession now, "what I've noticed is that the language gets softer and more female, because in engineering there's a great deal of emphasis on soft skills, on communication and team work, on negotiation, on sensitivity to context. There's always been a sort of housewifely role in engineering. You're building the things that people need to get their work done and you're maintaining them and taking care of them and doing the dirty work of society. But the emphasis on the soft skills, which you will find in the engineering curriculum, they just become more and more important. In that language sense, engineering is being feminized."

Another major consequence of invention is the assertion of power and control. As in the extreme case of Ford's assembly line, "I think a hugely underestimated aspect of invention is its use to control people, its use as a tool of power." As an example, she cites the installation of a new accounting system for the MIT administrative offices. “What strikes me is how the language of technical innovation was used to disguise what was really going on. Instead of just saying, ‘We really need to keep track of what you guys are doing because if we don't know, we can’t control you,’ they say ‘Here’s our new technology. It’s SAP. If you resist it, then you’re resisting technological change.’ When I heard that language being used against people in the Registrar's Office, who are the most techie people on the face of the earth, I thought ‘this is bizarre.’ They weren't resisting technology or change even, they were resisting consultants coming in telling them how to do their work.” One administrator told her: ‘We are suffering from innovation.’

That gets to perhaps the biggest consequence of invention, that it eventually changes everyday existence. “We live in life-world,” says Williams, “and inventions have all sorts of connections that affect our daily experience.” She cites new communications technology. “Our experience of time and space have been radically altered because we have to integrate all these inventions that allow so many connections of communication to be layered onto our lives and allows us to be in so many places at so many times and in some many different ways. This has distorted our daily experience of life. The result is a life-world where the crowding of time and space is acute. We all feel barraged by things, messages, people, and information. And our attention and patience get shorter and shorter.”

The implications have hit home. “There is no other topic at MIT that is so discussed as the fullness of the life-world and the worry -- the deep anxieties – that technology is creating an environment where invention is no longer nurtured or even possible. So, by creating inventions, we are in a reflexive way, undercutting MIT's institutional ability to invent and it's a paradox that is not purely intellectual. When you do surveys of the faculty and say, "What are your problems?", money is not on the top of the list. Time is on the top of the list. Time and this attention disorder. We all have attention deficit disorder. And so the worry is that we are going to cut ourselves off from the very sources of creativity and inventiveness that have made MIT what it is.”

Finally, in the post 9-11 world, we are only beginning to grapple with the societal consequences of invention. “MIT, of course, is famous as a place that produces inventions,” she says. “It's much less famous as a place that confronts the effects of those inventions." In the epilogue to her most recent book, Williams writes from the perspective of the days that followed the attacks in the World Trade Center and the Pentagon: "Disasters are revelations. We never understand a technological system better than when it collapses. The process of destruction unmasks design flaws, and so technological disasters are followed by technological post-mortems. We peer into the ruins to figure out what needs fixing: the O-ring on the Space Shuttle, the cooling of the nuclear reactor, the building struts, the cockpit door. But when a technological disaster is caused by deliberate human action, when 'normal' civilian technologies are turned into weapons, we are forced to think more deeply about technological systems – not only their material design but their meaning. . . Now we peer into this familiar world and see in its depths a frightening one, which we have been constructing all along with only the faintest awareness what we were doing. We cannot keep generating innovations without giving much more attention to our ability to live with the changes we generate."[40]

Policy Implications

Our goal in convening this particular workshop and putting together this report is not to make specific legislative proposals, but to identify key areas of policy considerations, and to recommend further study of these issues in order to suggest more precise policy changes in the near future. We are not only focused on national public policies, with recommendations to legislators and other government officials but on imperatives for two other audiences as well. The first is the educational community, from elementary to higher education, and how that community can best cultivate the next generation of inventive individuals and institutions. The second is the corporate community, the leaders of the many companies who are concerned with and directly benefit from invention and creativity. Our participants highlighted six areas of consideration:

(1) **Setting the Invention Agenda:** Who decides what problem areas are targeted for invention and who allocates the resources accordingly? Is the agenda set by the pull of market demand, by media coverage of certain issues and problems, or by a more structured top-down approach? Since we know so little about how the agenda is set, this

becomes a natural focus for further study by policy makers, educators, and corporate leaders.

