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Exceptional Creativity in Science and Technology

Introduction

Andrew Robinson

> Fundamental research . . . may be curiosity driven, but may also result in an Aladdin's cave of new knowledge from which who knows what prizes may come in the future. . . . Anyone casting their eyes over the work going on in Oxford University in the late 1950s, looking for groups doing research with commercial potential, would probably have put the high-magnetic-field team in the Clarendon Laboratory at the bottom of the list. That work was the starting point for Oxford Instruments, and the taxes paid and generated by the Company over the years would, in total, be enough to finance, say, a new university or a hospital. The economic ramifications of one successful company can be very wide.
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> —Audrey Wood, cofounder with engineer Martin Wood of Oxford Instruments, in *Magnetic Venture: The Story of Oxford Instruments* (2001)[1]

In the evolution of science and technology, laws governing exceptional creativity and innovation have yet to be discovered. Writing in his influential study, *The Structure of Scientific Revolutions* (1962), the historian Thomas Kuhn noted that the final stage in a scientific breakthrough such as Albert Einstein's theory of relativity—that is, the most crucial stage—was "inscrutable."[2] The same is still true half a century later.

This lacuna is certainly not for lack of systematic investigation, stretching back to the creativity research boom of the 1950s and even to the time of the inventor Thomas Edison. Scientists, engineers, designers, and inventors have a vital interest in understanding and promoting exceptional creativity and innovation. So do business corporations, patent offices, government committees and departments for science and technology, universities, and educational foundations around the world. Creativity and innovation are also much studied by academics from disciplines as diverse as psychology, business and management, economics, sociology, and history. However—at the risk of stating the obvious—exceptional creativity and innovation are extremely complex, varied, and far-reaching phenomena, which have proved resistant to measurement, regulation, and planning. Indeed, these very characteristics are intrinsic both to their importance and their allure. The long-term effects of scientific discoveries and innovations are generally unpredictable. According to Henry Ford, writing in 1929, "The motion picture with its universal language, the airplane with its speed, and the radio with its coming international programme—these will soon bring the world to a complete understanding. Thus may we vision a United States of the World. Ultimately, it will surely come!"[3] In the past decade, similar utopian claims have been made for the Internet and the World Wide Web.

In science, to take just one example of the mystery, consider high intelligence and exceptional creativity. One might naturally expect there to be a strong correlation between these two mental faculties. Lewis Terman, the Stanford University psychologist who first popularized IQ testing in the United States (and the father of one of the engineers, Frederick Terman, who founded Silicon Valley), discovered a substantial group of high-IQ (135-plus) school students in California in the early 1920s—soon to be nicknamed "Termites"—and then monitored their success or failure as they grew into adulthood. But after following the group's individual careers over several decades, Terman and his coworkers were obliged to admit that none of these gifted students, for all their considerable worldly success, had achieved anywhere near genius in any field. None of the Termites had won a Pulitzer Prize or a Nobel Prize, for instance; moreover, Terman's initial IQ tests rejected the future Nobel Prize–winner William Shockley, after twice testing him at school, as they also did another future Nobel Prize winner in physics, Luis Alvarez. Had Terman tested Richard Feynman, yet another future Nobel laureate and an icon of twentieth-century American physics, Terman would have rejected Feynman for his gifted group, too—given the latter's reported IQ score (a relatively modest 125), as measured at his school in New York around 1930. Today, it is widely accepted by psychologists that above an IQ of about 120 there is no correlation between IQ and exceptional creativity.[4]

In technology, the path from invention to innovation—that is, an invention that leads to a commercially successful product—often defies rationalization. When the telephone was invented in the 1870s, it was initially regarded not as an altogether new technology but rather as an improvement of the electric telegraph, which had been invented in the 1830s. Alexander Graham Bell's 1876 patent on the telephone was titled "Improvements in Telegraphy." In a letter to potential British investors, Bell argued, "All other telegraphic machines produce signals which require to be translated by experts, and such instruments are therefore extremely limited in their application. But the telephone actually speaks."[5] Almost as surprising, at least with the wisdom of hindsight, is the fact that the scientists and engineers who founded the computing industry in the 1940s–1960s did not foresee that personal computers would be useful to white-collar workers in offices; that vision arrived only in the mid-1970s with the founding of the companies Apple and Microsoft. Perhaps more understandable, yet still surprising, is the story of the invention of the laser and its subsequent widespread applications. When the first lasers became operational in the early 1960s, they were regarded as potentially useless for several years. Colleagues of Charles Townes, one of the laser's inventors at Bell Laboratories, famously used to tease him by saying, "That's a great idea, but it's a solution looking for a problem." As Townes admitted some four decades later, "The truth is, none of us who worked on the first lasers imagined how many uses there might eventually be."[6]

