"THE ARCHITECTURE OF INVENTION"

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FOREWORD

This draft document is the complete report of a workshop held at Massachusetts Institute of Technology in August 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

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

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

However, despite the transparent importance of invention and the prospects of amplifying human creativity further, invention and inventors remain misunderstood, colored in the popular eye by a range of myths—the inventor as wizard with superhuman talents, the inventor as an outsider disconnected from mainstream society, the inventor as a nutty genius. These myths need to be exposed, for they may be harmful to the motivation of aspiring inventors.

For an area of such fundamental importance to human civilization, technological invention is substantially under-investigated in the scholarly literature. Much remains to be done. That said, research in cognitive psychology, historical and contemporary case studies of the work of inventors, investigations of industrial laboratories, and numerous other sources speak to the nature of invention and inventors. They illuminate creative personality characteristics, the place of knowledge and skills, the cognitive processes involved, and the roles of collaboration and context. They suggest approaches to fostering inventiveness in children and adults at the individual and organizational levels, and point the way to further fundamental inquiry.

The August 2003 workshop on the Architecture of Invention convened a small group of informed and insightful individuals representing the worlds of cognitive science, the history of technology, and the practice of invention itself to define what was known and outline what needed to be known concerning the fundamental nature of the inventive mind and the fundamental processes of invention — hence the phrase "architecture of invention." The findings of this group are given in detail in the main report and summarized below.

1. ***The products of invention.*** **Technological invention contrasts with scientific inquiry in its focus on developing things that fulfill practical functions, while showing striking range in the nature of its products and the scope of their impact.**
The products of technological invention characteristically fulfill practical functions. They contrast with the products of science, theories and findings that typically opt for a clean model of underlying fundamental processes while factoring out "complications" like friction or impurity.

When we ponder inventions, we perhaps most often think of a physical device that does a very particular job, like a light bulb or a bicycle. However, the world of invention is wide and deep. The products of technological invention include physical devices but also processes, algorithms, designed biological structures, and the like.

Inventions vary substantially in other ways: in their social impact, some having little impact while others like the automobile transform society; their knowledge extension, some building on received knowledge while others, as in the area of nanotechnology, require deep research; and system level, some occurring at the level of components or elements, others at the product or process architecture level, and others dealing with whole systems.

Historically, many inventions did not have identifiable inventors. They persisted and spread and underwent refinements and diversification in a society over long periods of time, with innumerable small contributions from unknown individuals. However, in today's world we can focus on inventors as having a clear social role, and we can explore the process and context of invention.

2. ***Invention as contextual.*** **Invention always occurs in a context—social, institutional, technological—and must be understood in terms of that context. Inventors function within that context and "negotiate" with it in various ways to advance their work, as well as are shaped by it.**
Invention always occurs in context—social, economic, institutional, cultural—and must be understood in terms of those contexts. One way to look at this is that inventors must "negotiate" their work on two fronts: on the one hand with nature, to ground their work in an understanding of what materials, natural processes, and so on afford; and on the other hand with society, to arrive at inventions that find a practical and valued place.

Invention has thrived in some societies much more than in others, reflecting the needs and values of the society, and indicating the profound effect of society on inventiveness.

Inventors sometimes respond to social needs by tackling already recognized problems. But sometimes they, in a sense, "invent" the problems themselves, discerning a problem or opportunity that previously was not recognized as such. To put this in the language of economists, sometimes inventions are "demand-pull," meaning that inventors respond to demands already being voiced in the marketplace; but many important inventions are "supply-push," meaning that they arise out of what inventors find ways to do, generating the further task for the inventor and colleagues of articulating a need that the invention fulfills and then convincing people that they have this need.

3. ***The inventive person and personality.*** **Although there is no formula for the inventive mind, a number of abilities and dispositions are associated with inventive productivity in trend.**
Effective inventors tend to display personality characteristics including resourcefulness, resilience, a commitment to practical action, nonconformity, passion for the work, unquenchable optimism, high persistence, high tolerance for complexity and ambiguity, willingness to delay gratification, a critical stance toward your own work. They are able to embrace failure as a learning experience. Successful inventors are self-critical of their own work. They learn to abandon knowledge that may be too constraining, and they embrace failure as a learning experience

Effective inventors show a range of skills and abilities, including mental flexibility, alertness to problems and opportunities, and deep knowledge. Some notable aspects of skill include: mental flexibility, alertness to practical problems and opportunities, ability to match one's talents with the problem, using a tool kit of effective ways to conceptualize and break down the problems, and self-knowledge helpful in managing one's endeavors. Characteristically, inventors are deeply knowledgeable about their areas of endeavor, in both a theoretical and “hands-on” basis, while comfortable working on the margins of established knowledge.

Many of these traits are characteristic of high performance of almost any sort, and several mark most creative endeavors. A few, such as alertness to practical problems and opportunities and a mix of scientific and hands-on knowledge, are fairly specific to invention.

It is important to emphasize the dispositional side of the inventive mind — the alertness to problems and opportunities, the curiosity, the enthusiasm, the commitment. While many accounts of inventors and inventive thinking foreground knowledge and abilities of various sorts that swing into operation as a problem is solved, it is especially notable that inventiveness is not just a matter of knowledge and ability. The *dispositional* side of invention is crucial, including high alertness to problems and opportunities in the first place, strong intrinsic and extrinsic motivation that fuels energetic and sustained engagement, and an enthusiasm for challenging entrenched ways of doing things.

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

4. ***The role of knowledge in invention.*** **Invention depends on a deep and diverse knowledge of theory and craft, but also on the selective abandonment of what is "known."**
Popular visions of the inventor often picture him or her as less educated, and indeed several notable inventors left formal education early. However, case studies reveal that effective inventors, whatever their formal education, are almost always profoundly knowledgeable about their areas of work in both theoretical and practical terms. They

draw on a wide range of knowledge from varied disciplines, according to the needs of their endeavors, often working on the margins of what is well-established. Studies of expertise and its development argue that this range and depth of knowledge in a specialty typically requires about 10 years of experience before an individual can function at a truly expert level.

Effective inventors are not trapped by what they know or think they know. They are boundary transgressors. They mobilize their knowledge flexibly, selectively and critically. They often abandon what is "known" in several senses — setting aside previously effective approaches that don't seem helpful in this case, bracketing knowledge as not helpful here, challenging prior knowledge as perhaps false or flawed, and so on.

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

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

5. *The relation between science and invention.* Today, invention and science advance in a complementary and synergistic relationship.
Science contributes to invention by providing theories and frameworks that sometimes suggest entirely new applications and sometimes technological solutions to particular problems. Inventors often extend science, pushing the limits of what's understood, finding anomalies in established theories, and disclosing new phenomena that call for scientific explanation. Moreover, the growth of science has depended greatly on the invention of instruments. The telescope, the radio telescope, the microscope and the electron microscope are simply a few of the most familiar.

Over the course of history, the relationship between invention and science has changed. Historically, invention is as old as human civilization and generally proceeded fruitfully in the absence of any substantive science, which dates back to Greek civilization and truly gathered momentum only in the 17th century. Today, the relationship between the two endeavors is deeply synergistic.

The combination of science with invention results in unique forms of knowledge. For instance, the Hungarian philosopher Michael Polanyi pointed to "operational principals"—not natural laws because they apply to artifacts, but nonetheless powerful generalizations based on scientific principles. An example is the idea that differential airflow above and below a wing-like surface creates a displacing force, an idea equally applicable to wings and propellers for example.

6. ***The process of invention in broad stroke: 11 basic principles.*** **In its overall organization, the process of invention is complex, extended, purposeful, knowledge-generating, boundary-transgressing, and notable for a number of other features.** Often seen in the popular eye as a matter of a sudden "Eureka!" or hands-on tinkering, invention typically is a long complex process blending systematic inquiry in science, practical experience in technology, and marked by insights at both the individual and group level. Here is a selection of 12 notable features.

1) Invention is an extended process. The story of any significant invention typically stretches over years (the telephone), decades (the steam engine), and sometimes centuries (the airplane). This extended, complex process contains a rich mix of agents (individuals, groups, teams) engaged in a variety of activities and processes that defy simple, formulaic description.

2) Invention is a highly purposeful activity, but purposes vary. Purposes take many forms at different levels in the process of invention. Broad visions—e.g., serving medicine or human communications—often drive the overall endeavors of inventors. Sometimes an invention is driven by a specific need. Sometimes it is a response to a perceived possibility. Sometimes the purpose is to improve upon an existing product, and sometimes it is to accomplish the same goal as an existing product, but in a radically new way. Many purposes arise in the maze of sub-problems that an overarching goal usually generates. Sometimes invention is driven by the goal of repurposing processes and devices that originally served some other end.

3) Both problem finding and problem solving figure centrally in the process of invention. While most inventions require systematic problem solving, broader inquiry reveals that "problem finding" in several senses plays a critical role. Successful inventors identify problems and opportunities, isolate important sub-problems, re-frame, re-define, and re-represent problems along the way to an invention. Indices of various kinds of problem finding may be better markers of exceptional inventiveness than indices of the skill of solving pre-defined problems.

4) Invention is a knowledge-generating process. Although some inventions are a matter of craft, involving practical inquiry that does not push the boundaries of science, it is more common that the inventor strives to understand the possibility space of the invention under development — what is the effect of changing such and such a variable? What's going on when such and such an effect happens? Inventors spend substantial time doing experiments, manipulating prototypes, and taking measurements to illuminate underlying mechanisms and inform choices between alternative approaches. Technological inquiry of this sort generates prescriptive knowledge—operational principles and guidelines for design—that is uniquely technological, but it can also extend basic scientific principles and lead to scientific discoveries.