Northwestern's Joel Mokyr puts it this way: "Who sets the agenda in the entire endeavor of creating new knowledge? Is it demand-driven? Has society established certain new priorities, problems it wants solved all of the sudden? A recent example is enormous amounts of money that's going into research on bioterrorism. The budget has, I think, quadrupled in one year. And obviously, this is demand-driven -- just as the big spurt in virology and immunology in the 1980s was driven by another shock, which was the occurrence of AIDS."

"There is also a supply side to this," Mokyr continues. "Society allocates resources to areas where they think that this resource can be productive. It does not want to spend more money on things that the consensus is they can't be done. So, the amount of money that's going into nuclear fusion is declining, not because we don't think it's a valuable social product, but because general consensus is that this problem, at the moment, is too difficult. And so, the setting of the agenda is something in which we actually know remarkably little. The market plays a very important role in this. But [there are] political factors as well because clearly the market is never allowed, by itself, to set the agenda on its own. There's always an incredible amount of input from political and social organizations." As a giant consumer of new technology, for instance, the military throughout history has played an enormous role in setting the invention agenda.

Some categories of invention are not only achievable and urgent, but they also fail to find their way to the top of the agenda, for whatever reason. For instance, there have been scattered calls for a Manhattan Project to achieve energy independence, to replace the internal combustion engine with hydrogen fuel cells, or to create other technologies that would reduce the dependence of industrial societies on imported oil. How can considerable resources be allocated to issues such as this? Who has the power to get this issue on the national agenda, or to keep it off?

(2) **Commercializing New Technology**: What are the best ways to get new inventions out of the universities and into the marketplace? As discussed, the Bayh-Dole Act of 1980 set the stage, enabling university-based laboratories to license patents deriving from

government-funded projects. But much has changed since that law was enacted. Perhaps the biggest change has been in the allocation of funding. Whereas the largest category of academic R&D budgets back then was the physical sciences, the biological sciences have now moved into that top spot.

The consolidated budget of all American university research shows that about 56 percent of the total is represented by life sciences, including biomedical and biotechnology. The physical sciences has shrunk down to about nine percent, while electrical engineering and computer science stand at about 19 percent. “We're now living in a biological world much more than the world of Newtonian physics and engineering,” notes Mokyr.

What are the implications deriving from the move from this physical world to a biological one? Should universities retain patents on genes, or genetic-manipulation techniques, or genetic material? In many cases, says the Smithsonian’s Arthur Molella, academic labs are moving into the place of prominence that corporate labs, now downsizing, once held. This is especially true in the biomedical field. Indeed, there have been several high-profile patent lawsuits between universities and corporations in recent years, one example being the University of Rochester versus Pfizer and Pharmacia, a suit over patents on the multi-billion dollar painkiller, Celebrex. What are the patent licensing implications when so much biotech invention happens at universities? In addition, should universities benefit financially when their professors or students start companies. In the case of Netscape, for instance, cofounder Marc Andreesson developed his early Web browser technology at the NSF-funded supercomputing center at the University of Illinois at Urbana-Champaign. What is the best way to deal with these situations? At the very least, agree Rosalind Williams and David Mindell, policy makers should acknowledge the public funding that goes into such innovations, rather than portray the success of such startups as a pure product of the “free market.”

(3) **Creating Interdisciplinary Environments:** An increasing amount of action in the world of invention is occurring across different disciplines and across different types of institutions, yet cross-disciplinary environments have proven difficult to create and sustain at existing institutions, from corporations to universities. What kind of policies

could help sustain such environments? Lillian Hoddeson, of the University of Illinois, pointed to this as a policy problem that needs to be addressed. “In policy statements, there should be an emphasis on interdisciplinary work -- the word "hybrid" is coming to my mind -- between academic and industry.” She believes in “stressing the mixing of all kinds.”

Agrees MIT’s Rosalind Williams: “There's no question that the really creative, exciting work in both engineering and science is being done at that point of interface with the life sciences and both the other sciences and engineering. Can we find patterns that are familiar from other research that's been done in inventiveness or is there something new going on?” Is the marriage of biology and information technology different from other cross-disciplinary combinations of the past? Says Stanford’s Nathan Rosenberg: “I would suspect that it shares a lot of characteristics with the marriage of engineering and the physical science of the 20th century. So, it's not necessarily a radically new thing, but rather is yet another merging of engineering practice, which has already merged with physics in the creation of the electronics industry.”