Exceptional Creativity in Science and Technology arises from a symposium with the same title held in November–December 2008, at the

Institute for Advanced Study (IAS) in Princeton. Organized by the John Templeton Foundation, the symposium had as its chair the Nobel Prize–winning doctor and geneticist Baruch Blumberg, while its IAS host was the physicist Freeman Dyson.

Nine of the chapters in the book (chapters 1, 2, 4, 5, 6, 7, 8, and 11, plus the Afterword by Freeman Dyson) are from participants in the symposium, while a further three (chapters 3, 9, and 10) are invited contributions from nonparticipants, intended to extend the range of the book by discussing a seminal institution, Bell Laboratories, during its most creative period; the development of innovative ideas into commercial products; and the experiences of a current inventor working within a leading university physics department. The original intention was that the book would be jointly edited by its current editor with the assistance of Baruch Blumberg, but sadly he passed away in 2011.

The IAS symposium's chief aim was to discuss the relationship between exceptional scientific creativity and innovation, individuals, and institutions—with the focus on the United States and Europe during the modern era. Key questions for the participants included: What characterizes a creative environment? Which environments most effectively nurture the highest levels of scientific creativity? What is the sequence and range of steps leading to the creation of a high-creativity institution? Do structures such as organizational governance and operating principles matter? To what degree is autonomous self-governance in research institutions important? What effect do government funding and regulation have on creativity? To what extent does freedom of inquiry matter? The study of failures and declines, as well as successes, is highly illuminating. What are the dynamics that portend fiascos in attempts to build creative institutions? When and how does an institution lose its creative edge? How do geographically large, amazingly creative domains such as Silicon Valley come to be, and how can they be developed elsewhere? How are gifted young people most effectively encouraged and prepared to pursue careers marked by exceptional creativity in mathematics, science, technology, or technologically based industry? All of these questions were discussed at the symposium, and the responses to them form part of this book.

The complexity of the subject is well illustrated by the Princeton University physicist Philip Anderson in his chapter on "Physics at Bell Labs, 1949–1984: Young Turks and Younger Turks"—a personal, entertaining, but nonetheless penetrating memoir by a Bell Labs insider who was a member of the technical staff of Bell Labs from 1949 to 1984 and was awarded a Nobel Prize in 1977—one of seven Nobels in physics awarded for work done at Bell Labs. Before the Second World War, Bell Telephone Laboratories, though already significant innovators in the communications business, did not encourage curiosity-driven research. What was it, asks Anderson, that turned the postwar Bell Labs into an international byword for scientific creativity and invention?

Many people have pondered this question, including several of the contributors to this book in addition to Anderson. As the science writer Jon Gertner makes clear in his well-researched study published in 2012, *The Idea Factory: Bell Labs and the Great Age of American Innovation*, Bell Labs veterans, not to mention outside commentators, have come up with somewhat different answers.[7]

All agree that the government-approved monopoly over the U.S. telephone industry enjoyed until 1984 by AT&T, Bell Laboratories' parent company, created a unique situation that encouraged the company to support fundamental research—at least partly for reasons of public interest, but also to protect their telephone monopoly from periodic government attempts at deregulation. (One is somewhat reminded of a similar situation in Britain with the BBC, which enjoyed a monopoly in broadcasting until the mid-1950s.) Another key factor in the Labs' success was surely the generous salaries and the prodigious resources lavished on Bell Laboratories' technical staff as a result of AT&T's financial wealth. But according to Anderson, the deeper answer to the question is more subtle than simply these political and financial advantages. It involves both the culture of the postwar United States and the culture of Bell Labs' management, which for a long period attached more value to scientific and technological creativity than to the commercial exploitation of its groundbreaking inventions. Anderson writes:

> Thinking about [the situation] after all this time, it almost seems inevitable. The key is that in that early burst of hiring after the war, and the next round brought on by the exhilaration of success, the Labs had done far too well: they had all but cornered the market. At the same time, the rest of the world was more and more waking up to the fact that solid-state physics was something worth pursuing. Finally, the people they had hired were of a type and quality that was certain to find the status of docile wage slave, no matter how paternally coddled, a bit uncomfortable.

