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## Institutions: A Brief Excursion through History

with Stephen M. Maurer

The United States currently devotes about 2.6 percent of GDP—\$264 billion—to research and development.<sup>1</sup> Of this, the federal government pays more than a quarter, a fraction that was much larger for most of the twentieth century after World War II. Some federally funded research is done in-house (27%) and in national laboratories (13%), but more than half is given to industry and universities, which receive similar amounts. Looked at from the other side, about 10 percent of industry's R&D effort and 60 percent of universities' R&D effort are funded by the federal government. Foundations and lower levels of government also make important contributions to research, mostly by giving research funds to universities, private firms, and individuals.

The numbers mask a bewildering array of funding schemes and incentives. Most R&D investments made by private firms are aimed at securing a market advantage. Market advantage is often, but not always, given as intellectual property, mostly patents and copyrights. Firms also compete for contracts to carry out government research agendas and can even receive grant funding, under the federal Small Business Innovation Research Program (SBIR). They receive research funding for military hardware and space exploration as well. Universities receive direct grants from industry, often in return for promised intellectual property rights, and also from government. Some government funding, such as that for the human genome project, carries an obligation to put the resulting knowledge in the public domain (available for free access). The output of other government funding can be patented.

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1. Unless otherwise noted, the data quoted in this chapter refer to the year 2000 and were compiled by the National Science Foundation. See, generally, the statistics available at [www.nsf.gov/sbe/stats.htm](http://www.nsf.gov/sbe/stats.htm), and more specifically *Science and Engineering Indicators 2002*.

All forms of funding are implicitly incentive schemes, since they set the direction of research and encourage people to do it. Some funding is given *ex ante*, such as grants, whereas other funding is given *ex post*, such as patents and prizes. Prizes were eclipsed by patents during the Industrial Revolution, but they have never vanished as an incentive mechanism. For example, the Defense Advanced Research Projects Agency (DARPA), which is the research arm of the Department of Defense, has offered a \$1 million prize to elicit a fortyfold improvement in robotic vehicles for rough terrain (Defense Advanced Research Projects Agency, 2003; Holden 2003).

Research, like art, has always relied on wealthy patrons. In the modern world, this fact is evident in the names Stanford, Ford, Rockefeller, Carnegie, Mellon, and so forth, that are attached to universities and grant-giving foundations. Government funding, whether for military purposes, pure science, or targeted industrial objectives, has also been a common thread, although the nature of the governments providing the funds has changed, as has the process by which they are given. Government funding in modern democracies arises from a more inclusive political process than that used by the Greeks or medieval monarchies, and might therefore be more directed to creating knowledge or technology with widespread benefits. In many of its current forms, it has the advantage of peer review by fellow scientists. Some government funding has always been mission-directed, often in search of better war machines. Archimedes was supported for such purposes, and so was Robert Oppenheimer, director of the Manhattan Project in World War II.

The only fundamentally new incentive scheme of the past 400 years is intellectual property. Whereas wealthy benefactors and governments can indulge in basic science and curiosity-driven research, a research agenda driven by patents is hostage to the market and to consumer sovereignty. The consumers who are sovereign are those with resources.

The tale told in this chapter is one of institutions in flux. Before R&D could arise as an organized activity, societies needed both the ability and incentive to fund it. The *ability* to fund research requires command over resources. Governments, with their ability to tax, and private concentrations of wealth emerged some time after farming appeared in Mesopotamia (modern Syria and Iraq) around 8000 BC. Innovation also requires an *incentive* to fund research. If research leads to widespread benefits for citizens, governments may have an incentive to invest as part of their legitimate missions. Wealthy individuals may invest in R&D for many reasons, including philanthropy, curiosity, or a

desire for acclaim. Inventors who are not wealthy need a means to appropriate the benefits they create for others. As we will see, innovation has always been spurred by governments and wealthy individuals, but the main means of appropriating benefits—intellectual property—developed much later. One of the ways that governments have spurred invention in recent eras is through what is sometimes called “regulatory push,” namely, creating commodity standards that can only be met with some new innovation.

Appropriability follows both from the nature of the knowledge and from the institutions that support discoveries. When we make a distinction between pure science and technology, we are often distinguishing knowledge that is not appropriable (such as the knowledge that planets orbit the sun) from knowledge that could have commercial value (such as engineering discoveries). To the extent that this distinction relies on institutions such as markets, and on preferences, it is not fundamental.<sup>2</sup>

## 1.1 The Ancients

The story begins much earlier than the written record—without innovation, it is difficult to make a record.<sup>3</sup> We can guess that invention in prehistoric societies was haphazard and unplanned. Although prehistoric societies made some clever inventions like the boomerang and Eskimo toggle-joint harpoon, the archeological evidence suggests that they were technologically conservative. Artifacts like flint tools and pots remained essentially unchanged for centuries. If invention was slow to take off, one explanation can be found in a dearth of social institutions to support research. People who spent their time improving the technology of subsistence might improve the well-being of the community as a whole, but could put their own survival at risk. There were presumably no social

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2. Nevertheless, many scholars have made distinctions of this type. Schumpeter (1942) distinguished between “invention” and “innovation.” Mokyr (2002) distinguishes between “propositional knowledge” and “technological knowledge.” Such distinctions are not central in this book, because the relevant aspects of knowledge are revealed in economic models. This book uses words like *technology* and *engineering* because they are the English-language words for certain kinds of knowledge, but it does not rely on any precise definition.

3. Our discussion of prehistoric and ancient technology in section 1.1 is largely drawn from De Camp 1980 and Finley 1973. The emphasis here is on the institutions in which these technologies developed, as a prelude to our later discussions of incentives.

institutions like intellectual property or funding agencies to compensate them for their efforts.<sup>4</sup>

The first known inventor was a “government employee,” Imhotep, who lived in Egypt about 2650 BC. He built the first pyramid, and was probably a Da Vinci–like genius who also served as a priest, scholar, sculptor, carpenter, poet, and doctor. Greek and Roman writers continued to revere him, albeit as an exaggerated, wizard-like figure, well into the Christian era. Imhotep’s innovations were steadily eclipsed by later pyramid builders, all “government employees.” Within a few decades, other government employees working for Khufu (aka “Cheops”: d. 2613 BC) figured out how to move 50-ton granite slabs. Four hundred years later, workers for Ramses II (d. 1212 BC) moved 1,000-ton statues routinely. In modern terms, all of these achievements amounted to direct government procurement of R&D.

The Greek city-states produced a golden age of science and technology between 600 and 300 BC. Along the way, the Greeks added new institutions of research and discovery to the direct government procurement model of Cheops. First, Greek culture accorded respect and reputation to wealthy individuals who devoted their time and resources to science. Examples include the astronomer Anaxagoras (d. fifth century BC); the engineer Archytas (d. fifth century BC), who worked out the theory of the pulley and built toys powered by compressed air; and the mathematician and inventor Archimedes (d. 212 BC).