For an example of how critical and how difficult this issue is, one can turn to the example of Leroy Hood, the inventor of the DNA sequencing machine and other instruments that have made the Human Genome Project possible. The winner of the 2003 Lemelson-MIT Prize, Hood often tells the story of how he felt he was forced to leave Caltech and then the University of Washington because he couldn’t create or sustain the interdisciplinary environments that were necessary to invent and develop new biological technology. He requires biologists, engineers, physicists, chemists, and others to work in close collaboration, but such cross-department partnerships were shunned by administrators. This is why he had to set up his independent Institute for Systems Biology, in Seattle. Do such institutions have to be set up independently, or can existing institutions change to accommodate these new ways of invention and research?

(4) **Achieving Diversity**. While much has already been done to increase the numbers of females and minorities in the formerly all-white-male worlds of corporate and university-based laboratories, much more needs to be done to inspire kids of all kinds to pursue a life of science, engineering, and invention in the first place. One particular issue of

diversity discussed by several of our participants is the need to tolerate non-conformists who might not have the top grades to match their peers. John Bardeen, for example, won two Nobel Prizes, but his grades back when he was in high school and college wouldn't be good enough to win acceptance into MIT today, notes Hoddeson. This presents a paradox. We know that invention is often practiced by radical thinkers, yet top corporate labs and universities often require straight As a prerequisite. Can there be some way of making sure that the MITs of the world get truly creative students, not just the ones who perform best on graded tests and on similar standard measures of youthful accomplishment?

(5) **Improving Research Tools.** As discussed, the Internet has transformed all kinds of research, lowering the access costs of many types of information. In the past, whenever access costs to information have been reduced, there has been an outpouring of inventive activity. But our participants focused on the limitations of the Internet as a research tool. Nathan Rosenberg even went so far as to suggest that perhaps "search costs have gone way too low." In other words, students often put whatever they can find in a Google search into their papers, without doing rigorous research and without considering the material that isn't online.

Given the fact that McElheny and others have stressed the critical importance of libraries and other "tools for self-education," should we be alarmed that Google is becoming the library of the future? Mokyr stressed the need to train students on the limitations of the Internet, pointing out for instance the need to trace an online document back to its sources or to check which institution is publishing it. Are there ways to improve the Internet and are funds needed to put more historical and current material online?

(6) **Sustaining Creativity:** Do some inventions undermine inventiveness? Rosalind Williams points out that this paradox "is a huge policy issue." As she puts it, "how do you shield inventiveness from the effects of invention?" Does the daily barrage of information – constant e-mail, ubiquitous cell phones, wireless Internet connections, round-the-clock "breaking news" coverage, etc. – intrude on our thinking time to such an

extent that it challenges our ability to engage in creative thinking? She advocates "finding ways to shield people from the ubiquity of technology so they have time to think on their own."

This is part of the broader question of effects of technologies, that we often adopt new tools without considering the ramifications. "I think there is something in our society that makes sure that invention, innovation and the big things never get touched or are assumed to be stable," says Williams. "In order to sustain creativity, there needs to be broad-based discussion on how new technologies affect our life-world." To quote Bruno Latour: "Innovation without representation is tyranny." In building the creative environments of the future, we need to anticipate the adverse consequences of new technologies and not let them intrude on our fundamental aims.

NOTES

[1] William Middendorf, *What Every Engineer Should Know About Inventing*
[2] Howard Gardner, *Intelligence Reframed*
[3] Ibid, Middendorf
[4] Nathan Rosenberg, *Inside the Black Box*
[5] Thomas P. Hughes, *American Genesis* (from Heidegger)
[6] Joel Mokyr, The Gifts of Athena
[7] Ibid.
[8] *The Concise Oxford English Dictionary, Tenth Edition (Oxford University Press, 1999)*
[9] *Encyclopedia Americana* (Grolier, 2001)
[10] Mokyr, *The Gifts of Athena*, page 19
[11] Ibid, Mokyr
[12] Ibid, Mokyr
[13] Ibid, Mokyr
[14] See Chandler, *The Visible Hand*
[15] Cipolla, *Before the Industrial Revolution*, p. 181
[16] Adam Smith, *The Theory of Moral Sentiments*
[17] *Inventing America*, page 144
[18] Inkster, page 287
[19] Mokyr, p. 66
[20] *Inventing America*, p. 267