Bell Labs' management, says Anderson, had two alternatives in the early 1950s. "One was to let us all go, once we had realized our value in the outside world—to replace us with more docile, if less creative, scientists who would do what they were told." The other alternative was to change the company's style of management by abandoning the conventional hierarchical structure of an industrial laboratory and introducing some of the elements of a high-flying university. This was the decision, Anderson observes, that William Shockley, one of the three discoverers/inventors of the transistor at Bell Labs in the late 1940s,[8] forced on the Labs as a consequence of his overbearing treatment of his co-inventor, John Bardeen. In 1951 Bardeen decided to leave Bell Labs to work more freely in a university setting, where in due course he became the world's only double Nobel laureate in physics. Bardeen's unwanted departure was a lesson to Bell Labs' management. "It is very much to the credit of the Labs' management of the time," comments Anderson, "that they chose the other alternative, namely to switch to a very different management style in order to hold on to what they realized was an irreplaceable asset."

We shall return to this overarching issue of the role of national and institutional culture in exceptional science and technology. But first, a few words on the structure of the book. The eleven chapters are arranged in a roughly chronological order. Thus, the first six are chiefly, though by no means exclusively, about the history of the subject. They begin with a survey of the past 250 years; move on to consider key institutions in science, such as Niels Bohr's Copenhagen Institute for Theoretical Physics, and key scientific and technological breakthroughs, such as the decoding of the structure of DNA at the Cavendish Laboratory in Cambridge and the building of an electronic computer at the IAS in Princeton; and end with the sources of modern engineering innovation, in a chapter which examines examples of historic technological breakthroughs—for instance, the electric power grid, the automobile, the airplane, and the microchip—and tries to draw lessons from these earlier innovations for our contemporary world. This leads naturally to the second half of the book, which deals mainly with the conditions required for the current flourishing of exceptional science, technology, and innovation in universities, research institutes, and companies, finishing up with potential future developments that may arise from current and projected space missions—in which Baruch Blumberg had a special interest as the founding director of the NASA Astrobiology Institute from 1999 to 2002. While the emphasis of the book's first half is more on exceptional science, that of the second half is more on exceptional technology.

In chapter 1, "The Rise and Decline of Hegemonic Systems of Creativity," the sociologist J. Rogers Hollingsworth and his coauthor David Gear examine the reasons for the successive dominance of four national systems of science in the world: first in France from about 1750 to the early decades of the nineteenth century; then in Germany from the mid-nineteenth century to the first decade of the twentieth century; then in Britain during the first half of twentieth century; and finally in the United States during the second half of the twentieth century to date—an American dominance that some fear may now be declining, possibly to give way to the rise of science and technology in

Asia, especially China. The authors argue that highly creative science systems became embedded only in those countries that were economic, political, and military hegemons. A country's economic, political, and military hegemonic power gave birth to its scientific hegemony. A scientific hegemon tended to dominate the world's leading scientific journals, it established standards of excellence in most scientific fields, its language became the dominant one in facilitating scientific communication with other countries, its leading scientists acquired prominence in the global world of science, and young people flocked to the hegemonic country for training. However, as a country's economic, political, and military power began to decline relative to other countries, a relative decline took place in its scientific creativity.