5) Inventors use a rich variety of representations and move nimbly among them. Inventors often work drawing diagrams, but they also use physical models and mockups, computer simulations, tabulated measurements, mathematical equations and calculations, and so on. An inventive process typically generates multiple representations, and inventors move easily back and forth between them.

6) Inventors sustain a dialog between ideas and instantiations. The process of invention mixes ideas, in the sense of theories, concepts and images of what might work, and instantiations, in the sense of prototypes, experiments, trials, tinkering, and so forth. The dialog between these has a variable rhythm and can be entered at various points, depending on the inventors and the occasion. For example, sometimes the process may begin with a theoretically driven idea and move toward instantiations, sometimes with various forms of hands-on exploration that lead to a better theoretical understanding. Whatever the entry point, there are almost always multiple cycles in this dialog. Effective work with instantiations requires ready access to materials, processes, tools, and undedicated work space.

7) The process of invention depends on iterative cycles of evaluation. The complexity of getting something to serve a purpose in the real world guarantees the need for many trials, with early notions and rough approaches leading toward more refined ones. Even after a workable device has emerged, many cycles of improvement and evaluation are typically needed to reach a useable form. The iterative evaluation of ideas, prototypes, and trial runs is a critical part of the inventive process. The means of evaluation vary, depending on the circumstances and the stage in the process. The inventor's experienced judgment or a scientific calculation might recommend or dismiss a particular approach early on. At other moments, inventors have to conduct extensive measurements to evaluate how well something is working, developing the evaluation criteria—even going so far as to design and construct the instruments to perform the measurements.

8) Successful inventors learn from failure. Evaluation implies the possibility of failure. Failure is indeed a normal and unavoidable part of the search and exploration processes involved in invention. Inventors recognize this and treat failure as a learning opportunity. Failure of a particular idea or trial or prototype typically does not represent failure of the overall initiative but rather plays a productive role, signaling a problem to fix, a puzzle to solve, a path to abandon in favor of others, or a need to reframe or redefine the problem. Organizations and cultures that support invention recognize the role of failure in invention. Rather than punish failure, they systematically foster “smart failure” and the structures that facilitate it, such as quick small-scale prototyping cycles with limited risk. Learning from failure is an integral part of the knowledge-constructing aspect of invention, hence the mantra: “Fail early, often, and cheaply!”

9) Invention requires boundary transgressions: Inventors override past experience, abandon prior knowledge, draw upon and "cross-breed" diverse areas of knowledge.

In the course of inventing, inventors often leave established belief and convention behind and draw upon knowledge and resources from any available source, irrespective of disciplinary or other boundaries. Concepts, findings, and methods are carried from one context to another. Knowledgeable people are consulted irrespective of background or organizational affiliation. Problems originally formulated within one conceptual domain can be reformulated within another. The main criteria for consideration is not source, origin, or classification, but usefulness for the problem at hand. The need to achieve a productive balance between selective use and selective rejection of prior knowledge explains, in part, why invention is difficult for most people.

10) Chance plays a significant role in invention, but not in a haphazard way. The direction of an inventive process can be significantly altered by unexpected discoveries, random inputs, and fortunate accidents. However, this should not be viewed as a matter of " sheer luck." Often inventors deliberately seek out the stimulation of ideas from less familiar areas or perspectives from people with expertise complementary to their own. Sometimes inventors conduct deliberate systematic surveys of large numbers of options and even devise technologies to make this more efficient. Also, inventors tend to be on heightened awareness for accidental discoveries that contain key insights. In Pasteur's well-known phrase, chance favors the prepared mind.

11) The process of invention is self-generating but resource-limited. Because the stock of existing devices, processes, tools, operating principles, and design rules is the raw material for further invention, the process of invention is expanding in a combinatorial fashion. As more possibilities are explored, more possibilities are uncovered. At the present time, there is no way of forecasting an end to this process, if indeed it has an end. The productivity of the inventive process is, to the best of our current knowledge, only limited by the resources that society is willing to invest in inventive activities.

7. *The process of invention as heuristic.* At various levels of grain, invention involves use of a wide range of "heuristics," strategies for dealing with recurrent process dilemmas.

Studies of human problem solving have identified a range of problem solving heuristics — strategies that, while they do not guarantee solutions, typically enable progress. Such heuristics are apparent throughout the process of invention. Here are a number of heuristics important in invention.

1) Subgoaling. Partitioning a problem into nearly independent subproblems that can be attacked separately can significantly reduce the search space. For example, the Wright Brothers succeeded, in part, because they partitioned the problem of flight into the component problems of lift, control, and power.

2) Repurposing. Finding novel uses for existing artifacts is a standard problem solving heuristic of technologists. For example, the steam engine moved from mines to factories and again to vehicles as inventors engaged in successive repurposing processes. Radio technology was repurposed from a communication to a detection device (radar) during World War II.

3) Combining. Inventors combine existing artifacts, materials, concepts, principles, and processes into new configurations. For example, the Swiss Army Knife combines a variety of physical tools (edge, pick, screw driver, …) as elegantly as the contemporary cell phone combines multiple electronic functions (organizer, music player, camera, …).

4) Analogy. Inventors see analogies between different processes and devices. For example, Alexander Graham Bell took inspiration from what was known of the human ear in working out the design for the first telephone.

5) Identify variables. Inventors turn what seem like constants into variables. For example, James Hillier's realization that the focus of the electron field could be varied electro-magnetically with adjustable iron screws was a crucial step in the invention of the electron microscope.

6) Deliberate evaluation. Inventors consider explicit measures and indices of how well their inventions are working. Such evaluation functions are sometimes obvious (it is better to fly higher, faster, and longer), and sometimes not (what makes one software interface better or worse than another?). The specification of a new evaluation function can itself be a significant advance. For example, the focus on "force per G", i.e., how much force has to be exerted on the control stick to produce a turn that subjects the pilot to some multiple of normal gravity, was a significant step in the development of high performance aircraft.

7) Exhaustive search. When other heuristics fail to provide guidance, inventors resort to systematically working through large sets of possibilities. For example, the Edison laboratory tested approximately a thousand different materials for the filament of the electric light bulb.

This list should be taken as illustrative rather than exhaustive. Strategies of this sort are part of the cognitive toolkit of the inventor, and their teaching is one way of cultivating invention.

8. *Invention as collaborative.* Despite the popular image of the lone genius, to invent is for the most part a deeply collaborative enterprise.

Almost all significant invention involves various forms of collaboration. The lone genius in a laboratory occurs from time to time but is relatively rare, especially today when significant invention tends to require well-supported teams. The diversity of skills and knowledge called for by complex inventive endeavors recommends collaboration.

Besides the benefits of complementary knowledge and skills, collaboration can feed divergent thinking and offer critical perspective, provide generative tension, foster spotting problems and opportunities, and allow breaking problems down better through division of labor. In addition, an immersion into the thought of another can sharpen one’s own thinking.

Invention characteristically builds on complementary roles. *Management roles* include planning, allocation of resources, setting deadlines, negotiation within larger institutional structures, etc. Persons assuming *visionary roles* have the imagination and daring to choose problems beyond the obvious. They address complex questions and have the personal charisma to draw talented and energetic participants who assist them in actualizing their dreams. The *bridge role* is important when a collaboration is at the interface of two or more organizations with different institutional cultures. The person assuming such responsibility knows how to facilitate a language, which spans the differences between the diverse groups engaged in collaborative innovation.

Although too much conflict certainly can be counterproductive, collaboration often involve "productive tension"—patterns of discord, debate, and rivalry that are generative, helping to work out dilemmas, sparking new ideas, and inspiring greater effort. At a broader level, competition between groups paradoxically often produces some of the results of collaboration, as inventors in different settings learn actively from one another's work and try to leapfrog one another.

9. *Invention as a distinct form of creativity.* Invention shares important features with many other creative endeavors, but has distinctive features reflecting its characteristic challenges.
In many ways, the similarities between technological invention and other creative endeavors are more striking than the contrasts. There is a common trend toward high commitment, effort and persistence, something we find in virtually any enterprise involving high-performance, creative or not. There is the tendency toward independence and flexibility of thought. Relatedly, a variety of boundary transgressions are apparent in many creative endeavors, as are a range of familiar problem-solving heuristics, the importance of problem finding as well as problem-solving, and so on. It is certainly reasonable to think of technological invention as a member in good standing of the family of creative endeavors, sharing many family resemblances.

Material affordances shape the possibility space — we don't really need to understand the underlying theory of the object to get at its affordances, the uses that it invites and encourages. These tend to become apparent from manipulating it. The object in this case may be material, or a process or algorithm, of course. The resistance of the medium generates rich feedback and complements the affordances of the medium. (This would also be true of the arts, by the way.)

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

A scientist knows there is a solution. Nature must be doing something, and it's the job of the scientist to figure out what. An inventor doesn't know that there is a solution. It may be that there is no way to do the job or no way to do the job within reasonable parameters of cost, time, etc. Thus, the inventor lives with uncertainty in a way that the scientist does not. This may also be a contrast with artists. Artists can pretty much count on producing something viable as art, even if it's not exceptional. It doesn't have to "work" in the strong sense that an invention has to work.

10. *Cultivating invention.* While there is no expectation of creating Edisons by the thousands, the traits of the inventive mind and the processes of invention can be cultivated by education and fostered by appropriate organizational structures and cultures, to the benefit of the individual and society at large.
The findings of our workshop support the prospect of cultivating invention and inventiveness in children and adults, in individuals and organizations. It is apparent that technological invention involves a range of strategies and a style of engagement between the world of ideas and the world of objects that, to some extent, can be specified and fostered.