[21] Ibid.
[22] Ibid., page 284. Quoting Census Bureau figures: In 1801, the population of the U.S. stood at 5.3 million, and doubled by 1820 and doubled again by 1840.
[23] Ibid.
[24] U.S. Census Data, Series W 96-106, Copyrights, Patents and Trademarks. And Hughes, American Genesis, table on page 14
[25] Whitehead, page 120
[26] Hughes, *American Genesis*, page 3
[27] Ibid., page 8. Also see Noble, *America By Design.*
[28] Buderi, *Engines of Tomorrow*, p. 52
[29] U.S. Census Data, Series W 96-106, Copyrights, Patents and Trademarks
[30] "Over Time, America Lost its Bullwackers," *The Wall Street Journal*, Sept., 24, 2002, page 1.
[31] Hughes, *American Genesis*, page 217
[32] Ibid.
[33] *Inventing America*, page 898
[34] Hoddeson, *Crystal Fire*
[35] Hoddeson, *True Genius*
[36] Ibid.
[37] Hoddeson is citing the Yiddish term for an aggregate of related things; the Spanish translation is, roughly, enchilada.
[38] See research.ibm.com
[39] Mokyr, *Lever of Riches*
[40] Williams, *Retooling*, pages 216 to 218

<u>BIBLIOGRAPHY</u>

Brown, David, and Lester Thurow, *Inventing Modern America* (Cambridge, Mass.: MIT Press, 2002)

Buderi, Robert, *Engines of Tomorrow: How the World's Best Companies Are Using Their Research Labs to Win the Future* (New York: Simon & Schuster, 2000)

Chandler, Alfred, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: Belknap Press, 1977)

Cipolla, Carlo, *Before the Industrial Revolution* (New York: Norton, 1980)

Friedel, Robert, and Paul Israel, et al, *Edison's Electric Light: Biography of an Invention* (New Brunswick, New Jersey: Rutgers University Press, 1986)

Ferguson, Eugene S., *Engineering and the Mind's Eye* (Cambridge, Mass.: MIT Press, 1992)

Gardner, Howard, *Intelligence Reframed: Multiple Intelligences for the 21st Century* (Basic Books, 1999)

Hoddeson, Lillian, and Michael Riordan, *Crystal Fire: The Birth of the Information Age* (New York: W.W. Norton & Co., 1997)

Hoddeson, Lillian, and Vicki Daitch, 2002. *True Genius: The Life and Science of John Bardeen* (National Academy Press, 2002)

Hughes, Thomas, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Viking, 1989)

Hughes, Thomas, *Rescuing Prometheus* (New York: Pantheon Books, 1998)

Inkster, Ian, *Science and Technology in History: An Approach to Industrial Development* (Rutgers University Press, 1991)

Maier, Pauline; Merritt Roe Smith, Alexander Keyssar, and Daniel J. Kevles, *Inventing America: A History of the United States* (W.W. Norton & Company, 2003)

McElheny, Victor, *Insisting on the Impossible: The Life of Edwin Land* (Reading, Mass.: Perseus Books, 1998)

McElheny, Victor, *Watson and DNA: The Making of a Scientific Revolution* (Cambridge, Mass.: Perseus Books, 2003)

Middendorf, William H., *What Every Engineer Should Know About Inventing* (New York: Dekker, 1981)

Mindell, David, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Johns Hopkins University Press, 2002).

Mokyr, Joel, *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton University Press, 2002)

Mokyr, Joel, *The Lever of Riches: Technological Creativity and Economic Progress* (Oxford Univ. Press, 1992)

Needham, Joseph, *Science and Civilization in China* (Cambridge University Press, 1954)

Noble, David, *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (New York: Knopf, 1977)

Rosenberg, Nathan, *Inside the Black Box: Technology and Economics* (Cambridge University Press, 1982)

Rosenberg, Nathan, and David C. Mowery, *Paths of Innovation: Technological Change in 20th Century America* (Cambridge University Press, 1998)

Smith, Adam, *The Theory of Moral Sentiments* (Oxford: Clarendon Press, 1976)

Smith, Merritt Roe, and Leo Marx, *Does Technology Drive History?: The Dilemma of Technological Determinism* (MIT Press, 1994)

Schumpeter, Joseph, *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle* (Cambridge, Mass.: Harvard University Press, 1934)

Schwartz, Evan I., *The Last Lone Inventor: A Tale of Genius, Deceit, and the Birth of Television* (HarperCollins, 2002)