Second, Greek city-states purchased research. In one famous example, Dionysius, the tyrant of Syracuse, hired Archimedes as a consultant to determine whether a crown was really made from pure gold. The task led to the buoyancy principle that bears Archimedes’ name. Dionysius also pioneered the use of what would now be called large research teams. In 399 BC, he used a combination of conscription, high wages, and bonuses to attract skilled workers from all over the Mediterranean to work on military technologies such as giant warships and missile weapons. This early experiment led, among other things, to the catapult.

Third, the Greeks introduced a new type of self-funding research institution: schools organized around one or more great teachers. As in

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4. Macroeconomists speculate that invention was slow to take off because there was only a small population generating new ideas; see Romer 1996 for a summary. Although mathematical treatments of the hypothesis date from the 1990s, this insight was anticipated by De Camp forty years earlier. See Finley 1973, 6.

modern universities, the ancient schools created a powerful incentive for would-be academics to build their reputations through research and publication. Still, the scientific and technological benefits were limited. Socrates (d. 399 BC), Plato (d. 347 BC), and Aristotle (d. 322 BC) all belonged to schools, but only Aristotle was a scientist.

Finally, the Greeks' scientific tradition led to the establishment of the Library of Alexandria. When Alexander the Great transplanted Greek culture to Egypt, he found himself in what seemed to him an intellectual wasteland. Alexander's successors Ptolemy I (d. 283 BC) and Ptolemy II (d. 246 BC) built the library to remedy this problem. In a book-starved world, the library's core asset, 750,000 papyri purchased all over the world, was a unique resource. The Library of Alexandria foreshadowed modern research facilities like Princeton's Institute for Advanced Study. It included facilities for housing specimens, conducting experiments, delivering lectures, and storing library books. An endowment recruited scholars from throughout the known world to study, write, and teach.

Both basic science and engineering flourished as never before. Resident scholars prepared star charts of unprecedented accuracy (Hipparchus (d. 120 BC)), measured the size of the earth to 15 percent (Eratosthenes (d. ca. 194 BC)), invented the heliocentric theory of the solar system (Aristarchus of Samos (d. 230 BC)), and formalized geometry (Euclid (fl. ca. 300 BC)). The library also produced two first-rate engineering-type inventors. The first, Ctesibius (ca. 270 BC) is sometimes referred to as the "Edison of the Ancient World." His inventions included improved water pumps, the first metal spring, the first pneumatic pipe organ, the first keyboard, and an improved water clock. He also built a compressed air catapult that failed because no one could machine adequate parts. The library's other most noteworthy inventor was Hero of Alexandria (d. AD 62). In addition to publishing works on mathematics and physics, Hero invented improved gearing, a surveying instrument, an air-driven fountain, and a famous engine driven by jets of steam.

After Greek hegemony declined, the Romans created an empire across Europe. They are not remembered for as much inventiveness as the Greeks, nor did they improve memorably on the institutions of research and learning, but they did contribute to technology. Like large corporations today, the Romans' huge administrative machine was large enough to capture the positive externalities associated with innovation. State ambition was a powerful incentive for engineering feats like building aqueducts. Roman innovation also benefited from a second practice,

in which successful inventors routinely petitioned the emperor for rewards. This allowed inventors to recover at least some of the benefits that their work conferred on society. Examples of government-sponsored innovators include Sergius Orata, a building contractor who invented central heating (ca. 75 BC) and Marcus Vipsanius Agrippa, a Roman statesman and military commander who designed novel siege weapons and catapults (d. 12 BC).

Assessing the performance of ancient institutions is a messy business. For example, we do not know what R&D rate would have been optimal, or whether more resources would have accelerated technological development. There is no evidence that the ancients themselves thought very systematically about how to organize incentives. Even an experienced engineer like Vitruvius (d. 25 BC) seems to have viewed innovation as a series of accidental discoveries and frivolous projects. His writings never argue that a more systematic inquiry could accelerate progress or benefit the economy through cost-savings. Despite these ambiguities, most scholars share a lingering suspicion that the ancient world should have done better. In the words of one classicist, “Great things emerged from the [Alexandria] Museum, in military technology and ingenious mechanical toys. But no one, not even the Ptolemies themselves, who would have profited directly and handsomely, thought to turn the energy and inventiveness of a Ctesibius to agricultural or industrial technology. The contrast with the Royal Society in England is inescapable” (Finley 1973, 148).

There is some evidence that modern institutions like intellectual property would have helped matters, at least at the margin. We know that the ancient world repeatedly discovered and forgot the same inventions, such as central heating and the arch. Partly these failures were due to the absence of printing, without which the recording and dissemination of knowledge is difficult. However, inventors also tended to keep their discoveries secret, so that inventions sometimes died with their inventors. Available evidence suggests that secrecy was especially prevalent in shipbuilding. A modern system of patents would have ameliorated the problem by providing an economic reward for disclosure. However, this is far from saying that modern institutions would have accelerated classical innovation in any substantial way. In the end, all institutions are limited by factors in the broader society. First, ancient societies tended to look down on engineering as a subject not fit for gentlemen. This was notoriously true of Plato and Socrates, and according to Plutarch, even of Archimedes. Second, most ancient societies were

more interested in preserving the existing social order than adopting potentially subversive innovations. When a mechanical engineer found a better way to move heavy columns, the Emperor Vespasian (d. AD 79) gave him a reward but refused to adopt the technology. Said the emperor, “You must let me feed my poor commons.” A similar but less heart-warming story is also told about the Emperor Tiberius (d. AD 37), who supposedly met the inventor of plastic (“unbreakable glass”). Tiberius had the man beheaded, lest, he said, “gold be reduced to the value of mud” (Finley 1973, 149; see also De Camp 1980, 178).

## 1.2 In Between: Monasteries, Guilds, and Universities

After the fall of Rome, most ancient texts were lost, and so far as we know, basic science stagnated. Nevertheless, a modest interest in engineering continued throughout the so-called Dark Ages.<sup>5</sup> In the East, citizens of Antioch produced the first artificial streetlights (ca. AD 350) and improved water-clock designs (ca. AD 450). Even in the West, government patronage remained important. When the Goth Theodoric (d. 526) conquered Rome, he hired the philosopher Boethius as a minister. Among his other duties, Boethius built advanced sundials and water clocks as gifts for adjacent rulers.

Europe emerged from the Dark Ages with important new institutions. It was not their stated purpose to foster innovation, but they nevertheless did so. The new Church monasteries combined practical economic activity with increasingly sophisticated research. After AD 500, monasteries started operating small libraries so that monks could learn to read. For the next 600 years, monasteries and cathedral schools were Europe’s main centers of learning. Monasteries also operated some of the most technologically advanced mills, factories, and farms in Europe. In the process, they overcame the traditional prejudice against mere technology (Mokyr 1990, 203–204).