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

It is important to note that direct teaching may not be the best way to convey the craft and spirit of inventive thinking. Equally important might be modeling, mentoring, project-based learning, group participation in an atelier model and the like. That said, it is not difficult to list some of the elements that invite development. The several heuristics of invention outlined earlier – subgoaling, repurposing, combing, and so on—and others in similar spirit make up one aspect of craft. Likewise, the overall structure of inventive activity—long timeline, purposeful in a flexible way, problem finding as well as solving, and so on—constitutes part of the agenda. Debunking misconceptions and fostering sound beliefs about the character of invention go hand in hand with this. The dispositional side of inventiveness recommends attention to curiosity and exploration, confidence and the willingness to take risks, and opportunities for choice and discovery. Equally important here is what to avoid: punishing failure, discouraging challenge, and centering learning experiences on the rote and routine.

Much of this could be said for cultivating creativity of any sort. But the specifically inventive side of invention must not be ignored: the dialog between abstract thought and hands-on exploration, the role not only of scientific knowledge but operational principles, and the importance of different levels of inventive thought from the overarching system to the smallest components.

All this looks toward a comprehensive curriculum for invention. However, there is no need to think exclusively in such grand and sweeping terms. The reality is that in most settings most learners encounter hardly any opportunities to advance the knowledge, skills, and dispositions that constitute inventiveness. A little can go a long way. We look toward an era when almost everyone develops a richer understanding of fundamentals of invention, while many go much further with this deeply human process that helps to translate endless realms of possibility into a better world.

WORKSHOP DISCUSSIONS

Introduction

The products of inventors and human invention pervade our lives, from modern medical miracles to the digital revolution, from the alarm clock that wakes us up to the sedative that helps us sleep. Indeed, inventions offer us the oldest record we have of the creative mind at work. The stone axe, the prehistoric hearth, and ancient ceramics all demonstrate the ingenuity of our ancestors far before any written records recount their thoughts and even further before anything like formal science existed. Old as it is, invention also represents one of the newest frontiers in extending the reach of human endeavor. If we can understand deeply the thinking processes and the social context of invention, we may be able to leverage our ingenuity in systematic ways that will address the most fundamental problems of our times and accelerate the advance of civilization. Today, with effort and insight, we may be able to cultivate invention in more powerful forms.

To that end, the Lemelson-MIT Program, convened a workshop in August of 2003, which brought together a group of informed and insightful individuals representing the worlds of cognitive science, the history of technology, and the practice of invention itself. The aim of the workshop was to define what is known and outline what needs to be known concerning the fundamental nature of the inventive mind and the fundamental processes of invention. The title "architecture of invention" refers to this framework of understanding.

Despite the transparent importance of invention and the prospects of amplifying human creativity further, invention and inventors remain misunderstood, colored in the popular eye by a range of myths. These myths need to be exposed, for they may be harmful to the motivation of aspiring inventors. One well-known myth is the inventor as a wizard with superhuman talents -- that because his insights come magically or naturally, he needs little or no training or education. Epitomized by the mythical Dr. Victor Frankenstein or Doc Brown in the movie *Back to the Future* or as creators of destructive robots in *The Terminator* series, such portrayals have inventors working outside mainstream social and academic contexts, and they depict inventors as irrationally passionate, emotionally unstable, or downright mad.

Yet case studies show that actual inventors, from Thomas Edison to our own workshop participant, Dr. William P. Murphy Jr., do not fit this myth. “There is nothing mystical, irrational, or uncanny about them or their inventive process,” observes Lillian Hoddeson, professor of history and physics at the University of Illinois at Urbana-Champaign. “Whether in formal education, or through rigorous self-study, inventors typically spend at least a decade building up their knowledge base. Among the many other examples of misleading invention myths are those that center around unfounded fears, such as that humans who venture too close to secret knowledge will be punished, or that inventions will inevitably destroy jobs or alienate and dehumanize workers. While some inventions do cause unfavorable social effects, at least for a time, many more do just the opposite.” Indeed, inventions have proven to make life longer, more comfortable, more informed, more engaging, for the most part safer from disease and violence, and more productive in innumerable ways.

For an area so fundamental to human civilization, technological invention is substantially under-investigated in the scholarly literature. Much remains to be done. That said, research in cognitive psychology, historical and contemporary case studies of inventors, investigations of industrial laboratories, and numerous other sources speak to the nature of invention and inventors. This base of research illuminates creative personality characteristics, the role of knowledge and skills, the cognitive processes involved, and the roles of collaboration and context. It also suggests approaches to fostering inventiveness in children, college students, and adults, both at the individual and organizational levels, and it points the way toward further fundamental inquiry. Building on that previous work, this report is an effort to focus our understanding of how to cultivate inventiveness and produce inventions that will benefit society on many levels.

The Products of Invention

Scientific inquiry and technological invention are profoundly synergistic, and they often mix in highly generative ways. But these two realms can be distinguished from one another by the types of products they produce. Technological invention contrasts with scientific inquiry in its focus on developing things that fulfill practical functions, while showing striking range in the nature of its products and the scope of their impact. Science, meanwhile, typically produces theories and findings that opt for a clean model of underlying fundamental processes, while factoring out "complications" like friction or impurity in materials that functional products must deal with.

Emphasizing this point is Thomas Ward, the director of creativity sciences at the University of Alabama's Center for Creative Media. He brought to the workshop several examples of practical inventions that he purchased at his local OfficeMax. Among them were a "light pen," a thumb-sized "jump drive" for holding several megabytes of data, and a nine-in-one, all-purpose tool. He cited these new products as examples of how inventors pay close attention to practical problems and how inventors often combine existing ideas to come up with something new. More broadly speaking, however, these gadgets are just one of many products of invention. "There are different types of invention, and there are different processes that play a role, and there are different stages of the inventive process," says Ward. "So, there are enormous variations in the complexity of inventions."

Invention takes many forms, including physical devices, software algorithms, business processes, medical treatments, and biological methods. When we ponder inventions, we perhaps most often think of the physical devices, such as Ward's tools, light bulbs or bicycles, that do very particular jobs. However, the world of invention is enormously wide and deep. "Although many characteristics of the invention process are quite similar for different inventions, it is important nonetheless to realize that not all inventions are exactly the same," says Christopher Magee, a 35-year veteran of the Ford Motor Company and currently the director of MIT's Center for Innovation in Product Development.

According to Magee, the most important characteristics that differ among inventions include: 1) the social impact of the invention; 2) the knowledge extension implicit with the invention; and 3) the system level of the invention. All of these variables, he says, "can cause important differentiation among elements of the processes and even can lead to differing degrees of importance of particular traits in inventors involved in differentiated types of invention." Magee offers up some definitions and clarifications for these three ways of assessing the importance of an invention:

1.) Social Impact: Some inventions, such as Ward's tools, lead to little social impact, whereas others, such as the mass-produced automobile, "lead to cascading and profound change in human existence." Magee also notes that "the effects of invention are notoriously difficult to assess at the time of invention and even well afterwards."
2.) Knowledge extension: Some inventions, such as those in the field of nanotechnology, may require extensive research associated with the problem at hand (discovery of relevant new "what" knowledge) in order to proceed, while others, such as a new design for a baby stroller or laptop computer, may require only a moderate amount of 'how' knowledge. "It is important to not undervalue 'how' knowledge," he adds, but in every invention there are typically many major and minor knowledge extensions. Sometimes, "the simple combination of well-known functions or simple extensions of current tools or processes can eventually fail the test of 'Is it an invention?' But it is reasonable to try and measure this characteristic when comparing different inventions side by side.
3.) System Level: "Some inventions occur at the component or element level, others occur at the product or process architecture level, and some at an overarching system level," notes Magee. "Many important inventions at the component level eventually lead to entirely new systems sometimes without additional invention at the system level. Instead, they grow, as in an evolutionary process, with many contributions building to large-scale "human-designed" systems. Nonetheless, clear inventions (the World Wide Web, the telecommunication system developed by Bell Labs, and others) are made at the system level and are necessary to have major social impact."

Magee offers up this model for not only understanding but also for evaluating the differing products of the invention process. By attempting to rate each invention according to the above three dimensions, one can construct a grid showing how the products of invention differ from one another. The model is based on rating each invention either "high," "medium," or "low" in relation to one another on these three dimensions, as discussed above. Ford's assembly line, for instance, would likely relate high on "social impact," medium on "knowledge extension," and high on "systems level." Magee suggests that this model could form the basis of further study.

In evaluating the impact of various inventions, however, we also need to pay attention to a special question that some of our participants posed. What about the negative consequences of certain inventions? Clearly, some inventions do have negative ramifications. The atomic bomb is a straightforward example. But often, such consequences aren't anticipated and could hardly even be imagined by the inventors themselves. Everything from cars to computers to video games to television falls into this category. Indeed, almost all inventions pose tradeoffs and require bargains to be struck within the society that makes use of them. Yet our participants agree, in general, that the products of invention overwhelmingly tend to increase the human desire for order, control and comfort. Only the most ardent romantics would care to swap their lives today for ones of 500 years ago, and much of the difference between now and then stems directly and indirectly from technological invention.

Historically, many inventions did not have identifiable inventors, but in today's world we can focus on inventors as having a distinct social role, and we can explore the process and context. In addition, inventions cannot always be thought of as invented at a particular time by a particular individual or group. Many inventions persist and spread and undergo refinement and diversification in a society over long periods of time, with innumerable small contributions from unknown individuals. However, in this analysis, we focus on the more familiar case—especially in today's world—where one can indeed identify not only the individuals who do the inventing, but also the mental processes involved, and the contexts that motivate and support their endeavors. With that in mind, we will turn to contextual questions.

The Contexts for Invention

Invention always occurs in one or more contexts—social, economic, institutional, cultural—and must be understood in terms of those contexts. Inventors function within these contexts—indeed, they are shaped by them—and they must "negotiate" with these contexts in various ways to advance their work.