Williams, Rosalind, *Retooling: A Historian Confronts Technological Change* (MIT Press, 2002)

Whitehead, Alfred North, *Science and the Modern World* (London: Free Association Books, 1985; first edition. 1926)

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Claire Calcagno is a maritime archaeologist currently working in STS as a member of the Research Group in Technology, Archaeology and the Deep Sea (DeepArch). Currently, she is conducting research on Harold E. Edgerton and his seminal engineering contributions to archaeology conducted in submerged contexts. For this investigation, which reviews the developing technologies of underwater archaeology, she is particularly interested in exploring the processes of cross-pollination between the engineering, oceanographic and archaeology communities, both with relevance to how the discipline of maritime archaeology first evolved, as well as to current issues in remote sensing and deep-water research.

Calcagno received her bachelor's degree in fine arts (art history) from Harvard in 1982. Graduate work in archaeology at the University of Oxford led her to a master's in maritime archaeology (M.St. 1991) and a doctorate (D.Phil. 1998), with a dissertation on seafaring and maritime exchanges in the Central Mediterranean region between the 12th to 9th centuries BC (due to be published with BAR Archaeopress, Oxford). In recent years, she has taught courses in maritime archaeology and technology at Boston University (1999-2000), and the University of Southampton (2001), as well as in humanities studies at Stanford University (2000-2001). Her archaeological fieldwork experience has included surveys and excavations on land, in addition to under water in Italy, France, Tunisia, Turkey and Bermuda, and will extend to American waters this spring with a remote sensing project on the USS *Monitor* with M.I.T./DeepArch.

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

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

Rayvon Fouché
Assistant Professor, Science and Technology Studies
Cornell University

As a cultural historian of technology, Rayvon Fouché studies the ways in which the social, cultural and political spheres we inhabit interact with scientific and technological artifacts, practices, and knowledge. His research interests also include American and African American cultural history, the intersections between technology and media representations, and theories of race and racial identification. He aims to bring STS scholarship together with studies of race to understand how racism and racial identification differentially influence various cultural communities during technological creation, development and production.

Fouché's current research continues to consider the relationships between race and technology by exploring the effects that technological developments, pre-analog to post-digital, have on racial and cultural relations. In this work, he examines the ways that technological change references and reflects the fluid meanings of race and the nature of race relations in the United States. He is exploring the ever-shifting racial terrain of the United States in the twenty-first century to provide a new mapping of technological and race relations.

Fouché has been a post-doctoral fellow of African and Afro-American Studies at Washington University in St. Louis and an assistant professor of African American Studies, American Studies and History at Purdue University. He is the author of *Black Inventors in the Age of Segregation* (Johns Hopkins University Press, 2003).

Robert Friedel
Professor of History of Technology, History of Science, Environmental History
University of Maryland

Robert Friedel received his Ph.D. from The Johns Hopkins University in1977. Prior to joining the faculty at the University of Maryland he was a historian at the Smithsonian Institution and at the Institute of Electrical and Electronics Engineers. He continues extensive work with museums, consulting and collaborating in a range of projects for museums and agencies in Calcutta, Delhi, Stockholm, Munich, Pittsburgh and Washington. He has held fellowships at the Smithsonian, the Hagley Museum, the American Antiquarian Society, and the Dibner Institute for the History of Science and Technology. He has written several monographs on the history of technology, focusing largely on the nature of invention (*Pioneer Plastic*, *Edison's Electric Light*, *and Zipper:*

an Exploration in Novelty). In addition he has published numerous articles and shorter works on material culture, as well as the history of technology, ranging from the history of materials to changes in the engineering profession. He is active in numerous capacities for the Society for the History of Technology, and has been a contributing editor for *American Heritage of Invention and Technology* since 1985, and an advisory editor for *Technology & Culture* since 1993.