Meanwhile, in the secular world, craftspeople organized themselves into guilds. Guilds passed strict laws against revealing their secrets to outsiders, but encouraged members to share innovations among themselves. Potentially, the guilds’ market power gave them the ability to capture the positive externalities associated with innovation. However, this same cartel-like character proved their undoing. Mokyr (1990,

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5. This discussion of medieval technology in section 1.2 is largely drawn from Gimpel 1977.

178–179, 258–259) tells how Dutch guilds opposed progress in ship-building, Swiss printers obtained laws to bar an improved printing press, and French paper producers used sabotage and arson to block machines that would have speeded up pulp production. Even if the guilds had been a force for innovation early on, they had become a net drag by the time they mostly vanished in the eighteenth century.

On the institutional side, the rise of universities created still more incentives for scholars to perform and publish research. Prior to 1100, learning had been limited to monasteries and cathedral schools. Beginning in the twelfth century, Europeans rediscovered mathematics and the classics, which were taught in the new universities along with medicine and natural science. Medieval teachers organized guilds to decide who would be entitled to earn student fees by lecturing. This led to diplomas and the first formal institutions of higher learning. By 1450, Europe hosted eighty universities. The new system also encouraged R&D. Roger Bacon (d. 1292), who discovered the formula for gunpowder and speculated on visionary technologies, taught at Paris and Oxford. In 1348, Giovanni Di Dondi built one of the first mechanical clocks while working as an astronomy professor in Padua.

Together, the new institutions unlocked medieval creativity. Thirteenth- and fourteenth-century writers marveled at the rate of invention and treated the engineers as heroes. Furthermore, the engineers themselves developed confidence. Surviving notebooks are filled with ideas for novel power sources and machines. Contemporary accounts describe how clockmakers had agreed on needed improvements and were working to achieve them in a systematic way.

### 1.3 Early Modern Europe: Patents, Prizes, and Patrons

Science grew explosively from the beginning of the Renaissance (in fourteenth-century Italy) through the Industrial Revolution (ca. 1750–1850). The growing realization that innovation could lead to prosperity persuaded European governments to make unprecedented efforts to promote it. In the process, they developed the first systems of intellectual property rights and reinvented existing institutions based on prizes, patronage, and other rewards.

Medieval monarchs had long rewarded supporters by giving them patents—legal monopolies over the right to provide particular goods and services. By the fifteenth century, rulers were also offering patents to foreigners who agreed to import new technologies. By the sixteenth

century, French local authorities were using a similar system to encourage domestic inventors. Eventually, patents became a reward for innovation.

In the beginning, patents were given at the discretion of the ruling authority. Since they were not routinized under the authority of a disinterested administrative body, they were subject to abuse. People complained that rulers created patent monopolies too lightly or too arbitrarily, or for corrupt reasons. The patent system was formalized largely as a remedy.<sup>6</sup> The first formal patent statute was in Venice in 1474, and in 1623, the English Parliament passed the Statute of Monopolies. The Statute specified appropriate circumstances in which patents could be used to reward inventors, and was mainly aimed at limiting monopolies, rather than facilitating them.

The origins of copyright can also be found in the Crown's right to hand out monopolies.<sup>7</sup> The Stationers Company in England, a guild, had been given a monopoly on printing. The system gave the guild the power to limit competition much as copyright does today. Because the guild needed a government license to print books, the system also served as a form of censorship. Eventually, however, the authorization for this licensing relationship expired, and when Parliament failed to renew it, the Stationers' interests became allied with authors rather than the Crown. They now petitioned Parliament for a copyright act, which resulted in the Statute of Anne, the first copyright law, in 1710. The copyright law provided for a limited term, similarly to patents.

Lucrative early patents include those on the pendulum clock (1657), the torsion pendulum clock (1675), the steam powered pump (1698), the first modern ("regenerative") steam engine (1767), and punch card-controlled looms (1802).

Prizes also became an important device for stimulating both basic science and technological innovation. Sometimes a challenge was posted without a prize, since winning it added to reputation and could attract a patron. Newton solved the era's most important challenge in 1697 by calculating the path that a ball should take for the fastest descent to a point not directly beneath it. The solution opened the way to multivariate calculus. In a later period, prizes led James Maxwell (d. 1879) to devise a mathematical theory of Saturn's rings and Heinrich Hertz

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6. For a more complete account, see Ryan 1998, chap. 2.

7. This discussion follows chap. 2 of Goldstein 1994, which should be consulted for more details. Ryan (1998) tells a similar story for the abortive history of copyright in Venice, much earlier.

(d. 1894) to detect radio waves. Prizes were also offered for technological contributions, as opposed to basic science. Some are mentioned in chapter 2.

Finally, governments reinvigorated the ancient practice of patronage. An important example was the Danish king's support of Tycho Brahe (d. 1601), who made the astronomical observations that underlie the conclusion (together with his assistant Johannes Kepler, d. 1630) that the earth revolves around the sun. This laid the groundwork for Newton's physics. Sometimes support was offered *ex post*, after the researcher had demonstrated his worth, in which case patronage also acted as a prize. In England, George III gave the astronomer William Herschel (d. 1822) a stipend of £200 a year after he discovered Uranus. Herschel used the money to build the biggest telescope in Europe. Similarly, Frederick the Great (d. 1786) lured Leonhard Euler (d. 1783) and Joseph-Louis Lagrange (d. 1813) to Berlin after declaring that "the greatest mathematicians in Europe should reside at the Court of the greatest king in Europe." When Frederick died, Lagrange considered offers from Naples and Spain before joining the ill-fated Louis XVI in Paris.

The widespread reliance on prizes and patrons had several drawbacks. The first was secrecy. Many mathematicians kept their techniques secret in order to win as-yet-unannounced challenges. When Scipione del Ferro died in 1526, he passed the secret of solving a special case of the cubic equation to just one student. In contrast, modern institutions are designed to overcome the urge to secrecy. Scholars in modern universities must publish in order to achieve advancement or acclaim, and patents are public by their very nature.

A second maladaptive feature, emphasized by Rosenberg and Birdzell (1986), is that systems of patronage and prizes are too centralized. An advantage of intellectual property is that responsibility for innovation is decentralized among the citizens. However, we will argue in chapters 2 and 8 that prize and grant systems can be equally decentralized, and can mimic the advantages of patents. Such prize systems were presaged by institutions that emerged in the Industrial Revolution. In the silk-weaving industry of Lyons in the late eighteenth and early nineteenth centuries, self-motivated inventors could apply for rewards to a central prize authority, without the innovation having been commissioned in advance (Foray and Hilaire-Perez, forthcoming; Foray 2004). This system is decentralized in much the same way as patents.