Because invention is so contextual, inventors can be thought of as intellectual bridges, says Bernard W. Carlson, associate professor of technology, culture, and communication at the University of Virginia. They are, in a real sense, “translators between the natural and social worlds.” They take phenomena out there in nature and convert them into something that fulfills practical functions. They have to be creative on both sides—wrestling with nature and wrestling with society.

In Carlson’s model, inventors are negotiating between two broad contexts—nature, on one hand, and society on the other. “One useful description of invention is that it is a device, process, or service that serves a human wish, need, or want. But to create the device or process, an inventor must often investigate phenomena in nature. In some cases, an inventor needs only to observe nature closely to discover what will work, but in other cases, he or she must tease out new insights by experiment or ingenious manipulation. Because nature does not yield up her secrets readily to the inventor, one could say that the inventor must ‘negotiate’ with nature.”

At the same time, Carlson continues, “invention is not simply discovering how to make something work in nature; an invention addresses a human need, wish, or want. Hence, an inventor must also connect his or her invention with society. In some cases, needs are well known and society readily takes up a new invention. In many other cases, though, there is no well-defined need and an inventor must convince society of the value of the invention. This is what we mean when we say that an inventor must ‘negotiate’ with society.”

Confirming this view is Bill Murphy, the inventor of medical instruments ranging from the plastic, flexible blood bag to an improved kidney dialysis machine to disposable medical trays to the physiologic cardiac pacemaker. “I have spent my entire career, my entire lifetime,” says Murphy, “looking at what's around me and asking: why this isn't working? What we are supposed to be doing? What could I do about it, if anything?” In addition to negotiating with nature and technology, Murphy has also negotiated with society and the world of for-profit medicine, starting at least three corporations to bring his inventions to as wide a market as possible. “If you are going to work on a creative idea, it must ultimately get to the people who need it. Why do it if it isn't applied to a problem?”

Inventors, then, must have a foot in both the natural and social worlds. "On the one hand," says Carlson, "inventors must be willing to engage nature, to find out what will work; on the other hand, inventors must also interact with society, negotiating a trade between their inventions and various rewards (money, fame, resources). To be successful, inventors often have to be creative on both sides—in how they wrestle with both nature and society." In doing this, "their efforts are shaped by the tools and instruments available and the help they get from patrons and assistants. In connecting their creations with society, inventors must often take into account the dynamics of the marketplace, the structure of business organizations, and the ways in which government promotes and regulates new technology. Most broadly, inventors must grapple with the overall perception of technological change in a culture: is invention welcomed and celebrated, or is it viewed by some groups with suspicion?"

Once again, Bill Murphy confirms this view, noting that the United States has provided a broad cultural context based on creative and economic freedom that promotes inventiveness. "The fact that we have the opportunity of doing things that in many other societies are limited or prohibited or impossible is a big part of the reason for our success," he says. The centerpiece of that context is our free market system that encourages entrepreneurship and enterprise. "While it's not part of invention," he adds, "it's part of the context. It's important for us to recognize that the way we set up our government fostered this creativity to a large extent. We're a nation of technologists, really. We build things, and a lot of them, with new ideas. This is why we as a nation have been so dramatically successful."

That this social and political context is so fundamental helps explain why invention has thrived in some societies while withering in others. "While it is easy to assume that all human societies value technological change, this is not always the case," Carlson concludes. "Over the last 250 years, Western industrial societies have equated technological change with progress, assuming that the production of material abundance should contribute to social order and cultural meaning, with the result that inventors are regarded as cultural heroes. However, other societies do not necessarily make this connection between technology and what constitutes the good society and instead may place a higher value on stability and continuity. In these societies, technological change is not necessarily welcome and invention is not encouraged or rewarded."

"Hence, it is important to realize that invention is a historical phenomenon, taking place in some societies in which technological change is perceived as conferring some advantage. For instance, as city states in Renaissance Italy found themselves in competition and unable to gain a distinct advantage over each other, some states turned to technology to gain an advantage. While some city states sought to improve their military technology, others sought to gain the advantage in terms of trade or manufacture. To provide this new technology, artists such as Leonardo da Vinci applied their creative powers and cast themselves as both artists and inventors. Likewise, in the decades after the Revolution, Americans looked to technology as a means of securing economic freedom from Britain, and inventors who developed new transportation (Robert Fulton), communications (Samuel Morse), or new manufacturing techniques (Eli Whitney) were regarded as heroes."

Inventors sometimes respond to social needs by tackling already recognized problems. But at other times, they "invent" problems, discerning an opportunity that was not previously recognized as such. One of the most popular sayings about invention is that "Necessity is the mother of invention." For economists, according to Carlson, this saying embodies the idea that inventions are "demand-pull," meaning that inventors respond to demands already being voiced in the marketplace. "While we often imagine that most inventions are demand-driven, that people are clearly articulating needs and wishes, this is not always the case," argues Carlson. "Indeed, many important inventions are 'supply-push,' meaning that they arise out of what inventors already know how to do—from the existing supply of technology. With 'supply-push' inventions, the creative task often involves articulating a need that the invention fulfills and then convincing people that they have this need.

In the 20th century, television is a classic example of both 'supply-push' happening first and then demand-pull following later. By ingeniously combining several ideas in science and electronics, Philo T. Farnsworth developed electronic television in the late 1920s and early 1930s. In this sense, Farnsworth negotiated with nature. But the associated challenge was to negotiate with society, to perform the supply-push, to create the infrastructure and market for television, and that is what David Sarnoff at RCA orchestrated in the late 1930s and beyond. In many cases, inventors look for opportunities within large-scale systems, such as railroads, the telephone system, the electrical grid, television, and computer networks. In doing so, they search for "salients" (parts of the system that have leaped ahead of everything else), or "reverse salients," (parts of the system that lag behind.) This model of invention is explored in the Lemelson-MIT Program's earlier report on "historical perspectives."

Sometimes an inventor is motivated by a large vision, but there is a great deal of small-scale invention as well. "In responding to their contexts and formulating problems, inventors can be drawn to large as well as small challenges," adds Carlson. "Some inventors are willing to take on huge tasks such as re-conceiving how energy is produced and distributed in a society (such as Thomas Edison, George Westinghouse, Nikola Tesla) while others choose to focus on small, well-defined problems (such as the inventor of the Post-It Note). In general, one of the most important skills that an inventor needs to have is being able to match the size of the problem with the resources and markets available. For example, both Marconi and Tesla attempted to develop in the 1890s radio-based communications systems; while Tesla dreamed of a system that would broadcast power and messages around the world, Marconi concentrated on developing his system for a specific niche market, ship-to-shore communications. Whether working on visionary or small-scale inventions though, inventors often have distinct ideas about what constitutes the 'good society' and how technology will contribute to improving that society."

The Inventive Personality

Although there is no formula for the inventive mind, a number of abilities and dispositions are associated with inventive productivity.

Effective inventors tend to display personality characteristics including resourcefulness, resilience, nonconformity, and a range of others, including passion for their work, unquenchable optimism, high persistence, a sense of play, high tolerance for complexity and ambiguity, willingness to delay gratification, a critical stance toward their own work, embracing failure as a learning experience, not the enemy, and a commitment to making things better through practical action.

Bill Murphy goes even further, speaking of his own “compulsion to be creative.” He emphasizes that this motivation is such a part of him that it is involuntary, almost beyond his control. “It’s not because I wanted to be creative, but because I see things around me that aren't accomplishing what they are intended to accomplish. And I have a compulsion to try to do something about that.” He says that his family background probably encouraged or helped form this compulsion. “I was raised in a medical family,” he says. His mother was a dentist and his father, William Parry Murphy, was a dedicated internist who shared the Nobel Prize in medicine in 1934 for the discovery of liver therapy in cases of anaemia “They were both doers,” he says. “They both believed that you could make things happen if you thought about it, and made the effort. And, as a result, I grew up believing that I could do things, and I could accomplish things.” Murphy says that other prolific inventors he knows share this same compulsion.

Linda Stone, during her years in creative and executive positions at Apple Computer Corp. as well as Microsoft Corp., worked closely with many accomplished inventors and product developers, including Andy Hertzfeld, a principal author of the original Macintosh operating system, as well as Paul McCready, the Caltech aeronautics inventor. Among the common traits Stone has observed is their ability to delay gratification, which she feels is a characteristic that is discouraged in our instant gratification society. “Culturally, we are behaving in a way that weeds out, or that selects out, an ability to really develop a sense of delayed gratification,” Stone says. “When I look at Dean Kamen, his iBot wheelchair took ten years. All of these things have taken at least ten years. The Internet was 30 years in the making before it found that place where technology met human needs and desires. So I'm both concerned and disturbed about the degree to which the ability to handle delayed gratification is not rewarded, and we are so aggressively looking for immediate gratification and we have such a compromised sense of time horizons today.”

Effective inventors also show a range of other abilities, including mental flexibility, deep knowledge of their area of endeavor, as well as hands-on skills that are rather specific to invention. Foremost among those aspects of skill and knowledge include alertness to practical problems and opportunities, the ability to match one's talents with the problem, using a toolkit of effective ways to conceptualize and break down the problems, and self-knowledge that is helpful in managing one's own endeavors. Many of these traits are characteristic of high performance individuals of almost any sort, and several mark most creative endeavors. But a few, especially the alertness to practical problems and opportunities and the mix of scientific and hands-on knowledge, are fairly specific to invention.

To advance their endeavors, inventors commonly needed a range of other skills concerned with relating to the constituencies around them. Often, inventors must play other roles that go beyond the purview of invention. To successfully bring their inventions to a base of users, inventors require the mindset and skills to promote, persuade, market, and marshal financial resources behind their invention. In some settings, these roles may be largely played by others, but, in others, inventors take much of the responsibility themselves, for instance, often needing to function as "intrapreneurs" to advance their missions within an organization.