There can be no doubt that France, Germany, Britain, and the United States did indeed dominate the world scientific scene during the periods ascribed to them above. Yet the existence of a direct link between exceptional scientific and technological creativity and national economic, political, and military dominance may not be as straightforward as appears at first sight. For example (as noted by the authors), science, especially physics, flourished at the University of Göttingen in the 1920s, despite the collapse of German power and the German economy after the First World War, until the rise of the Nazis in 1933. It also flourished in Copenhagen during the same period and after, despite Denmark's economic, political, and military insignificance. Although most of the credit for this belongs to Niels Bohr, his institute received financial support from both the Danish government and Danish foundations (as discussed by Gino Segrè in chapter 2). In India, exceptionally creative science was also carried out during the first half of the twentieth century by Indians such as the Calcutta-based theoretical physicist S. N. Bose, who collaborated with Einstein on Bose-Einstein statistics (hence the fundamental particles known as bosons), and the Bangalore-based experimental physicist C. V. Raman, who was awarded Asia's first Nobel Prize in science in 1930. None of this internationally renowned Indian scientific research was actively encouraged by the politically dominant British colonial power.[9]

But perhaps the most problematic example for the above thesis is that of Britain. Exceptionally creative science occurred in Britain long before the United Kingdom and its empire became the world's dominant power in the late nineteenth century, beginning in the seventeenth century with William Harvey, Isaac Newton, Robert Boyle, Robert Hooke, and some other fellows of the Royal Society. Their discoveries were followed by the first industrial revolution, starting in England in the second half of the eighteenth century. Exceptional science and technology continued in the second half of the twentieth century after the disappearance of Britain's international political dominance. As Hollingsworth and Gear observe, British scientists have received more than two dozen Nobel Prizes for work begun after 1950. Something more than Britain's economic, political, and military hegemony in the first half of the twentieth century must have been at work in the development of exceptional British science and technology.

A good picture of what this something was appears in the foreword to a recent book on science and technology in eighteenth-century England, written by two historians of science, the astronomer Patrick Moore and Allan Chapman. After mentioning some of the important seventeenth-century British scientists, Moore and Chapman comment:

> As well as providing this succession of great discoveries, Britain's wider culture proved very conducive to scientific and technological innovation. Despite the poverty and despair highlighted by artists like William Hogarth and other social commentators, Britain (and England in particular) had the largest, richest, and most independent middle class in world history: a people who had both formed and been formed by a variety of circumstances peculiar to Britain and its emerging American colonies. These included a Parliament-based

> political and legal tradition, a popular monarchy whose powers were limited by statute, a free press, a tolerant state Church from which one had the right to "Dissent," and a flourishing economy, with a great deal of spare cash being generated from overseas trade and industrial enterprise and by the already globally dominant City of London.
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> So Georgian England had numerous comfortably-off middling country gentry, clergy, and professionals, with money to spend and leisure in which to enjoy its fruits. Moreover, since it was regarded as a gentleman's prerogative to act freely, an individual might spend his money as wisely or as foolishly as he chose. Besides sport, theatre, balls, and fun, such people actively pursued art, music, and science. Indeed, a gentleman's credibility rested on his knowledge of "culture," and by 1750 this would include such things as Newton's Laws or how clocks worked, as well as architecture, perspective drawing, literature, racehorses, dogs, and boxing.[10]

Just such a culture encouraged the development of one of England's greatest polymaths, Thomas Young, who was born in the rural county of Somerset in 1773 and grew up among Quaker bankers, about whom I wrote a biography titled *The Last Man Who Knew Everything*. Best known in science for his discovery of the interference of light waves in his double-slit experiment around 1801, Young (whose profession was actually medicine) has numerous other claims to fame—in physics, the physiology of the eye, linguistics, and even Egyptology, where he was the first to decipher the Rosetta Stone with a degree of success and thereby launched the decipherment of the Egyptian hieroglyphs. In an exhibition on Young arranged by London's Science Museum for his bicentenary in 1973, the organizers went so far as to state, "Young probably had a wider range of creative learning than any other Englishman in history. He made discoveries in nearly every field he studied."[11]

National cultures, even though we may struggle to define them, are therefore influential on exceptional creativity in science and technology. Moreover, they can inhibit creativity, as well as encourage it. Inhibition has tended to be the case, at least until very recently, in Asian cultures. Postcolonial India, for example, has failed to fulfill the scientific promise shown by its exceptional scientists in the first half of the twentieth century, largely because of the Indian government's bureaucratic dominance of Indian universities and even the best Indian research institutes, coupled with the debilitating effect of caste politics. Although Indians—for instance, the astrophysicist Subrahmanyan Chandrasekhar—have won Nobel Prizes since C. V. Raman in 1930, in each case the prize was awarded for work carried out in universities in the United States or Europe, not in India. Regarding Japan, the Japanese-born engineer Shuji Nakamura, who pioneered the white and blue LEDs (light-emitting diodes) while working for a company in Japan, later immigrated to the United States because he found it difficult to function successfully in Japan as an inventor. "Everything is different in the U.S. Individuals are important, whereas in Japan the group as a whole is valued more," Nakamura said in 2007. "This might be the strength of U.S. research, because inventions always come from individuals rather than from groups. I think individual creativity is more likely to flourish in the U.S. system, whereas the system in Japan is more suitable to mass production."[12] Regarding China, a Chinese-born environmental scientist, Peng Gong, with experience of working in universities in both China and the United States, wrote in the scientific journal *Nature* in 2012,