A third maladaptive feature was that, to compete for a prize, the researcher had to fund the effort himself or find backers. Even if this

only required subsistence levels of funding, as with mathematical prizes, it could be a deterrent. Universities ameliorated this problem by giving scholars the time, funding, and incentive to pursue self-motivated research, rather than the research agendas chosen by patrons. Copernicus (d. 1543), Galileo (d. 1642), Isaac Newton (d. 1727), John Dalton (d. 1844), Alessandro Volta (d. 1827), André-Marie Ampère (d. 1836), and James Maxwell (d. 1879) all spent at least part of their careers as university professors. Newton's predecessor resigned from his endowed chair so that the twenty-four-year-old genius could devote himself to full-time research. University staff jobs supported still more scientists, including James Watt (d. 1819) and Michael Faraday (d. 1867). Our modern universities are similar in many respects.

#### 1.4 Patents Come into Their Own

The last half of the nineteenth and early twentieth centuries were a golden age of invention.<sup>8</sup> The era brought electric lights, movies, phonographs, radio, telephones, airplanes, and automobiles. Inventors were admired as never before or since.<sup>9</sup> The lure of patents played a central role in this transformation.

The period also illustrated the defects of patents, prefiguring debates that still rage today.<sup>10</sup> One unavoidable difficulty is that patents reward inventors *ex post*, which leaves them the problem of funding their research up front. Many of the era's most prominent inventors dodged this problem by working in basements and garages until they were established. Thomas Edison (d. 1931), Gottlieb Daimler (d. 1900), John Dunlop (d. 1921), Alexander Graham Bell (d. 1922), George Eastman (d. 1932), and Guglielmo Marconi (d. 1937) all obtained their first patents while working in modest home laboratories in their spare time. But this model was not sustainable. Most of the twentieth century's hallmark inventions required large design teams and

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8. The discussion of modern scientific and technological history in section 1.4 is largely drawn from Strandh 1979, Newhouse 1988, and Jeans 1967. Detailed descriptions of leading scientists are also found in Gillespie 1970.

9. Henry Ford received 5,000 fan letters and nearly ended up in the U.S. Senate. Journalists talked about "The Ford Craze" and claimed that a better public speaker could have been elected president.

10. Machlup and Penrose 1950 describe the debates of the nineteenth and early twentieth centuries. The arguments are marvelously similar to those in the current literature.

laboratories.<sup>11</sup> This technological imperative put innovation beyond the reach of basement tinkerers.<sup>12</sup>

Inventors reacted by developing three broad strategies to obtain financing. The first solution, prefiguring Silicon Valley, was to become an entrepreneur. Many of the era's foremost inventors traded on their reputations to hop from one start-up to the next. In the process, they structured remarkably sophisticated venture capital deals based on a mix of private stock offerings, joint ventures, spin-off companies, revenue sharing, and stock options.<sup>13</sup> Some companies took off and made investors rich. Others ended in stock swindles and vaporware.<sup>14</sup>

The second solution was to turn the activity of invention into a business in its own right. In the 1870s, Edison founded an "invention factory" entirely devoted to R&D. The factory followed a bewildering variety of business models including performing contract research for

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11. By the 1920s, companies in the high-technology industries of that era (e.g., aircraft or gyroscope manufacturers) typically employed about a dozen engineers. By midcentury, a product like the V-2 missile contained 90,000 parts. Designing and building such a weapon required 1,960 scientists, engineers, and technicians; this did not include the 3,852 people who served as support staff. Large design teams proved indispensable for such twentieth-century innovations as airplanes, automobiles, computers, microelectronics, and large software development.

12. There were still solitary geniuses, but they seem like escapees from the nineteenth century. Albert Einstein (d. 1955) discovered special relativity while working alone in a Swiss patent office. Edwin Land (d. 1991) broke into a Columbia University laboratory night after night so that he could work on his Polaroid filter. David Williams (d. 1975) worked out key elements for the U.S. Army's revolutionary M-1 carbine while serving time in a North Carolina penitentiary.

13. The case of Elmer Sperry (d. 1930) was fairly typical. In 1882 he and his former employer started a spin-off company to manufacture arc lights and generators. In 1888 Sperry launched a second company based on his patents for streetcars and electric automobiles. In 1890 he organized a syndicate to develop streetcars. The enterprise's stated purpose was to obtain patents that could either be sold off or used to start a manufacturing company. In 1903, Sperry persuaded a wealthy capitalist to join him in a joint venture to develop new batteries and electroplating methods. Finally, in 1910, he persuaded a small group of capitalists to fund the Sperry Gyroscope Company. Sperry received stock, salary, and a percentage of revenues.

14. In 1902 a group of investors hired Lee deForest as a front man for a chain of radio stations. The company had no stations and a minuscule R&D budget. It was, however, extremely good at persuading investors to part with their money. See Lewis 1991, 39–41.

others, providing consulting services, selling patents for cash and stock, participating in joint ventures, and spinning off discoveries into Edison-controlled manufacturing businesses. Edison believed that this mix of strategies was the key to managing risk. In his view, routine contract R&D was just as important as high-profile inventions like the lightbulb.

The third solution was for established companies to develop innovations in-house.<sup>15</sup> The first modern industrial laboratories were in the German chemical industry (Mowery and Rosenberg 1998). In the 1850s, chemical research moved out of the university and into industrial laboratories organized by firms like Bayer, BASF, Hoechst, Casella, and AGFA. Around 1900, similar industrial laboratories started to proliferate in the United States. Early examples included General Electric (1900), Dow (1901), DuPont (1902), AT&T (1908), Goodyear (1909), and Eastman Kodak (1912). Most of the new laboratories were concentrated in the electrical and chemical industries. By 1910, 300 laboratories had been founded. By 1940, industry was operating 13,500 laboratories at a combined annual budget of \$200 million.

The other big problem that patents presented was how to cash out. The simplest model was for inventors to sell their patents and leave development and manufacturing to others. The problem, as Edison pointed out (and it is still true today), was that inventors and investors seldom agreed what a particular innovation was worth.<sup>16</sup> In such cases the inventor had little choice except to become a manufacturer. When Charles Hall (d. 1914) discovered a cost-effective way to refine aluminum, existing manufacturers spurned his patents. He succeeded in finding venture capitalists to buy stock in what later became Alcoa Aluminum. Similar stories produced Ford Motor Company, RCA, Eastman Kodak, and other twentieth-century giants.

These problems would have occurred even if the patent system was perfect. In fact, the nineteenth-century patent system—like the current

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15. Schumpeter (1942) early saw the trend away from individual inventors to formal institutions, and gives an interesting account. See also Mowery and Rosenberg 1998.