It is important to emphasize the *dispositional* side of the inventive mind—the alertness to problems and opportunities, the curiosity, the enthusiasm, the commitment. While many accounts of inventors and inventive thinking highlight abilities of various sorts that swing into operation as a problem is solved, it is especially notable that inventiveness is not just a matter of knowledge and ability. The dispositional side also encompasses strong intrinsic and extrinsic motivation that fuels energetic and sustained engagement, or the "compulsion to create," as Bill Murphy puts it.

The Role of Knowledge

Invention depends on a deep and diverse knowledge of theory and craft, but also on the selective abandonment of what is "known."

Characteristically, inventors are deeply knowledgeable about their areas of endeavor, while comfortable working on the margins of established knowledge. Popular visions of the inventor often picture him or her as less educated. Indeed, several notable inventors, most notably Thomas Edison, left formal education early. Dean Kamen was consistently impatient with formal instruction methods and rebellious of the structure of schoolwork during high school and college, preferring to engage in learning through his own self-directed invention projects.

Whatever their formal education is like, however, inventors are almost always profoundly knowledgeable about their areas of work in both theoretical and practical terms, in almost all case studies. They draw on a wide range of knowledge from varied disciplines, according to the needs of their endeavors, and they often attempt to push beyond what is currently well-established. Studies of expertise and its development argue that this range and depth of knowledge in a specialty typically requires about ten years of experience before an individual can function at a truly expert level.

Bill Murphy, who completed advanced education in both medicine and engineering, emphasizes that receiving education and obtaining degrees is not enough. Inventors tend to actively seek knowledge that falls outside of schoolwork. “I have a thirst for knowing how things work and what goes on,” Murphy says. “I have characterized life as an opportunity to learn. It seems to me that anybody who doesn't learn something new every day is wasting their life. A broad base of knowledge gives one the opportunity to solve problems that one envisions, and the built-in compulsion to do that seems to me to be a very strong aspect of creativity.”

Effective inventors are not trapped by what they know or think they know. They mobilize their knowledge flexibly, selectively, and critically. They often abandon what is “known” in several senses -- setting aside previously effective approaches that don't seem helpful in this case, bracketing knowledge as not helpful here, challenging prior knowledge as perhaps false or flawed. Alexander Graham Bell, for instance, abandoned prior, flawed models of creating a telephone based on extensions of the telegraph, instead constructing a new model that was analogous to the human ear.

Historically, the relationship between science and invention has changed. “The two activities have emerged in different times out of different traditions and have only in the last three centuries grown together to form a symbiotic relationship,” says Lillian Hoddeson. “Invention may well be as old as humankind with many inventive individuals found in social classes where workers—craftsmen, tradesmen, builders, sculptors, artists—typically use their hands in real-world activities. In contrast, the beginnings of what we call science dates back only to ancient Greek times, with modern science starting only in the 17^{th} century. After that, slowly but surely, through the seventeenth, eighteenth, and nineteenth centuries, a number of inventions, such as the steam engine, the microscope, and the telescope, began to wield a transforming influence on science."

"By the early years of the twentieth century, such inventions as the vacuum tube began to transform many areas of scientific study, while at the same time inventors realized their need to call on scientific knowledge to help them advance in fields such as telecommunications, radio, medicine and medical equipment. At the same time, inventors increasingly felt the need to study and draw on the evolving sciences, scientists more frequently drew on new inventions, such as computers. Thus, the relationship between invention and science gradually developed into their present symbiosis, in the process blurring the earlier sharp distinction." [For a more detailed discussion on the history of the symbiosis between "what" knowledge ("discovery-type") and "how" knowledge ("invention-type"), please refer once again to the earlier Lemelson-MIT report.]

This distinction between these two broad types of knowledge still survives. While invention involves strong roles for both theoretical and hands-on knowledge, it is not just a process of applied science, a straightforward translation of scientific principles into products. "Their main difference lies in their purpose," says Hoddeson. Science is aimed at knowledge of nature, and scientists generally aim to publish papers in respected journals. Invention is aimed at social usefulness, and the inventor generally aims to obtain patents.

Inventors characteristically depend on a mix of deep theoretical understanding and hands-on experiential knowledge of how things work in the physical and social worlds. Inventors often gain new insights by investigating objects. "They hop from objects to the ideas, and then back down again," says Carlson. "The classic example is the Wright Brothers." Looking at it from another angle, inventors are also the people "who think long and hard about an idea and then try to manifest it in objects. There's a backing and forthing in each case." In some examples, inventive duos and teams separate the two functions among different individuals. As Lillian Hoddeson emphasizes from her study of the invention of the transistor at Bell Labs in the late 1940s, physicist John Bardeen served as the "head" of the team. Meanwhile, Walter Brattain served as "the hands" of the team. He was the experimentalist. "Brattain was operating on the experimental side, evaluating techniques," she says. "Bardeen was thinking about what was going on and why."

The combination of science with invention results in a unique form of knowledge that the Hungarian philosopher Michael Polanyi called "operational principals." "Such principles are not natural laws," says Stellan Ohlsson, professor of psychology at the University of Illinois at Chicago, "because they are too closely connected with what's normative and goal directed, and often apply only to artifactual systems with no straightforward natural instances." As examples of operational principles, Ohlsson cites the knowledge that "differential air flow above and below a wing creates lift." Since airplane wings are man-made, this cannot be a natural law. "Flying on the basis of this operational principle is very different from flying by Archimedes principle (hot air balloon) or by friction (parachute). One can spin each of these operational principles into a device in a variety of ways (prop planes and jet planes fly in the same way from this perspective)."

As all our cases make clear, science and invention play synergistic roles. Science contributes to invention by providing theories and frameworks that sometimes suggest entirely new applications and sometimes technological solutions to particular problems. Inventors often extend science, pushing the limits of what's understood, finding anomalies in established theories, and disclosing new phenomena that call for scientific explanation. Moreover, the growth of science has depended greatly on the invention of instruments.

Robert J. Weber, professor of psychology emeritus, takes it even further. He argues that invention is not just practical in the sense of having direct impact on everyday life. Devices like the telescope, electron microscope, the linear accelerator, the computer, and gene sequencer are in fact "discovery machines" that really do fuel science. Continuing with the machine metaphor, invention also creates "communication" machines: writing, printing with movable type, the telephone, the Internet. All of this makes invention close to a full partner with science in understanding the world we live in and in letting others know about that understanding.

It follows from the above that the development of invention depends on appropriate knowledge resources and access to them. In addition, access to discovery machines and communications machines are crucial for the cultivation of invention. This open access to knowledge can take many forms: technical manuals, journals, reports, patent descriptions, libraries that compile such materials, the Internet, the availability of samples and prototypes, the wisdom of peers and more experienced practitioners accessed through conversation and collaboration, appropriate cross-fertilization between different groups. The ready and appropriate flow of knowledge has, over time, become more and more crucial to the endeavor of invention.

The Processes of Invention: Twelve Basic Principles

Often seen in the popular eye as a matter of a sudden "Eureka!" or hands-on tinkering, invention typically is a long complex process blending systematic inquiry in science, practical experience in technology, and marked by insights at both the individual and group level. In order to understand how the inventive process works across many different case studies and domains, three of our participants, Thomas Ward, Stellan Ohlsson, and Bob Weber, synthesized the workshop's findings on the process of invention into twelve basic principles.

1) Invention is an extended process. The story of any significant invention typically stretches over years (the telephone), decades (the steam engine), and sometimes centuries (the airplane). This extended, complex process contains a rich mix of agents (individuals, groups, teams) engaged in a variety of activities and processes that defy simple, formulaic description.

2) Invention is a highly purposeful activity, but purposes vary. Purposes take many forms at different levels in the process of invention. Broad visions—e.g., serving medicine or human communications—often drive the overall endeavors of inventors. Sometimes an invention is driven by a specific need. Sometimes it is a response to a perceived possibility. Sometimes the purpose is to improve upon an existing product, and sometimes it is to accomplish the same goal as an existing product, but in a radically new way. Many purposes arise in the maze of sub-problems that an overarching goal usually generates. Sometimes invention is driven by the goal of repurposing processes and devices that originally served some other end. The fact that invention can arise from multiple purposes means that multiple cognitive processes are relevant, because the optimal process to use depends heavily on what the inventor is trying to accomplish.

3) Both problem finding and problem solving figure centrally in the process of invention. While most inventions require systematic problem solving, broader inquiry reveals that "problem finding" in several senses plays a critical role. Successful inventors identify problems and opportunities, isolate important sub-problems, re-frame, re-define, and re-represent problems along the way to an invention. Indices of various kinds of problem finding may be better markers of exceptional inventiveness than indices of the skill of solving pre-defined problems.

4) Invention is a knowledge-generating process. Although some inventions are a matter of craft, involving practical inquiry that does not push the boundaries of science, it is more common that the inventor strives to understand the possibility space of the invention under development — what is the effect of changing such and such a variable? What's going on when such and such an effect happens? Inventors spend substantial time doing experiments, manipulating prototypes, and taking measurements to illuminate underlying mechanisms and inform choices between alternative approaches. Technological inquiry of this sort generates prescriptive knowledge—operational principles and guidelines for design—that is uniquely technological, but it can also extend basic scientific principles and lead to scientific discoveries.