> Two cultural genes have passed through generations of Chinese intellectuals for more than 2,000 years. The first is the thoughts of Confucius, who proposed that intellectuals should become loyal administrators. The second is the writings of Zhuang Zhou, who said that harmonious society would come from isolating families so as to avoid exchange and conflict, and by shunning technology to avoid greed.

> Together, these cultures have encouraged small-scale and self-sufficient practices in Chinese society, but discouraged curiosity, commercialization, and technology. They helped to produce a scientific void in Chinese society that persisted for millennia. And they continue to be relevant today.[13]

The influence of cultures, whether national or institutional, or both together, turns out to be a connecting theme of this book. Although it is explicit in chapters 1, 2, 3, 4, 7, and 11, it is implicit in chapters 5, 6, 8, 9, and 10, as well as the Afterword.

In chapter 2, "Exceptional Creativity in Physics," physicist Gino Segrè identifies the circumstances that foster exceptional creativity in science, especially physics, by concentrating on two important historical institutions: the Copenhagen Institute for Theoretical Physics (now renamed the Niels Bohr Institute) during the 1920s, and Enrico Fermi's group at the University of Rome during the 1930s. The first institution played a key role in the development of quantum mechanics, the second in the development of nuclear physics. The chapter considers the particular times, places, environments, mentoring, and individuals involved, and tries to draw some general conclusions. What is the opportune time to recognize that a field has evolved to the point where exceptional intellectual challenges—the 1913 Bohr model of the atom (for Bohr's group) and James Chadwick's 1932 discovery of the neutron (for Fermi's group)—or their applications can significantly alter the way people live and work? In what kind of institutions can one address these challenges? What sort of encouragement is beneficial, and how important is it to have a variety of backgrounds and training? In what ways do mentors need to be involved in the research in question? Who are the exceptional individuals who can respond to these challenges, and how are they identified? What type of educational system promotes their development? How can such individuals be encouraged and supported? Although Bohr was essentially a theorist while Fermi was an experimentalist who was also a theorist, many of their answers to the above questions were similar, and their approaches later influenced the working of other research institutions in Europe, including CERN, and in the United States, where Fermi settled in 1938 and played a key role in making the atomic bomb.

Next we come to chapters on two leading U.S. research institutions: the first on Bell Laboratories by Philip Anderson, discussed earlier, and the second on the Institute for Advanced Study in Princeton, "The Usefulness of Useless Knowledge," written by historian of science and technology George Dyson. His title is borrowed from the title of a magazine article published in 1939 by Abraham Flexner, the founding director of the IAS. "The pursuit of these useless satisfactions proves unexpectedly the source from which undreamed-of utility is derived," wrote Flexner.[14] The IAS does not maintain laboratories, develop new technology, or grant appointments to engineers. The one exception to this policy—John von Neumann's Electronic Computer Project, launched in 1945 and terminated in 1958—contributed more to the advance of human knowledge (including mathematics, physics, biology, economics, environmental science, politics, and nuclear weaponry) than any other undertaking in the history of the IAS. This chapter reviews the founding of the IAS and the birth of its intellectual culture, and explains how one of the most influential engineering achievements of all time came to fruition at an institution specifically designed to avoid experimental research. Instead of importing a handful of mathematical logicians into one of the existing organizations that had the facilities and resources to build a computer (like the Massachusetts Institute of Technology), von Neumann imported a handful of engineers into the IAS. Free of any preconceptions as to how the new machine should be designed, built, or used, they unleashed one of the more exceptionally creative episodes in the history of humanity, technology, and biology.