16. Sometimes the disagreements were technical. When the telephone was invented in the 1870s, most people thought that television would follow within a few months. In fact, it took sixty years. People also disagreed about what kind of inventions consumers needed or would find useful. After Hertz demonstrated the existence of radio waves in 1889, building a crude wireless telegraph was technically straightforward. In fact, it took five more years for Marconi to realize that consumers might want such a thing.

one—was very far from perfect. First, patent applications were complicated and usually required multiple approvals. This kept transaction costs high well into the nineteenth century. Second, enforcement costs were often ruinous. During his lifetime, Charles Goodyear (d. 1860) spent far more on his lawyer, the aging Daniel Webster, than he ever made from patenting vulcanized rubber. Third, patent litigation created uncertainty and slowed the growth of industry. Contemporary observers blamed patent litigation for stifling development of the telephone, movies, automobiles, radio, television, and airplanes, rather than serving their intended purpose of stimulating discovery. Some scholars also blame excessive patent litigation for the slow progress of early photographic processes in England compared to that in France. Finally, some inventors used patents to impose their own technological prejudices on competitors. This happened repeatedly in the case of the steam engine.<sup>17</sup>

### 1.5 Modern Patrons: Foundations

Prior to 1900, university science budgets were not much larger than those in the humanities.<sup>18</sup> The rise of big science in the twentieth century required huge expenditures.<sup>19</sup> One immediate consequence was that

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17. Thomas Savery (d. 1715) used his overbroad patent for a steam-powered mine pump to stop Thomas Newcomen (d. 1729) from manufacturing the first true steam engine in 1712. The impasse was only resolved when Savery died and his heirs agreed to a license. Later in the century, James Watt (d. 1819) used his patents to block high-pressure improvements that he considered dangerous and technically complex. Watt's refusal to license competitors froze steam-engine technology for two decades. Finally, George Corliss (d. 1888) revolutionized efficiency by adding slide valves to pistons. Despite their evident superiority, competitors did not try to extend the idea until Corliss's patents expired in 1876. For an interesting discussion of this, see Scherer 1984. Surprisingly, some disputes had a silver lining. Watt designed his celebrated "sun-and-planets" gear in order to design around a previously patented crank.

18. During the 1880s, Albert Michelson (d. 1931) measured the speed of light using only a modest grant from the U.S. National Academy of Sciences. Soon afterward, Heinrich Hertz (d. 1894) and an assistant built enough equipment to demonstrate radio. Existing university endowments were more than enough to cover these needs.

19. Big science was not just expensive; it also forced administrators to create "institutional memories" for experiments that might take decades. Perhaps the most extreme example is NASA's Gravity Probe B project, an experiment designed to test the general theory of relativity from space (Reichhardt 2003). Stanford physicists first proposed the project in 1960. After forty years and more than one-half billion dollars, the satellite was scheduled for launch in 2004.

funding decisions could no longer be made in ad hoc contacts between individuals. The era of big science was ushered in with astronomy, where state-of-the-art telescopes were too expensive for any individual university and also generated more data than a single university could analyze. This led to large, semiautonomous observatories, even in the 1800s.<sup>20</sup> Similar research institutes were built around specimen collections and other special-purpose facilities, often funded by wealthy individuals. In the twentieth century, such institutes were largely funded at taxpayer expense.

The Gilded Age (late nineteenth century) put unprecedented fortunes into private hands.<sup>21</sup> About seventy foundations were established between 1900 and 1930. Like the federal government in later years, the foundations were so rich that they often ended up setting R&D priorities for the country as a whole. For example, the first Carnegie and Rockefeller institutions each had \$10 million endowments, a figure equivalent to the total annual operating budgets of the country's top fifteen research universities and also commensurate with the total federal research budget around the turn of the century. Foundation resources continued growing until the Depression. By the late 1930s, foundations were spending about \$80 million per year, including \$40 million in research grants. At the time, only six U.S. universities spent more than \$2 million per year (including faculty salaries) on R&D.

The foundations needed new strategies to spend such sums productively. For the first thirty years or so, they searched for ways to keep decision making in their own hands. Their first initiatives centered on identifying and attacking problems that universities and government had ignored. Beginning in 1901–1902, the Rockefeller and Carnegie foundations created a host of new institutes dedicated to medicine, geophysics, botany, and astronomy. By World War I, these were the strongest sectors in American science. When these opportunities were exhausted, the foundations began identifying and eliminating bottlenecks in particular fields. This typically involved long-term investments in physical capital (e.g., large telescopes, university laboratories, and atom

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20. California's Lick Observatory was an early example. During the 1870s, scientists persuaded real estate magnate James Lick that a 36-inch telescope would preserve his memory more effectively than his original choice, a pyramid to be built in downtown San Francisco. The facility was completed in 1880 at a cost of \$700,000. Lick's body is interred inside the pier that supports the telescope.

21. Our discussion follows Geiger 1993.

smashers) and human beings (e.g., research fellowships). This strategy deserves much of the credit for propelling United States science, particularly physics and astronomy, into rough parity with Europe.

By the early 1930s, these opportunities had also been exhausted. Even the largest foundations discovered that researchers were proposing more projects than they could possibly evaluate. At this point, foundations did the only thing they could do: give money to trusted researchers or departments, and hope for the best. This type of benevolence started prior to World War I and accelerated during the 1930s. Over time, foundations refined these arrangements into a formal peer review system. After World War II, the federal government adopted more or less the same process, namely, to solicit open-ended research proposals and fund the best ones (see chapter 8).

For all practical purposes, the scientific community ended up regulating itself, even though the money came from wealthy patrons. This is a major departure from previous eras, when patrons either chose the research agenda or delegated that authority to the inventors themselves but did not use peer review. Of course, peer review has an upside and a downside. It can weed out duplicative efforts or inquiries that are known to be unpromising, but it can also institutionalize groupthink.<sup>22</sup>

Foundation spending declined rapidly during the Depression. Despite creation of the massive new Ford Foundation in 1950, foundations never recovered their prewar share dominance. That said, they continue to be major players in such diverse niches as university infrastructure, medicine, large telescopes, and social science research.

## 1.6 Big Science and the Growth of Government Funding

In the end, an intellectual property system supplies what markets want. By contrast, patrons can make judgments and choices. In the twentieth century, “patron” has come to mean “government.” Since the 1930s, the U.S. federal government has launched repeated, high-profile initiatives to develop new technologies for aviation, space, nuclear energy, electronics, and health care. The current research establishment institutionalizes those long-ago choices.

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22. An example of groupthink on an international scale was the development of civilian supersonic transport in the 1960s. See the discussion in chapter 2.

**Government Laboratories** In the opening years of the twentieth century, much of the R&D performed by government employees was military. Government armories and design bureaus produced astonishingly sophisticated technologies, particularly for naval weapons like torpedoes and battleships.<sup>23</sup> By 1918, battleships were firing 1,400-pound projectiles at ranges up to 12 miles. Achieving that kind of performance required concurrent advances in multiple unproven technologies, including gyroscopes, analog computers, electric data transmission, turbine propulsion, and large castings. Government bureaus continued to play a major role in building new weapons systems throughout the twentieth century.

In the civilian world, the most ambitious nineteenth-century projects were run by the U.S. Geological Survey and the Department of Agriculture. Government efforts to map and explore North America made geology one of the first sciences where Americans could compete with Europe. Following the Civil War, the Department of Agriculture purchased substantial contract research from the country's land grant universities. Most other government efforts were modest and focused on practical problems like mine safety. As a result, government R&D had relatively little impact on universities or industry. In-house government R&D increased dramatically in the first decades of the twentieth century as agencies moved from studying society's problems to regulating them. By the late 1930s, total federal R&D spending had increased about tenfold from the turn of the century, although it was still small by today's standards. Government scientists also remained focused on practical problems like agriculture, geology, meteorology, and conservation.