Lillian Hoddeson
Professor of History and Physics
University of Illinois at Urbana-Champaign

Lillian Hoddeson specializes in the history of twentieth-century physics and technology. Her current research on scientific creativity and problem-solving draws on her training in physics (Ph.D., Columbia, 1966) and the history of science (Princeton, 1973-1975), as well as her earlier research on how children learn science, and her more recent studies in cognitive psychology at the University of Illinois. All her books—on the atomic bomb (*Critical Assembly*), solid-state physics (*Out of the Crystal Maze*), big science in particle physics (*The Ring of the Frontier*, *The Birth of Particle Physics*, *Pions to Quarks*, and *The Rise of the Standard Model*), the transistor (*Crystal Fire*), and the life and science of the double Nobel Prize winning physicist John Bardeen (*True Genius*)—deal with questions of creativity and invention in the production of science and technology. Her extensive use of oral history interviews as a research tool over the last 30 years and her regular graduate seminar on this subject have brought her deeply into questions of individual and collective memory, a subject she is pursuing presently in collaboration with psychologists in the context of a faculty seminar and undergraduate honors course. She is a Fellow of the American Physical Society and of the Center for Advanced Study at the University of Illinois, in addition to a 2002 John Simon Guggenheim Memorial Fellow.

Thomas P. Hughes
Mellon Professor Emeritus, University of Pennsylvania
Distinguished Visiting Professor, Massachusetts Institute of Technology

Thomas P. Hughes's most recent books include *Rescuing Prometheus* (Vintage, 2000); *American Genesis* (Penguin, 1990), a Pulitzer Prize finalist; and *Lewis Mumford: Public Intellectual* (Oxford University Press, 1990), edited with Agatha Hughes. He is a member of the American Philosophical Society, U.S. National Academy of Engineering, Royal Swedish Academy of Engineering Sciences, and the American Academy of Arts and Sciences. Hughes is a recipient of the Leonardo da Vinci Medal from the Society for the History of Technology. He has also been awarded honorary degrees from The Royal Institute of Technology in Stockholm and Northwestern University.

Victor K. McElheny
Visiting Scholar, Program in Science, Technology and Society
Former Director and Founder, Knight Science Journalism Fellowship Program
Massachusetts Institute of Technology

Victor K. McElheny began The Knight Fellowships program at M.I.T. in 1983, originally known as the Vannevar Bush Fellowships in the Public Understanding of Technology and Science. McElheny was the program's creator and leader—mentoring more than 140 science writing fellows—until he retired in June of 1998 to devote full time to writing. Along the way, McElheny assured the program's survival in perpetuity by securing an endowment from the combined funds of the John S. and James L. Knight Foundation and M.I.T. itself.

McElheny is a longtime science writer who worked for *The Charlotte Observer*, *Science* magazine, *The Boston Globe* and *The New York Times*, reporting on such topics as science in Antarctica and Europe, the Apollo lunar landing program, and the green revolution in Asia.
While at *The New York Times* during the 1970s, he wrote the first newspaper story describing the genetic engineering technique called recombinant DNA, the subject of intense controversy over several years in the 1970s. Also at *The New York Times*, he founded one of the first technology columns in American newspapers. McElheny's freelance work has included numerous articles for newspapers and magazines in addition to television writing and appearances. In 1978, he joined Cold Spring Harbor Laboratory as the first director of the Banbury Center for conferences on environmental health risks and fundamental biology. He came to M.I.T. in 1982 to create the fellowships program with funding from the Sloan Foundation and the Mellon Foundation.

In 1998, McElheny published a major biography of Edwin Land, the inventor of instant photography and founder of Polaroid Corporation, titled *Insisting on the Impossible: The Life of Edwin Land*. He is currently at work on a biography of James Watson.

David A. Mindell
Dibner Associate Professor of the History of Engineering and Manufacturing
Massachusetts Institute of Technology

David A. Mindell received his B.S. in electrical engineering and his B.A. in literature from Yale University in 1988, followed by his Ph.D. in the history of technology from M.I.T. in 1996. He was a National Science Foundation Graduate Fellow and a fellow at the Dibner Institute for the History of Science and Technology. Before coming to M.I.T., Mindell worked as a staff engineer in the Deep Submergence Laboratory of the Woods Hole Oceanographic Institution, where he is currently a visiting investigator. He is also currently an adjunct researcher at the Institute for Exploration in Mystic, CT. His research interests include technology policy (historical and current), the history of automation in the military, the history of electronics and computing, and deep-sea archaeology. Mindell heads M.I.T.'s "DeepArch" research group in deep sea archaeology. He is the author of *War, Technology and Experience Aboard the USS Monitor* (2000) and *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (2002).

Joel Mokyr
Robert H. Strotz Professor of Arts and Sciences
Professor of Economics and History
Northwestern University

Joel Mokyr has an undergraduate degree from Hebrew University of Jerusalem and a Ph.D. from Yale University. He has taught at Northwestern since 1974, and has been a visiting professor at Harvard, University of Chicago, Stanford, Hebrew University of Jerusalem, the University of Tel Aviv, University College of Dublin, and University of Manchester.