My own chapter, "Education and Exceptional Creativity," focuses not on a single institution, but on the way in which several educational and research institutions contributed to the solving of two important problems in the 1950s. I begin by looking generally at the education of exceptionally creative scientists (and some artists, too, by way of comparison). Formal education has long had an uneasy relationship with exceptional creativity—perhaps most notably in the arts, but also in science. Pioneering figures such as Newton, Darwin, Marie Curie, and Einstein had university training, which they found necessary and sometimes stimulating. Yet their initial breakthroughs were made when working outside of a university, and required them to reject ideas then prevailing in the academy. There are plenty of other examples of this phenomenon, such as the extraordinary Indian clerk-turned-mathematician Srinivasa Ramanujan a century ago, and the phenomenon continues to be important and intriguing, if hard to analyze. It reveals itself in a thought-provoking way by comparing the decoding of the structure of DNA in 1953 with the decipherment of Minoan Linear B, achieved at the same time. Both discoveries involved five key individuals, four men and one woman in each case, who played curiously similar roles; however, the roles of the major participating academic institutions significantly differed. The two stories do not point to a straightforward link between institutional support and the encouragement of exceptional creativity. The vigorous culture of give-and-take at the Cavendish Laboratory in Cambridge clearly encouraged creative theoretical solutions to the decoding of DNA. The lack of this culture at King's College, London discouraged them, but permitted crucial accumulation of data. Linear B was deciphered essentially without any institutional support. The California Institute of Technology and the University of Oxford, despite having major resources and highly relevant expertise, failed to grasp the opportunities. Perhaps the most striking overall conclusion is that the two most creative figures in these triumphs—Francis Crick (DNA) and Michael Ventris (Linear B)—were the least institutionalized.

Reference has already been made to the content of chapter 6, "The Sources of Modern Engineering Innovation," written by Princeton University engineer David P. Billington and David P. Billington Jr. They argue that the transformation of American life by its industrial revolution in the late nineteenth and early twentieth centuries "was primarily the work of engineering that embodied radically new technical ideas, in which the contribution of science came after the breakthrough, not before it." They describe in several case studies how major engineering innovations actually occurred in the United States, including Edison's development of the electric power grid, the first powered flight by the Wright brothers, and the inception of the integrated circuit (the microchip) by Jack Kilby and Robert Noyce. These examples show that trained knowledge and skills are not sufficient to generate radical innovations. The breakthroughs were the result of deeply original thinking by one or two individuals who broke with conventional notions. The institutions and settings commonly associated with technical creativity, such as industrial laboratories and centers of high technology, have been the result of these breakthroughs and not the cause of them. Given the mounting concern in the early twenty-first century over whether the United States and other advanced countries can sustain the technical capacities that enabled them to prosper in the twentieth century, the authors propose that a new generation can best learn how to innovate radically by studying examples of radical innovation as part of a general high school and undergraduate education.

The engineer Susan Hackwood, who was a member of the technical staff at Bell Laboratories from 1979 to 1984 and later moved to the University of California, is also preoccupied with technical education in the United States. In her chapter, "Technically Creative Environments," she accepts that we have much more reliable knowledge of the factors that inhibit creativity—such as the appointment of intelligent but not creative people as managers and leaders—than of what causes or enhances creativity. Based on her exposure to the creative technical and management culture at Bell Labs, and her wide-ranging experience of science education in California, she outlines such academic knowledge of creativity and uses it to consider how to foster technically creative environments. In particular, how does a group of technically expert and creative individuals work together to achieve higher creativity?

How should they be governed, supported, and appreciated as independent thinkers? Investigating to what extent the quality of life of the community in which research centers and universities are located correlates with the creative output of the institution is an important field of research, she argues. After looking at the factors that influence the production and retention of creative people, the chapter discusses a few practices that are disastrous and some that work. It also argues that the number of technically creative people who can realistically be imported into the United States far exceeds the maximum number that can ever be produced in-house, even with the best social and educational methods. Thus, the United States should continue to foster the international brain mobility of scientists of recent decades in all possible ways.