We have already noted how twentieth-century technologies shifted inventive activity from individuals to large research institutions. Within the federal government, the earliest example of big science was the National Committee for Aeronautics (NACA). NACA began as an emergency measure during World War I to promote industry/academic/government coordination on war-related projects. By the early 1920s, it had adopted a new and more ambitious mission: to promote military and

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23. Researchers did receive valuable input from civilian scientists and engineers. Both the self-propelled torpedo (1866) and steam-turbine propulsion in warships (1897) were completed without official support or interest. Once demonstrated, government design bureaus enthusiastically developed both technologies.

civilian aviation through applied research that looked beyond current needs. NACA's researchers pursued this mission through the agency's impressive collection of in-house wind tunnels, engine test stands, and flight test facilities. Commercial and military clients were also permitted to use NACA's facilities on a contract basis.

In 1922, NACA had 100 employees. By 1938, it had 426. In addition to formal assignments, staff were encouraged to pursue unauthorized "bootleg" research, provided that it was not too exotic. The result was a long string of fundamental breakthroughs, including the "NACA engine cowl" (1930s), the "NACA wing" (1940s), and the "area rule" for supersonic aircraft (1950s).<sup>24</sup> The NACA experience provided a powerful model for World War II research, the postwar government laboratories, and NACA's successor, the National Aeronautics and Space Administration (NASA).

Modern government laboratories are a product of World War II. During World War I, the United States had drafted thousands of scientists into government laboratories. Twenty years later, U.S. academics persuaded the government to follow a different strategy. It created the Office of Scientific Research and Development (OSRD) to run military research. Unlike earlier initiatives, OSRD did not try to micromanage research. Instead, it limited itself to setting priorities and identifying problems that could be solved in time to affect the war. After that, bureaucrats stayed out. Implementation was delegated to self-governing laboratories composed of academic researchers from around the country. The largest OSRD laboratories were located at Los Alamos, New Mexico (atomic weapons research), and MIT (radar). Each employed about 1,200 civilians.<sup>25</sup>

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24. NACA's aircraft were the first to break the sound barrier and eventually flew to the edge of space. The story is told by Wolfe 1979.

25. The army's atomic bomb project eventually cost \$2 billion. OSRD spent \$1.5 billion on radar. Smaller groups included the Applied Physics Laboratory at Johns Hopkins (advanced artillery fuses), the Jet Propulsion Laboratory at Cal Tech (rockets), the Harvard Underwater Sound Laboratory (torpedoes), Penn State's Moore School (the ENIAC computer), Columbia (operations research for bombing), and Harvard (sonar and radar laboratories). Universities provided management and, in most cases, facilities under "no loss and no gain" contracts. Additional work was done at research institutes and industrial laboratories. In at least one case, a particularly urgent problem—finding an industrial-scale process for making RDX explosive—was sent to several different competing laboratories at Michigan, Cornell, and Penn State.

OSRD's wartime laboratories were so successful that Congress preserved the Los Alamos facility and created additional atomic facilities at Brookhaven, NY, and Argonne, IL. These became the nucleus for the current network of national laboratories. Congress also extended the OSRD model to biology by founding the National Institutes of Health (NIH).<sup>26</sup> The second wave of national laboratories came during the Korean War and was designed to accelerate electronics and nuclear technology. These early-1950s institutions included the Lincoln Laboratory, Lawrence Livermore National Laboratory, and the Applied Electronics Laboratory. The final wave of OSRD-style laboratories came in the 1960s and was dedicated to big science. Most of these institutions were focused on physics (Stanford Linear Accelerator, Fermilab) and astronomy (National Radio Astronomy Observatory, National Astronomy and Ionosphere Center, National Optical Astronomy Observatories).

The end of the Cold War (1989) eliminated the threats that justified big physics research. Managers of national laboratories responded with more or less frantic efforts to find new missions to justify their continued existence. These included technologies for simulating nuclear weapons ("stockpile stewardship"); applying atom-smasher technologies to molecular biology; advanced computing initiatives; and gene sequencing. More than ten years later, their missions were still in flux.<sup>27</sup>

**Government Grants** Nineteenth-century governments did not solicit grant applications, did not promise to make funds available, and made no particular effort to choose the best proposals. If funds were made available, they went to whichever scientists mounted the most persistent lobbying efforts. Having an ally in government also helped. In England, the British government funded Charles Babbage's famous Difference Engine—predecessor to the computer—in 1823 (Newhouse 1988). Similarly, the British Admiralty paid for a wave tank so that William Froude could conduct his pioneering studies of boat hulls, leading to modern

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26. Anomalously, medical research had not followed the same model as OSRD and national laboratories in World War II. Instead, most life scientists spent the war working in their own labs. There they produced important breakthroughs, including penicillin and blood plasma.

27. Lawrence Berkeley Laboratory, always on the short list of possible closures, made the biggest effort to reinvent itself. By 2000, 17 percent of the lab's funds came from private sources. The lab also redirected its traditional focus on physics to include life sciences (22%) and computing (17%).

hydrodynamics (Porter 1994). In the United States, Congress financed Samuel Morse's experimental telegraph between Washington, DC, and Baltimore. Morse later patented the technology. The U.S. and British governments also subsidized a transatlantic telegraph cable owned by financier Cyrus W. Field (Standage 1998).

The first steps to formalize government-funded research took place in Germany. In 1884, electrical magnate William Siemens (d. 1883) persuaded the German government to set up the Imperial Physical and Technical Institute to attack problems in applied physics. The Kaiser Wilhelm Institute for Chemistry followed in 1910 (reorganized as the Max Planck Society after World War II).

In America, government support for universities remained minuscule until the 1940s. At the end of the Depression, universities, like the rest of the U.S. economy, were operating far below capacity. World War II changed that. By 1944, government contracts accounted for three times the R&D that universities had performed before the war. Wartime success permanently changed the landscape. During the early postwar period, universities continued to support themselves by maintaining or extending wartime programs aimed at developing particular weapons or technologies. However, academics worried that these programs would damage research by skewing work toward a handful of militarily useful disciplines, promoting classified work that had limited value to science and to the university's mission of disseminating knowledge, and exhausting the store of basic knowledge on which wartime successes had been built.<sup>28</sup> Congress agreed. Over time, new institutions like the National Institutes of Health (1946), the National Science Foundation (1950), and even the Office of Naval Research (1946) shifted federal support back to the kind of curiosity-based research that foundations had pioneered in the 1930s. Although slow to get started, the budgets of the new agencies rose steeply after 1950. By 1958, NIH and NSF accounted for 40 percent of the federal government's \$219 million budget for university R&D.