5) Inventors use a rich variety of representations and move nimbly among them. Inventors often work drawing diagrams, but they also use physical models and mockups, computer simulations, tabulated measurements, mathematical equations and calculations, and so on. An inventive process typically generates multiple representations, and inventors move easily back and forth between them. Mentally, inventors also seem able to move easily between multiple representations, e.g., between visualizing a device and describing it to someone else. There is ample testimony to the importance of visualization and visual representations from inventors as well as scientists and others involved in creative endeavors. We still lack a strong theory to explain the advantages of visual representations for inventiveness.

6) Inventors sustain a dialog between ideas and instantiations. The process of invention mixes ideas, in the sense of theories, concepts and images of what might work, and instantiations, in the sense of prototypes, experiments, trials, tinkering, and so forth. The dialog between these has a variable rhythm and can be entered at various points, depending on the inventors and the occasion. For example, sometimes the process may begin with a theoretically driven idea and move toward instantiations, sometimes with various forms of hands-on exploration that lead to a better theoretical understanding. Whatever the entry point, there are almost always multiple cycles in this dialog. Effective work with instantiations requires ready access to materials, processes, tools, and dedicated work space.

7) The process of invention depends on iterative cycles of evaluation. The complexity of getting something to serve a purpose in the real world guarantees the need for many trials, with early notions and rough approaches leading toward more refined ones. Even after a workable device has emerged, many cycles of improvement and evaluation are typically needed to reach a useable form. The iterative evaluation of ideas, prototypes, and trial runs is a critical part of the inventive process. The means of evaluation vary, depending on the circumstances and the stage in the process. The inventor's experienced judgment or a scientific calculation might recommend or dismiss a particular approach early on. At other moments, inventors have to conduct extensive measurements to evaluate how well something is working, developing the evaluation criteria—even going so far as to design and construct the instruments to perform the measurements.

8) Successful inventors learn from failure. Evaluation implies the possibility of failure. Failure is indeed a normal and unavoidable part of the search and exploration processes involved in invention. Failure of a particular idea or trial or prototype typically does not represent failure of the overall initiative. Rather, it plays a productive role, signaling a problem to fix, a puzzle to solve, a path to abandon in favor of others, or a need to reframe or redefine the problem. Inventors expect many moments of failure, recognize them as a natural part of the process, and deal with them skillfully as learning opportunities rather than causes of despair. Organizations and cultures that support invention recognize this. Rather than punish failure, they systematically foster "smart failure" and the structures that facilitate it, such as quick small-scale prototyping cycles with limited risk. The key step in smart failure is to seek an explanation or understanding of the reasons for the failed outcome. Learning from failure is an integral part of the knowledge-constructing aspect of invention. The mantra: “Fail early, often, and cheaply!”

9) Inventors override past experience and abandon prior knowledge. Repeated failure is often an indication that a problem has been posed in an unproductive way, that a situation has been understood or represented in a way that does not provide a good fit to the reality of the case, the inventor's prior knowledge, or the goals that are driving the process. In such situations, the way out of the resulting impasse can require fundamental revisions in how a problem is represented and understood. Any cognitive process proceeds from some (possibly implicit and intuitive) assumptions, and one form of re-representation is to relax or abandon one or more of those assumptions, thus creating a less constrained search space. In designing the space shuttle, the initial assumption that the outer layer of the shuttle should not catch fire during re-entry had to be abandoned before the ceramic tile solution currently in operation could be found. German inventor Philipp Reis failed to invent a workable telephone because he assumed that it should work with a sequence of discrete signals, telegraph-like, while Bell succeeded with a device based on continuously undulating current. Sometimes, overriding the prior knowledge that is interfering with a solution can be accomplished by representing the problem at a higher level of abstraction thereby overcoming constraints imposed by the particular properties of previous specific devices (e.g., devising a new braking system for a land vehicle by considering multiple ways of transforming kinetic energy rather than being limited by the properties of prior disc brake systems). The need to achieve a productive balance between selective use and selective rejection of prior knowledge explains, in part, why invention is difficult for most people.

10) Invention requires boundary transgressions. In the course of inventing, inventors draw upon knowledge and resources from any available source, irrespective of disciplinary or other boundaries. Concepts, findings, and methods are carried from one context to another. Knowledgeable people are consulted irrespective of background or organizational affiliation. Problems originally formulated within one conceptual domain can be reformulated within another. The main criteria for consideration is not source, origin, or classification, but usefulness for the problem at hand.

11) Chance plays a significant role in invention, but not in a haphazard way. The direction of an inventive process can be significantly altered by unexpected discoveries, random inputs, and fortunate accidents. For example, John J. Wild in experimenting with sound imaging of living tissue discovered by accident that different types of tissues, and, crucially, different kinds of cancer tumors, gave distinct echoes, initiating a search for an originally unanticipated diagnostic device. Or when Bill Murphy dropped a blood bag and watched it splatter all over someone in a white suit, he got an idea for an improvement from the mishap. Over time, searching possibility spaces for random inputs can spawn new possibility spaces. Yes, inventors often come across new knowledge by sheer chance. But we say that chance is not haphazard because inventors tend to be on heightened awareness for accidental discoveries that contain key insights.

12) The process of invention is self-generating but resource-limited. Because the stock of existing devices, processes, tools, operating principles, and design rules is the raw material for further invention, the process of invention is expanding in a combinatorial fashion. As more possibilities are explored, more possibilities are uncovered. At the present time, there is no way of forecasting an end to this process, if indeed it has an end. The productivity of the inventive process is, to the best of our current knowledge, only limited by the resources that society is willing to invest in inventive activities.

The Processes of Invention: Cognitive Strategies of Inventors

Much of what we have learned about the cognitive processes used by inventors comes from anecdotal accounts and historical sources. Meanwhile, much of what we have learned about creativity comes from studies of artists, scientists and other non-inventors. The former yields a rich picture of inventive minds at work but does not allow conclusions about how much better or worse the outcome might have been if the inventor had adopted a different thought process. The latter allows conclusions about causality, but risks artificiality and lack of applicability to real-world situations confronted by inventors. Progress in understanding and fostering invention will occur more rapidly through convergent approaches.

To that end, our participants articulated a set of "heuristics," in the form of cognitive strategies that are employed by inventors. Studies of human problem solving have identified a range of problem solving heuristics—strategies that, while they do not guarantee solutions, typically enable progress. Such heuristics are apparent throughout the process of invention. Some of the most important cognitive strategies include the following, as outlined by Ward, Ohlsson, and Weber.

(a) Subgoaling. Partitioning, or decomposing, a problem into nearly independent sub-problems that can be attacked separately can significantly reduce the search space. For example, the Wright Brothers succeeded, in part, because they partitioned the problem of flight into the component problems of lift, control, and power.

(b) Repurposing. Finding novel uses for existing artifacts is a standard problem solving heuristic of technologists. For example, the steam engine moved from mines to factories and again to vehicles as inventors engaged in successive repurposing processes. Radio technology was repurposed from a communication to a detection device (radar) during World War II.

(c) Combining. Inventors combine existing artifacts, materials, concepts, principles, and processes into new configurations. For example, the Swiss Army Knife combines a variety of physical tools (scissor, pick, screw driver, …) as elegantly as the contemporary cell phone combines multiple electronic functions (organizer, music player, camera).

(d) Analogy. Inventors see analogies between different processes and devices. For example, Alexander Graham Bell took inspiration from what was known of the human ear in working out the design for the first telephone. The practice of drawing analogies that borrow and reapply principles from nature now has a term of its own: "biomimicry."

(e) Identifying variables. Inventors turn what seem like constants into variables. For example, James Hillier's realization that the focus of the electron field could be varied electro-magnetically with adjustable iron screws was a crucial step in the invention of the electron microscope.

(f) Deliberate evaluation. Inventors consider explicit measures and indices of how well their prototypes and models are working. Such evaluation functions are sometimes obvious (it is better to fly higher, faster, and longer), and sometimes not (what makes one software interface better or worse than another?). The specification of a new evaluation function can itself be a significant advance. For example, the focus on "force per G" (i.e., how much force has to be exerted on the control stick to produce a turn that subjects the pilot to some multiple of normal gravity), was a significant step in the development of high performance aircraft.

(g) Exhaustive search. When other heuristics fail to provide guidance, inventors resort to systematically working through large sets of possibilities. For example, the Edison laboratory tested approximately a thousand different materials for the filament of the electric light bulb. The cognitive process of exhaustively searching for ways to solve both reasonable and unreasonable problems has its own set of rules, sometimes going under the name of “Klondike logic,” after the problem of searching for clues in a clueless domain, such as an arctic wilderness.

This list should be taken as illustrative rather than exhaustive. Any one invention will involve some combination or subset of these processes and activities, but the particular mix emerges in the course of the activity and is contingent on the problem, the inventor, and the context in which he or she works. Yet other aspects of the relevant cognitive processes and activities are likely to become revealed as in further research that needs to be conducted--both from the point of view of understanding what inventors ordinarily do and from the point of view of gaining evidence about where, when and how certain processes ought to be used to enhance innovation. Strategies of this sort are part of the cognitive toolkit of the inventor, and their teaching is one way of cultivating inventiveness, the topic of the final section of this report.

Invention as Collaborative

But before we turn to the crucial topic of cultivating inventiveness, we need to explore one overarching point that goes to the heart of how invention happens. Debates about the origins of inventions often center around whether the individual was the centerpiece of the process, or whether the invention was the result of a group effort. This is false debate, as invention requires both.

Invention needs to be described on both levels of analysis at the same time. “One of these levels is indeed the individual mind,” argues Ohlsson. “Even after we have observed that invention is collaborative and extended in time, it remains true that a new idea or concept has to arise in one mind for the very first time. There was a moment sometime between 1920 and 1935 when some person first formulated the thought that perhaps we can detect airplanes at a distance by bouncing radio waves off them. That one moment did not give us radar, but it was one event on the path to radar, and a very interesting event to capture and understand."