In the next three chapters, the discussion moves to the realities of how inventions are developed and marketed as commercial products. The first of these chapters, "Entrepreneurial Creativity," is by Timothy Bresnahan, an economist working at Stanford University. He starts from a familiar truth: exceptionally creative scientists and inventors do not always exploit their research and inventions successfully. Indeed, a good example of this failure is Bell Laboratories, which even in its Nobel Prize–winning heyday was poor in entrepreneurial skills. Improvements in the standard of living for all the world call for both scientific creativity and "entrepreneurial creativity"—meaning the ability, as defined by the author, "to locate and exploit overlaps between what is technically feasible and what will create value for society." The conception of new ideas, the creation of new products and processes, and their market use in improving people's lives are all essential in creating a better-off society. Entrepreneurial creativity, like scientific and engineering creativity, is critical for long-run, innovation-based economic growth, but although it is related to scientific and engineering creativity, it is distinct from them. To the entrepreneur, market knowledge is no less important than scientific or technical knowledge. The author, who has studied the entrepreneurial culture of Silicon Valley over many years, draws his examples mainly from the history of computing. One of his goals is to state with reasonable precision what entrepreneurial creativity is, and to list with reasonable completeness the parts of technical advance for which entrepreneurial creativity has been responsible. Another goal is to analyze the best institutions, especially at the boundaries between science or engineering and entrepreneurship, to see how to enhance creativity in the interests of long-run economic growth and improvement.

"Scientific Breakthroughs and Breakthrough Products," chapter 9, looks at entrepreneurial creativity from the point of view of the scientists and designers. It is jointly written by a former British university physicist, Tony Hey, who is now a vice president at Microsoft Research, based in the United States, where he is responsible for building partnerships with the academic community, and his son Jonathan Hey, a user experience designer based in London, who previously studied design at the University of California, Berkeley. Academic scientists have long had links with industry; even Einstein, the onetime patent clerk, designed a leak-proof refrigerator for the companies Electrolux and AEG. But successful new product development is a challenging activity, with only 30 percent of new products surviving to their second year on the store shelves. How do such very different institutions—universities and companies—encourage creative outcomes in the marketplace? To the scientist, originality is paramount for a research breakthrough, whereas the majority of a company's customers do not care that a product is new and different, only that it meets their needs. In universities, scientists typically work alone or in small groups, whereas in industry large teams are typical, often drawing their input from multiple research laboratories. The authors examine university and industry roles in the development of the World Wide Web, wireless sensor technology, Microsoft's Kinect motion sensor for the Xbox video game, and the Segway Personal Transporter, a novel vehicle that has so far failed to find a large market. The importance of framing design challenges around user needs emerges from these case studies.

Through a better understanding of user-centered technology design and multidisciplinary teams, it is possible to formulate a set of guidelines and practices to help new product design teams navigate the difficult design phases.

The former Oxford University physicist Joshua Silver is at the sharp end of such design issues. His professional career has been spent in atomic physics at Oxford's Clarendon Laboratory. However, in the 1980s he used his university-trained knowledge of optics to invent a new type of self-adjustable eyeglass—using fluid-filled lenses. His initial impetus was simply curiosity to solve the problem of a variable-focus lens. But soon he visualized the invention's usefulness for the many millions of people in the developing world who have no access to an optometrist and no money to pay for a pair of conventional, fixed-focus eyeglasses. In chapter 10, "A Billion Fresh Pairs of Eyes," Silver describes his invention and the subsequent lengthy process of its development. After some years of field trials in Africa, China, and the United States by vision specialists, with the support of bodies such as the World Health Organization and the World Bank, the self-adjustable eyeglasses are now in production as a collaboration between the U.K.-based Centre for Vision in the Developing World in Oxford—which Silver helped to found in 2009—and the U.S.-based Dow Corning Corporation, a global leader in silicon-based technology. Although earlier versions of the eyeglasses, known as Adspecs, have been successfully used by wearers in Africa and Asia, their relatively clunky appearance continues to pose a problem, especially for younger, fashion-conscious wearers, but Silver is confident that technical improvements to the design will enable aesthetic improvements. In 2011 an audience of health professionals in London at the National Health Service's Innovation Expo, following Silver's demonstration of the Adspecs, voted self-adjustable refraction to be "The idea most likely to make the biggest impact on health care by the year 2020." His ambitious goal is to have a billion people wearing self-adjustable eyeglasses by 2020.