Basic research got a further boost after the Soviet Union shocked the West by launching the first artificial satellite in 1957. Over the next ten years, university R&D rose from 0.1 to 0.2 percent of GNP, and

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28. The most famous statement of this view is found in Vannevar Bush's *Science: The Endless Frontier* (1946). Despite initial indifference, the report eventually became the cornerstone of postwar science policy.

shifted toward curiosity-driven basic research.<sup>29</sup> By 1970, total university R&D budgets had reached \$2.3 billion, and almost four-fifths was devoted to basic research. Federal spending paid for 70 percent of this effort. But this happy expansion of federal R&D funding could not survive budget pressures from the Vietnam War and the economic downturn that followed. Between 1968 and 1974, spending in universities by the NSF and Defense Department fell by 50 percent in real terms. Budgets remained tight for the rest of the 1970s. Since then, real growth has rarely exceeded 1 or 2 percent, although funding remains much higher than before the expansion.

### 1.7 Modern Hybrid Institutions

The U.S. research establishment has very few research laboratories or funding mechanisms that are purely public, purely academic, or even purely industrial. Hybrid institutions, blending public funding with intellectual property, were the twentieth century's "new idea" about research funding.

**The Military-Industrial Complex** Society devotes enormous resources to weapons procurement.<sup>30</sup> Since World War II, at least half of federal R&D spending has been directed to military wares, and usually more.<sup>31</sup> During the twentieth century, military research increasingly moved from government armories and ordnance bureaus to the national laboratories and private firms. President Dwight Eisenhower called this fusion of military objectives and private interests the "military-industrial complex." Whatever its drawbacks and dangers, there is no denying that the system produced breathtaking technological leaps. Successful megaprojects

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29. Between 1957 and 1968, NSF spending expanded from \$40 million to \$480 million. NIH spending went from \$85 million to \$722 million during this period.

30. In some sense, most military R&D does not qualify as "innovation" at all. Except for spin-offs, Pentagon spending is pure economic waste. Furthermore, the benefits of weapons research are largely nullified by the fact that the antagonist is also doing weapons research. Antagonists would be much better off if they could agree not to waste research funds on weapons, but they face the classic "prisoner's dilemma." If they agree to cut back, each side will have an incentive to cheat.

31. See chap. 2 of Mowery and Rosenberg 1998 for a more complete account.

included atomic reactors (1942), atomic bombs (1945), hydrogen bombs (1952), nuclear-powered submarines (1954), intercontinental ballistic missiles (1959), and missile-firing submarines (1960).

Given the sums involved, the Pentagon has had ample opportunities to experiment with different incentive systems. Most basic research is funded by targeted grants and contract research. Since the 1950s, DARPA has been particularly innovative. DARPA's most important invention, little noticed at the time, was the Internet (1969); see chapter 10.

Aircraft procurement is fairly typical. During the 1960s, the Pentagon's attempts to purchase aircraft based on paper studies produced cost overruns and disappointing performance. Since then, the Pentagon has experimented with various incentive schemes in which companies build prototypes for competitive "fly-offs." Particularly in recent years, government has rarely covered more than a fraction of the companies' development costs. Instead, parties compete for contracts that typically offer profits significantly higher (4.4%) than normal returns to capital. Conceptually, this very complicated system combines aspects of matching grants, prizes, and contests. We discuss these models further in chapters 2 and 8.

NASA provides a civilian counterpart to this basic Pentagon model. NASA's greatest successes included the Apollo moon landing (1969), weather and communication satellites (ca. 1964), and unmanned probes to Venus, Mars, and the outer solar system (1970s). All of these programs involved lavishly funded, military-style R&D with well-defined goals. Later projects such as the Space Shuttle (1980s), Hubble Space Telescope (1990s), and Space Station (2001) were notably less successful. Since the 1980s, NASA has suffered a troubling string of procurement failures, including two Shuttle disasters and billions of dollars spent on failed technologies designed to achieve low-cost access to space (the National Aerospace Plane and the X-33). Some of NASA's difficulties are probably inherent in trying to do directed research in an era of small budgets and poorly defined goals. Nevertheless, critics have widely criticized the agency's incentive structures and called for fundamental changes, including a return to prizes.

**Basic Research by Industry** At the beginning of the twentieth century, industry specialized in development and left basic research to academics. Shareholders no doubt approved, since basic discoveries rarely had any appropriable commercial value. By the 1920s, industry laboratories had

outgrown the universities that had been feeding them with scientific discoveries. Industrial laboratories spent six times more on R&D than universities did in 1930 and ten times more in 1940. These trends accelerated after World War II. Between 1953 and 1999 there was about a twelvefold increase in real R&D spending by industry, while real GDP increased less than fivefold. The fastest annual growth rates took place during the 1950s (18%).<sup>32</sup>

Industrial laboratories ended up pursuing basic research in-house rather than depending on academic research. During the 1930s, Bell Labs launched a solid-state physics program that led to the transistor, won a Nobel Prize, and opened the door to modern electronics. In the late 1930s, DuPont lured chemist Wallace Hume Carothers away from Harvard by promising to fund any polymer-related research that he wanted to do. Carothers invented nylon.

Postwar industry achieved breakthroughs in basic research such as the transistor (1948), the integrated circuit (1958), the laser (1960), high-temperature superconductivity (1986), and even relict radiation from the Big Bang (1965). These achievements required lavish R&D expenditures that could not be sustained after AT&T was broken up in 1974 and IBM lost its near monopoly over computer markets in the 1980s. By the mid-1980s, both laboratories had started to downsize and to refocus on explicitly commercial projects. It is unclear how to assess this development. On the one hand, Bell Labs' shareholders gained little or nothing when their company discovered the Big Bang. On the other hand, Bell Labs' other big postwar discovery, the transistor, made the current digital revolution possible. Will Bell Labs' diminished successors make similar transformative discoveries?<sup>33</sup>

**The Academic-Industrial Complex** Patents invaded the academy in the 1890s, largely due to the activities of Michael Pupin (d. 1935) at Columbia University, who became wealthy by patenting improvements to radio, telephones, and X-rays. Most scientists disapproved. One

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32. Most of this growth was fueled by increases in federal funding for research performed in private firms, which rose from 40 percent of industrial laboratory budgets in 1953 to 57 percent 1960. Thereafter, federal support became less important, and by the end of the century, the federal government was only funding about 10 percent of industrial research.

33. These observations hark back to Schumpeter (1942), who argued that R&D is much more likely to come from large firms with market power than from small firms.