Mokyr specializes in economic history and the economics of technological change and population change. He is the author of *Why Ireland Starved: An Analytical and Quantitative Study of the Irish Economy*, *The Lever of Riches: Technological Creativity and Economic Progress*, *The British Industrial Revolution: An Economic Perspective* and his most recent, *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton University Press, 2002). He has authored over 60 articles and books in his field. Mokyr's books have won a number of important prizes including the Joseph Schumpeter memorial prize (1990) and the Ranki prize for the best book in European Economic history. His current research is an attempt to apply insights from evolutionary theory to long-run changes in technological knowledge. He is also working on *The Enlightened Economy: an Economic History of Britain, 1700-1850*, to be published as a volume in Penguin's *New Economic History of Britain*.

He is a fellow of the American Academy of Arts and Sciences, a former vice president and currently president-elect of the Economic History Association. He served as the senior editor of the *Journal of Economic History* until July 1998, and is currently serving as editor in chief of the *Oxford University Press Encyclopedia of Economic History* (to appear in 2003) and the Princeton University Press *Economic History of the Western World*. He served as chair of the Economics Department at Northwestern University between 1998 and 2001 and was a fellow at the Center for Advanced Studies in Behavioral Sciences at Stanford between September 2001 and June 2002.

Arthur P. Molella
Director, Lemelson Center for the Study of Invention and Innovation
Smithsonian's Institution's National Museum of American History

Under the directorship of Arthur P. Molella, the Lemelson Center has sponsored a series of interdisciplinary programs and exhibits. Most recently, Molella co-curated the international exhibition, Nobel Voices: Celebrating 100 Years of the Nobel Prize. Invention at Play, another exhibition of the Lemelson Center, has embarked on a three-year national tour, following its run at the Smithsonian.

Previously, Molella served as chairman of the Museum's History Department and as head curator for the Smithsonian's Science in American Life exhibition, among others. He received his doctorate in the history of science from Cornell University. He is co-editor of volumes 1-4 of *The Papers of Joseph Henry* and has written extensively on the relations of technology and culture. Molella is currently preparing a book (with Robert Kargon) on "techno-cities" in the US and Europe. He is also co-editor of *Inventing for the Environment*, to be published by MIT Press in fall 2003.

He is on the Executive Council of the Society for the History of Technology and has served as the book review and advisory editors for the Society's journal, *Technology and Culture*. He is a member of the National Advisory Council for the Tang Teaching Museum and Art Gallery of Skidmore College, and sits on the Board of Sponsors for the Thomas A. Edison Papers at Rutgers University.

Nathan Rosenberg
Fairleigh S. Dickinson, Jr. Professor of Public Policy Emeritus
Stanford University

Nathan Rosenberg received his Ph.D. from the University of Wisconsin and A.B. from Rutgers University. He has taught at the University of Pennsylvania, Purdue University, Harvard University, the University of Wisconsin, The London School of Economics, and Cambridge University. Rosenberg has served as chairman of the Stanford Economic Department. He is a member of the Board of Directors of the National Bureau of Economic Research, chairman of the advisory board of the UN Institute for New Technology, and a fellow of the Canadian Institute for Advanced Research. He is an elected fellow of the American Academy of Arts and Sciences and the Swedish Royal Academy of Engineering Sciences. He is also the recipient of honorary doctoral degrees from the University of Lund and the University of Bologna.

Rosenberg’s current research interests are the economics of technological change, the economic role of science, and economic history and development. His current research deals with the role of scientific knowledge in influencing the rate and direction of technological change, determinants of technological change in the chemical sector, determinants of technological change in the medical sector, economic performance of "high tech" industries, and universities as economic institutions. Rosenberg’s teaching interests are science and technology in economic growth, comparative economic development, and European and American economic history. His cross-disciplinary interests are in the engineering disciplines, and in interactions between economic, scientific and technological phenomena. Recent Books include: *Schumpeter and the*

Endogeneity of Technology (2001); *Paths of Innovation*, with David Mowery (1998); and *Exploring the Black Box* (1994). His professional associations are AEA, Royal Economic Society, Economic History Association, and Swedish Royal Academy of Engineering Sciences.