To conclude, the last chapter conjoins exceptionally creative science and exceptionally creative technology. "New Ideas from High Platforms" by Baruch Blumberg moves into space, beginning with a personal memoir of the founding of the NASA Astrobiology Institute (NAI) in 1999 and its active links with astrobiology programs in other countries. As a deliberate part of its creative culture, Blumberg's management of the NAI was dispersed rather than command-and-control. As in universities (and at Bell Laboratories during its most creative years), NAI teams were encouraged to collaborate with whomever they thought would enrich their research. The second part of the chapter then deals with creativity in space. Searching in previously unreachable locations increases the possibility of encountering the new. By observing from high platforms never before available, we have a rich source of new observations and new concepts. A few of the current and projected range of space-related missions of exploration and discovery are described, with the contributions that these discoveries have already made to our earthbound life; and the multigenerational nature of long-term space research is emphasized. For example, NASA's Mars Science Laboratory rover is one of the most ambitious attempts to determine if microbial life does or could exist, or has existed, on Mars. NASA's projected Kepler Mission will seek planets around other stars that could nourish life like that of the "Pale Blue Dot"—the name given to the photograph of Earth taken from deep space by *Voyager 1* in 1990 on its way out of the solar system. New products arising from space-related activity include advanced lithium batteries to improve the capabilities of electric vehicles, space-suit materials to help protect divers in hostile marine environments, and a method for manufacturing an algae-based food supplement that provides the nutrients previously only available in breast milk. Thus, the exploration of space has enhanced, and will continue to enhance, not only science and technology but also the economy and life on Earth.

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NOTES

1. Audrey Wood, *Magnetic Venture: The Story of Oxford Instruments* (Oxford: Oxford University Press, 2001), 104. Oxford Instruments was started in 1959 in the garden shed of the Wood family in Oxford.
2. Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 50th anniv. edn. (Chicago: University of Chicago Press, 2012), 90.
3. Quoted in David Edgerton, *The Shock of the Old: Technology and Global History since 1900* (London: Profile, 2006), 114. Edgerton's book is a thought-provoking corrective to the common assumption that the latest technology is always the best, and that the pace of innovation constantly accelerates. "By the standards of the past, the present does not seem radically innovative," Edgerton notes. "Indeed judging from the present, the past looks extraordinarily inventive. We need only think of the twenty years 1890–1910 which gave us, among the more visible new products, X-rays, the motor car, flight, the cinema, and radio" (page 203).
4. See Andrew Robinson, *Sudden Genius? The Gradual Path to Creative Breakthroughs* (Oxford: Oxford University Press, 2010), especially chap. 2; and Joel Shurkin, *Terman's Kids: The Groundbreaking Study of How the Gifted Grow Up* (New York: Little, Brown, 1992).
5. Quoted in Tom Standage, *The Victorian Internet: The Remarkable Story of the Telegraph and the Nineteenth Century's Online Pioneers* (London: Phoenix, 1999), 185.
6. Charles H. Townes, *How the Laser Happened: Adventures of a Scientist* (New York: Oxford University Press, 1999), 4.
7. See Jon Gertner, *The Idea Factory: Bell Labs and the Great Age of American Innovation* (New York: Penguin, 2012), 300, 350–52 (for the analysis of the Bell Labs engineer John R. Pierce).

8. Bardeen referred to his (and Walter Brattain's) "discovery" of "transistor action," while Shockley thought of the transistor as a device and therefore an invention, which could be patented. See ibid., 106–7.
9. See Abha Sur, *Dispersed Radiance: Caste, Gender, and Modern Science in India* (New Delhi: Navayana, 2011).
10. Foreword to *Innovation and Discovery: Bath and the Rise of Science*, ed. Peter Wallis (Bath: Bath Royal Literary and Scientific Institution and the William Herschel Society, 2008), 5.
11. Quoted in Andrew Robinson, *The Last Man Who Knew Everything: Thomas Young* (Oxford: Oneworld, 2006), ix.
12. Interview with Nakamura by Jane Qiu, in "The Blue Revolutionary," *New Scientist*, January 6, 2007, 44–45.
13. Peng Gong, "Cultural History Holds Back Chinese Research," *Nature* 481 (2012): 411.
14. Abraham Flexner, "The Usefulness of Useless Knowledge," *Harper's Magazine*, October 1939, 548.

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