British journal summarized prevailing sentiment this way: “Working as he does with public funds, directing as he does the minds and hands of students, it is, to say, scarcely honest [for a professor] to go with the results of such work to the Patent Office.”<sup>34</sup>

One natural way to avoid these ethical dilemmas was to use patents to support the research program itself. In 1914, a Berkeley chemistry professor named Frederick G. Cottrell founded the Research Corporation to patent university discoveries. He hoped for an endless cycle in which the corporation’s patents would fund research in universities that produced still more patents. Despite its quasi-academic mission, the corporation maximized profits as ruthlessly as any business. In particular, it did not hesitate to use its patents to create cartels (to the extent of provoking an antitrust investigation), to rank research proposals according to their moneymaking potential, and to browbeat faculty into taking out patents and spending more time on applied research. During the 1930s, the corporation devoted most of its efforts to funding atom smashers at Berkeley and half a dozen other institutions in a vain attempt to corner the medical isotopes market.<sup>35</sup>

Such excesses made many academics nervous. The Wisconsin Alumni Research Fund (WARF) tried to bridge the gap between academic and commercial mores through socially responsible investing that balanced dissemination against “reasonable royalties.” Success was hard to measure. Nevertheless, WARF managed to avoid cartels and other offensive tactics.

When foundation support for university research fell during the Depression of the 1930s, faculty began to reevaluate industry support. By 1936, nine other universities had imitated WARF’s model. By mid-century, individual scientists’ attitudes toward patents were shifting. While the average scientist still frowned on patents, this did not keep Robert Goddard (rocketry), Enrico Fermi (medical isotopes), and Leo Szilard (atomic energy) from patenting their work. Conversely, other scientists resisted patenting or else filed patents for the sole purpose of preventing others from doing so. Today, this strategy would be called “copylefting.”<sup>36</sup>

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34. The remarks were published in 1884. See Heilbron and Seidel 1989.

35. The Research Corporation would probably have succeeded if World War II had not intervened. Nuclear reactors developed for the U.S. atomic bomb project drastically reduced the cost of making medical isotopes.

36. See Heilbron and Seidel 1989. In theory, patenting should not be necessary since publication bars any subsequent patent application. However, this notion has slippage.

Academic interest in industry support faded after federal funds became plentiful during World War II. Nevertheless, some postwar universities took advantage of military research to reap both scientific and industrial benefits. The principal innovator was Stanford University, which used military electronics research contracts to develop technologies that were later used in magnetic resonance and atom-smasher experiments. The work produced several Nobel Prizes and a world-class physics program. Stanford's electronics programs also spawned several start-up companies that donated money to the university.<sup>37</sup> Stanford's leaders could rightly claim that the triangular relationship between university, industry, and the military had made each partner stronger.<sup>38</sup> In 1970, Stanford University improved on the WARF model by opening a new kind of licensing office that specialized in marketing technologies to industry.

The Bayh-Dole Act of 1980, which authorized the patenting of federally funded innovations, signaled a return to corporate alliances. University interest in patents was further accelerated by the biotechnology boom that followed shortly afterward. The Reagan administration also took steps to promote closer academic-industry cooperation as a way of promoting U.S. competitiveness in electronics and other technologies.<sup>39</sup> By decade's end, most universities had opened licensing offices on the Stanford model.

University research was a natural investment for industry. In the last half of the twentieth century, U.S. companies used between 2 and 3 percent of their R&D budgets to fund academic research. The resulting contacts helped industry monitor emerging frontiers, kept its own scientists current, and provided useful advice when in-house projects hit snags. For their part, universities created Organized Research Units to attract commercial funds, often by promising intellectual property rights to resulting discoveries. This was particularly trendy in hot new technologies like biotechnology, microelectronics, manufacturing, materials

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37. Stanford also invented the concept of a university research park. By the early 1950s, Stanford spin-offs like Varian and Hewlett-Packard were leasing space from the university. Ten universities opened research parks between 1950 and 1975. In addition to making money, the parks were supposed to promote closer interactions with industry.

38. The Stanford Research Institute was an interesting variation on this theme. Founded to do contract research that Stanford's faculty were not interested in, it became more or less self-supporting by the 1960s.

39. NSF created fourteen Engineering Research Centers by 1987. Industry contributed about one-third of the funds; the balance came from NSF. By the late 1980s the centers accounted for 3 percent of NSF's budget.

science, and artificial intelligence. Universities also signed massive research contracts with industry.<sup>40</sup> In most of these deals, industry received generous promises of intellectual property that was at least partly funded by federal sponsors.

Observers blame these deals for making academic science (and particularly biology) more secretive and patent conscious. Oddly, university patenting has not been particularly lucrative. Even a successful research institution like the University of California earned only \$13 million from patent licenses in 1999, net of licensing costs. This was less than 1 percent of the \$1.5 billion that UC researchers received from the federal government.

In retrospect, the most striking legacy of the late twentieth century was to blur the line between industry and academia. There were hundreds of start-up companies during the 1980s, such as Chiron and Genentech, which arose from university innovations. Unlike earlier generations, the faculty who founded start-ups in the 1980s and 1990s seldom left the university. Universities blurred the line further by taking equity stakes in the new companies. At the same time, the new companies focused far more on research than traditional firms did, and retained some of the character of university laboratories. By the late 1980s, most biotech firms had evolved into research boutiques where scientists pursued patentable discoveries in campus-like settings.

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40. The experience in biotechnology is particularly instructive. In 1974, Monsanto contributed \$23 million to two Harvard scientists in return for patent rights. Besides bringing in patents, the deal strengthened Monsanto's in-house laboratories and allowed the company to move its old-fashioned chemical business into pharmaceuticals and agriculture. Hoechst signed a similar \$70 million deal with the Harvard Medical School in 1984. Hoechst used the deal to strengthen its in-house biotech capabilities and to influence Harvard's research agenda in directions that favored the company. In the 1990s, Novartis gave \$25 million to UC Berkeley in return for an option on patent rights in agricultural research.

During the 1990s, large pharmaceutical companies went beyond deals with individual universities and began offering money to entire academic communities. The largest of these grant programs, a \$50 million program called The SNP Consortium, paid academics to put gene sequences in the public domain. Apart from promoting basic knowledge, the program prevented small biotechnology companies from patenting the information, which made it less likely that pharmaceutical companies would have to pay extortionate royalties if a particular sequence later turned out to be valuable.

## 1.8 Conclusion

One of the questions that arises in this chronology is whether the historical development of institutions was in any sense inevitable. As suggested by North (1981), institutions are driven by technological imperatives, but technology is also driven by institutions. Without the large federal commitment to space exploration in the twentieth century, we could not have contemplated the far side of the moon. No commercial enterprise would embark on such a thing because that type of pure science has no obvious commercial value.

The financial requirements of big science that emerged in the past century afflicted both private industry and public institutions. In such an environment, a funding mechanism like patents, which reimburses the inventor *ex post*, must do its work within institutions that can also marshal funds *ex ante*. But there is also a question of sensible decision making. Those who put up the funds have a large impact on the direction of research. Especially for science that has no commercial value, whose values should govern the expenditure of resources? For that matter, whose views on the prospects for success should be heeded? And at the political level, was it sensible for the United States to devote such a large amount of resources to space exploration when the Germans or Japanese or French might otherwise have done it? We turn to international issues in chapter 11.

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