In short, these two levels of analysis do not contradict one another, but rather complement one another. "As for the lone genius, specifically, there are examples of those scattered here and there throughout the history of technology, so the lone genius is not unreal, just uncommon," Ohlsson continues. We need to realize that "the idea of detecting air planes with radio waves came to someone in an instant, and, on the other hand, the development of a working radar took a good many people the better part of a decade."

Almost all significant invention involves various forms of collaboration. The diversity of skills and knowledge called for by complex inventive endeavors recommends collaboration. Collaboration can feed divergent thinking and offer critical perspective, provide generative tension, foster spotting problems and opportunities, allow breaking problems down better through division of labor. In addition, an immersion into the thought of another sharpens one's own thinking. Within the collaborative process, there are peer roles, support roles, management roles, visionary roles—roles of many kinds.

According to developmental psychologist Vera John-Steiner, the presidential professor at the University of New Mexico, successful collaborations build upon this "complementarity" as well as "the effective synthesis of multiple perspectives." She cites how the Wright brothers "built on their commonalities as well as their differences." When collaborators disagree, she says, "differences at the conceptual level when combined with a respectful personal relationship result in significant technical advances."

John-Steiner outlines various roles that an individual may assume in such collaborations. "The very complementarity and diversity inherent in collaboration helps define roles that participants assume," she argues. "These roles are based both on cognitive and personal skills. *Management roles* include planning, allocation of resources, setting deadlines, negotiation within larger institutional structures, etc. Persons assuming *visionary roles* have the imagination and daring to choose problems beyond the obvious. They address complex questions and have the personal charisma to draw talented and energetic participants who assist them in actualizing their dreams. The *bridge role* is important when a collaboration is at the interface of two or more organizations with different institutional cultures. The person assuming such responsibility knows how to facilitate a language which spans the differences between the diverse groups engaged in collaborative innovation."

Leadership is a crucial function in any collaborative effort. "Leadership involves facilitating how problems are engaged so that the available team can deal with them effectively," John-Steiner adds. "Thus, the leader mediates between task and team. Only high-capacity cognitive agents can benefit from substantial rates of interaction with others. Otherwise they may not be able to use the connectivity well." One caveat: Visionary leaders are important, but it's not helpful to have too many of them on one project.

When it comes to the dynamics of collaborative effort, John-Steiner says, "intense intellectual work implies engagement, conviction, certain ways of seeing things and the possibility of value conflicts. Individuals engaged in close collaborative work may find themselves in disagreement which can facilitate productive tension." Citing team dynamics studies by Warren Bennis and Patricia Ward Biederman, she suggests that "the intensity of highly successful innovative teams drives productive tension and their very intensity limits their duration." In the realm of artistic creativity, the Beatles would be Exhibit A. "It has been found that many groups last for about ten years after which participants may choose solo work or look for a different collaboration in which to continue their work. The sustainability of a collaborative team is linked to the willingness of participants to confront disagreements rather than ignore them. Living with some amount of competition within a group can add to the intensity of the effort but can become counter-productive if it exceeds the level of trust."

Studies show that there are common patterns of collaboration that typically emerge. "In *distributive collaborations*, those partnerships based on the exchange of information (such as email discussion groups), values do not tend to go beyond the shared interest in the topic," notes John-Steiner. "*Integrated collaboration* is often long-term and dyadic and the partners may develop a more intimate exchange of ideas where values may be modified and developed during the collaborative exchange. *Complementary collaborations*, such as those found in classroom settings or in work environments, usually have a more precise role definition and division of labor. Whereas, in *family collaboration* roles may fluctuate based on the expertise of the participants. The construction of a new mode of thought or radically new invention thrives best in *integrative collaborations*. These partnerships require a prolonged period of activity. They thrive on dialogue, risk taking and shared vision. Integrative partnerships are motivated by the desire to transform (rather than just add) to existing knowledge." Styles and patterns of collaboration vary along with institutional cultures and social contexts.

Cultivating Inventiveness

One of the main goals of our series of workshops, dovetailing with the mission of the Lemelson-MIT Program at large, is to find systematic ways by which the traits of the inventive mind and the processes of invention can be cultivated by education and fostered by appropriate organizational structures and cultures, to the benefit of the individual and society. Several of our participants addressed this mission by providing examples of how such cultivation has been successfully done in the past as well as principles for cultivating inventiveness going forward, especially in young people.

Mark Myers, recently retired as senior vice president for corporate research and technology at Xerox Corporation, argues that everyone has the ability to be creative and inventive to some degree and that research shows that such traits and skills can be enhanced. On a group level, that could be done simply by hiring creative people to be members of a laboratory or development team, a practice put into place at Xerox's Palo Alto Research Center in the 1960s and 1970s. However, he says, we don't understand well enough how to go about cultivating such traits at the individual level. He notes that the process must begin with instilling a sense of purpose in people. "Specifically," says Myers, "very few people make contributions that would be considered technological inventions without intending to make them."

At a very basic level, John-Steiner notes that there is a high correlation among children between nutrition and creativity. Kids cannot develop high mental capacitates if they are poorly fed or underfed, and this is a major problem not only worldwide but in the

U.S. as well. Once such baselines are established, evidence suggests that very specific cognitive skills can be cultivated in kids at a young age. Bob Weber says that finding problems and scanning problem spaces is one such strategy. "The children's invention programs that I have been involved with ask the kids to go around their house or school looking for needs," Weber says. "The children also are asked to interview others about the needs they perceive, a kind of second-order observation. Activities like these serve to establish a mindset for looking at the environment as an entity that can be grasped and altered through invention."

Several of our participants warned of the harmful role that standardized testing can have, that such testing can promote narrow thinking and can stifle inquiry. The opposite of standardized testing would be to encourage individual initiative and non-conformity, says Tufts University research professor Raymond S. Nickerson, who retired in 1991 as senior vice president of Bolt Beranek and Newman, birthplace of the Arpanet, the precursor to the Internet, in the late 1960s. In addition, he says, such effort to foster creativity must be sustained over time. "The vast majority of attempts at innovation and invention fail, at least at first," he says.

Wondering whether specialized training needs to be concentrated in one place, one of our participants posed the question, "Do we need a Julliard for inventors?"

Ray Nickerson, for one, believes that creativity and inventiveness can be taught anywhere, and to all, but that some people will be better at it naturally. He believes that the best teaching method involves showing examples of invention, preferably by teachers who are enthusiastic about the subject matter or those who have actually done it. Inventiveness is "best spread by infection, as it were," he argues. Success stories can stimulate aspiring inventors, and a good way to start is to cultivate "the *intention* to invent," Nickerson says. Since most invention is done deliberately, as opposed to accidentally, it's useful to show young people examples from history in which individuals and groups set out to solve a problem. Such cases include the search for the chronometer to calculate longitude, vaccines for specific diseases, and the artificial heart. This would increase the chance that kids could learn to look for opportunities for invention. "Inventiveness is, in part, a mind-set," he notes. "Successful inventors have the ability not only to observe the world carefully and critically (in a productive sense), but to imagine how things might be different."

Bill Murphy emphasizes that inventiveness can be encouraged by programs that work outside of traditional classrooms. One example is FIRST (For Inspiration and Recognition of Science and Technology). Murphy was instrumental in helping Dean Kamen launch the non-profit organization back in 1992. With backing from corporations and universities, FIRST funds local robotics labs at high schools around the country, then organizes teams into regional competitions, which lead up to a big annual showdown at a stadium that holds tens of thousand of people. The idea is to apply the excitement and enthusiasm that typically surrounds sporting and entertainment events to the process of engineering. The program has been enormously successful in building self-confidence among the participants, developing teamwork skills, and steering kids into engineering-related careers. Last year, the competition drew more than 800 teams comprising nearly a hundred thousand students and mentors.

An experimental program, initiated by the Lemelson-MIT Program, funds "InvenTeams" in high schools. The teams work with a high school teacher and an outside mentor over the better part of an academic year to invent something relevant to their school or town. Ten InvenTeams are funded this academic year, and twenty-five will be funded next year, at up to $10,000 each. Other effective programs include Camp Invention, a series of regional summertime activity centers for cultivating inventiveness in kids ranging in age from 6 to 12, as sponsored by the Inventors Hall of Fame, in Akron, Ohio. The Lemelson Foundation also funds the National Collegiate Inventors & Innovators Alliance (NCIIA), which works with universities to build collaborative learning environments that nurture technical, business and social skills among budding inventors.

There was no shortage of ideas among our participants of how to supplement curricula at all levels of education to encompass the invention skills and the cognitive strategies we discussed. Our participants believe there are ways to foster observation, to teach kids how to look at the world closely, to show how to analogize, to perform boundary transgressions, to teach general problem-solving skills, not just techniques focused on mathematics, to find ways to stimulate and encourage curiosity and exploration, and to foster a sense of wonderment about the world. But many of the above organizations are founded on the principle that that there is no real lack of *supply of knowledge*. In other words, that the resources and the materials are there to do all this. What is lacking is the *demand*. You have to get kids excited about science and technology in the first place in order for them to want to learn how to become an engineer or inventor.

Our participants also agreed that there are many barriers to cultivating inventiveness. The culture of standardized testing, resistant teachers, conventional curricula, entrenched corporate cultures that are intolerant of risk, personal stereotypes about inventive people—all of these things act as barriers. As someone who worked as a teacher before joining Apple Computer and then Microsoft, Linda Stone asks: "What kinds of interventions in the educational process would support a broader set of learning styles than what's supported today in education?"