Evan I. Schwartz
Author and Independent Journalist

Evan I. Schwartz received his B.S. in computer science from Union College in 1986. He is an author and journalist who writes about innovation and the impact of technology on business and society. He is currently a contributing writer for MIT's *Technology Review*. A former editor at *Business Week*, he covered software and digital media for the magazine and was part of teams that produced 12 cover stories and won a National Magazine Award and a Computer Press Award. He has also published articles in *The New York Times* and *Wired*.

Schwartz' most recent book, *The Last Lone Inventor: A Tale of Genius, Deceit, and the Birth of Television* (HarperCollins, 2002) tells the story of television inventor Philo T. Farnsworth and his epic battle against RCA tycoon and NBC founder David Sarnoff. His first book, *Webonomics* (Broadway Books, 1997), anticipated the emergence of the Internet economy. His second book, *Digital Darwinism* (Broadway Books, 1999), anticipated the Darwinian shakeout among the dotcom species. Each was translated into nine languages and named as a finalist for a Computer Press Award for non-fiction book of the year. He is currently working on a book about the culture of invention, for the Harvard Business School Press. He has recently served as an adjunct lecturer at Boston University's College of Communication.

Merritt Roe Smith (Chair)
Leverett and William Cutten Professor of the History of Technology
Massachusetts Institute of Technology

Merritt Roe Smith received his B.A. in history from Georgetown University in 1963 and his M.A. and Ph.D. in history from Pennsylvania State University in 1971. Before coming to M.I.T. in 1978, he taught at Ohio State University and the University of Pennsylvania. Smith's book, *Harpers Ferry Armory* and *the New Technology* (1977), received the 1977 Frederick Jackson Turner Award, the 1978 Pfizer Award, and nomination for the Pulitzer Prize in History. He has received numerous fellowships and recognition, including a Regents Fellowship from the Smithsonian Institution, a Guggenheim Fellowship, a Senior Fulbright Scholarship in Sweden, a Thomas Newcomen Fellowship at the Harvard Business School, and the Leonardo da Vinci Medal from the Society for the History of Technology. Smith is a member of the American Academy of Arts and Sciences, a fellow of the American Association for the Advancement of Science, and currently serves on the boards of the American Museum of

Textile History, the Thomas Edison Papers Project at Rutgers University, and the public television series, "The American Experience." His research focuses on the history of American industrialization and the role of the military in technological innovation. He is editor of *Military Enterprise and Technological Change* (1985); *Does Technology Drive History?,* co-edited with Leo Marx (1994); and *Major Problems in the History of American Technology*, co-edited with Greg Clancey (1998). Most recently, Smith co-authored (with Pauline Maier, Alex Keyssar and Daniel Kevles) *Inventing America: A History of the United States* (2002).

Rosalind H. Williams

Robert M. Metcalfe Professor of Writing
Director of the Program in Science, Technology, and Society
Massachusetts Institute of Technology

Rosalind H. Williams attended Wellesley College and received a B.A. in history and literature from Harvard College, a M.A. in modern European history from the University of California at Berkeley, and a Ph.D. in history from the University of Massachusetts at Amherst. Williams came to M.I.T. in 1980 as a research fellow in the Program in Science, Technology, and Society. In 1982, she joined the Writing Program (now the Program in Writing and Humanistic Studies) as a lecturer. In 1990, Williams was named Class of 1992 Career Development Professor, and in 1995, the Robert M. Metcalfe Professor of Writing. From 1991 to 1993 she served as associate chair of the M.I.T. Faculty, and from 1995 to 2000 as dean of students and undergraduate education.

William's first book, *Dream Worlds: Mass Consumption in Late Nineteenth-Century France* (University of California, 1982), explores the complicated relations between technological change, cultural values, and marketing techniques at a critical moment in the development of modern consumer society. Her next book, *Notes on the Underground: An Essay on Technology, Society, and the Imagination* (MIT Press, 1990), explores the implications for human life in the transition from a predominantly natural to a predominantly built environment. As a cultural historian of technology, she has also considered the implications of this transition in studies of Lewis Mumford, Jules Romains, Enlightenment thinkers, and the issue of technological determinism. Her latest book, *Retooling: A Historian Confronts Technological Change* (MIT Press, 2002) draws upon her experiences as a historian and MIT dean to comment upon our "technological age." Her next book will use literary texts to examine experiences of the world in the late 19th and early 20th centuries, when global systems of transportation and communication began to affect those experiences in significant and complicated ways.