In the end, it comes down to incentives. "I always come back to how crucial it is to cultivate the basic personal qualities that every inventor must have to survive and thrive," Stone says. "I think much of what goes on in our education systems, K-12 through post graduate, works against developing the very qualities that inventors need to have. This likely is one of the reasons that those folks with the qualities of inventors often wind up dropping out of school at some point." Stone says that we don't need specialized schools. What we do need to do is to find ways of rewarding executives who encourage experimentation and innovation, and ways of rewarding teachers, parents, and kids who show signs of inventiveness. Creativity and inventiveness must be highlighted in a much higher profile way before it can bubble to the top of the agenda. As she concludes: "We get what we celebrate."

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W. Bernard Carlson teaches at the University of Virginia, with appointments in both the School of Engineering and the History Department. He received his doctorate in the history and sociology of science from the University of Pennsylvania in 1984. Carlson studies the role of technology and innovation in American business, and his research focuses on how inventors, engineers and managers used technology in the development of major firms between 1870 and 1920. Working with Michael E. Gorman, Carlson has also investigated the way inventors work—the mental models, strategies and heuristics they use to generate new ideas—by using Thomas Edison and Alexander Graham Bell as case studies.

Carlson has held fellowships at the Smithsonian Institution, the Harvard Business School and the Dibner Institute at the Massachusetts Institute of Technology. He is co-editor of the MIT Press book series, *Inside Technology: New Social and Historical Approaches to Technology*. Carlson has published widely in the field of invention, including *Innovation as a Social Process: Elihu Thomson and the Rise of General Electric, 1870-1900* (Cambridge University Press, 1991; paper reprint 2002). He is completing *Technology in World History* (Oxford University Press, 7 volumes), which surveys the role of technology in 18 different cultures. With support from the Sloan Foundation, Carlson is also currently writing a biography of the prominent inventor, Nikola Tesla.

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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.

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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 over the last thirty years of oral history interviews as a research tool 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.

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Raymond S. Nickerson received a Ph.D. in experimental psychology in 1965. He retired from Bolt Beranek and Newman Inc. in 1991, where he had worked for 25 years as a research psychologist and in various management positions, including Senior Vice President and director of a division whose departments conducted research on artificial intelligence, control theory, distributed information systems, educational technology, experimental psychology, interactive systems, signal processing and speech processing.

Nickerson has researched various aspects of human memory and cognition. Currently, his focus is on probabilistic reasoning. His books include: *The Teaching of Thinking* (1985, Erlbaum), with David N. Perkins and Edward E. Smith; *Using Computers: Human Factors in Information Systems* (1986, MIT Press); *Reflections on Reasoning* (1986, Erlbaum); *Technology in Education: Looking Toward 2020*, (1988, Erlbaum), edited with Philip P. Zodhiates; and *Cognition and Chance: The Psychology of Probabilistic Reasoning* (in press, Erlbaum). He is also the founding editor of the *Journal of Experimental Psychology: Applied*. Nickerson is a fellow of the American Association for the Advancement of Science, the American Psychological Association, the Human Factors and Ergonomics Society, the American Psychological Society, and the Society of Experimental Psychologists.

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Vera John-Steiner received her Ph.D. in social and developmental psychology from the University of Chicago in 1956. Her current research areas include psycholinguistics, cognitive psychology, collaboration, creative thinking, bilingualism and feminist studies. She is author of *Notebooks of the Mind: Explorations in Thinking* (Oxford University Press, 1997), which won the William James Award, and *Creative Collaboration* (Oxford University Press, 2000). John-Steiner has participated in establishing the interdisciplinary program in Educational Linguistics at the University of New Mexico. She has lectured extensively in Europe, South America and Israel. Her most recent publications demonstrate her commitment to combine Vygotskian cultural-historical theory and contemporary feminist thinking.

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

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

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Mark B. Myers' research interests include identifying emerging markets and technologies to enable growth in new and existing companies with special emphases on research, technology identification and selection, product development and technology competencies. Myers serves on the Science, Technology and Economic Policy Board of the National Research Council and currently co-chairs the National Research Council's study of "A Patent System for the 21st Century."

Myers retired from the Xerox Corporation at the beginning of 2000, after a 37-year career in its research and development organizations. Myers was the senior vice president in charge of corporate research, advanced development, systems architecture, and corporate engineering from 1992 to 2000. His responsibilities included the corporate research centers: PARC in Palo Alto, CA; Webster Center for Research & Technology near Rochester, NY; Xerox Research Centre of Canada in Mississauga and Ontario; and the Xerox Research Centre of Europe in Cambridge, UK and Grenoble, France. During this period he was a member of the senior management committee in charge of the strategic direction setting of the company.

Myers is chairman of the Board of Trustees of Earlham College and the Earlham School of Religion and has held adjunct and visiting faculty positions at the University of Rochester and at Stanford University. He received a Ph.D. degree in materials science from Pennsylvania State University in 1964 and was named an alumni fellow there in 1997.

Linda Stone
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Linda Stone held executive positions in high tech from 1986–2002. Stone played a key role in building Apple's multimedia marketplace from 1986–1993, helping to forge significant relationships between Apple and traditional creative media, such as book publishers. She is also credited for her strong contributions to building the multimedia developer community and for her visionary market development, evangelism and strategy. In her last year, Stone worked for Chairman and CEO, John Sculley, on a variety of special projects.

In 1993, Stone joined Microsoft Research under Sr. VP, Nathan Myhrvold. She founded and served as Director of the Virtual Worlds Group (now, Social Computing Group). With a focus on improving online social interactions, Stone and her team studied and developed technologies that would work on a human level. Stone was viewed as a leader and pioneer in the effort to create online communities. During this time, Stone also taught as an adjunct faculty at New York University's Interactive Telecommunications Program.

In 2000, CEO, Steve Ballmer tapped Stone for the newly created role, Corporate VP, Corporate and Industry Initiatives. Stone built a relationship between Microsoft and the World Economic Forum, and worked tirelessly on ambassador/ombudsman issues to create more constructive relationships between Microsoft and the industry. Stone initiated Microsoft's Visiting Speaker Series, hosting close to 100 speakers in two years.

Stone serves on the board of the World Wildlife Fund, which focuses on species preservation and global threats, and the Regional Committee for FIRST, dedicated to inspiring young people in science and technology.

In 2002, Stone left Microsoft to write, speak and consult. She is currently working with Harvard Business School Press on a book regarding social cycles and their impact on business innovation, corporate culture, management practices, marketing and product development. Stone has been recognized by *Upside* Magazine as one of the "Upside 100 Leaders of the Digital Revolution," by *Inventor's Digest* Magazine as one of the "I.D. 40," and she was featured in John Brockman's book, *THE DIGERATI*, which described her as a visionary both within Microsoft and to the industry at large.

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Stellan Ohlsson received his doctorate in psychology from the University of Stockholm, where he also studied the philosophy of science. During his student years, he developed a computer simulation model of spatial reasoning and worked on insight in problem solving. He held teaching and research positions both in Australia and Sweden before emigrating to the U.S. in 1983. Ohlsson collaborated with Patrick Langley at Carnegie-Mellon University on the development of a diagnostic module for intelligent tutoring systems, before moving to a full time research position at the Learning Research and Development Center (LRDC) associated with the University of Pittsburgh in 1985. At LRDC Ohlsson worked on questions of learning and discovery in arithmetic and science. He developed a computer simulation model of learning from error, and continued his work on insight in problem solving in collaboration with Jonathan Schooler. He was promoted to Senior Scientist in 1992.

Ohlsson moved to the Department of Psychology at the University of Illinois at Chicago in 1996, where he is currently Professor of Psychology. He served as Chair of the Cognitive Program from 1996–1999. His research areas include cognitive psychology—with special focus on acquisition of complex knowledge, computer simulation, creative thinking and technological applications of cognitive psychology. He has published approximately 80 scholarly works on questions related to knowledge, thinking and cognitive change. Ohlsson is currently preparing an integrative statement of his views on these topics, to be published by Cambridge University Press.

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

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

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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.

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Thomas B. Ward's research focuses on the nature of concepts, including how they are acquired, structured, combined and used in creative and noncreative endeavors. His most recent line of research examines the ways in which people apply existing knowledge to new situations, including tasks as diverse as imagining life on other planets and designing practical products. He has also conducted basic and applied studies concerned with increasing the creative potential of new ideas. Ward is one of the founding members of the Creative Cognition Research Group at Texas A&M University. In collaboration with colleagues of this group, he has published numerous articles and chapters, as well as four books concerned with creative cognition, and organized an international conference on the topic. Ward has also published broadly on categorization. He has served as Associate Editor of Memory & Cognition and currently serves as Editor of the Journal of Creative Behavior.

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Robert J. Weber received his Ph.D. in psychology from Princeton University. His interests include the psychology of invention and creativity. He took early retirement from Oklahoma State University, and most recently he has been Visiting Research Professor of Law at the University of New Mexico. Three of his books deal with invention, broadly conceived. *Forks, Phonographs, and Hot Air Balloons: A Field Guide to Inventive Thinking* (Oxford University Press, 1992) is intended for the general reader, but it is also an original account of invention as a thinking process. An underlying theme is that tools and simple inventions form the oldest known record of the creative mind. Weber is co-editor (with David Perkins) of *Inventive Minds: Creativity in Technology* (Oxford University Press, 1992). The proceedings of this conference brought together 18 experts on invention, ranging from inventors of important technologies to historians of technology to cognitive scientists—all to discuss and theorize about the mental processes involved in invention. In his book, *The Created Self: Reinventing Body, Persona, and Spirit* (W. W. Norton, 2000), the ideas of invention are applied to the creation of self, something now being done on an ever more regular basis, from tattoos and surgical enhancements to the invention of new religious practices. The processes of invention extend far beyond technology. Weber's current interests continue to be thinking processes underlying invention, but now he is focusing on social inventions—procedures that enable and regulate social functioning.

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

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

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