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The Government and Innovation in the United States: Insights from Major Innovators

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The role of the U.S. government in forming innovative capabilities, at least prior to World War II, is often understated. Building on recent insights into the government's role in interchangeable parts, biological, and mineral innovation, this essay maintains that from 1820 through 1929, federal, state, and local governments developed means to acquire and spread technological knowledge that shaped technologies across wide ranges of the economy. I study biographies of 1,123 major innovators; by selecting not only inventors but also engineers and agriculturalists, I am able to identify a wider range of innovations. Governments proved significant through two mechanisms. A quarter of the innovators learned in government-funded colleges, and over half learned from government employment and contracting in ways that shaped their innovations. Both forms of learning increased over time. Government learning was more prevalent among biological, construction, transportation, and mining technologies than among mechanical technologies. Types of innovation with the greatest government impact had low patenting rates but high publication rates. The publications and employment of innovators, in turn, strengthened government-funded colleges and agencies.

Though the U.S. government has affected technological innovation in many ways, its role, at least prior to World War II, is often understated.

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Between Independence and the Depression, the federal government did shape innovational incentives through the patent system; the low cost of patenting and the thorough examination of patent claims strongly supported invention.[1] Local governments funded primary and later secondary education. But because key inventive capabilities were learned in the economy, at times supplemented by mechanics institutes or scientific societies and publications, innovation has often been interpreted as the utilization of privately formed capabilities to meet the private ends of firms and inventors. Many of the big questions concerning the roles of independent inventors, large firms, science, and research and development implicitly assume that relevant knowledge was generated within the economy and the scientific community. In such an interpretation, the government was important largely through patent laws and background conditions involving education and the rule of law, but not through forming or spreading technological knowledge.

Yet scholars have pointed to a number of cases in which the government was considerably more active. The federal armory system developed interchangeable parts firearms production.[2] War and military procurement might have driven many major technologies.[3] State and federal governments were pivotal in biological innovation.[4] The U.S. Geological Survey enabled mineral production to expand quickly and widely.[5] Big businesses actively cultivated government involvement in engineering education.[6]

These cases were not mere exceptions; even in the "laissez-faire" period of American history, the government helped form the technological capabilities of most major innovators. In the United States from 1820 through 1929, federal, state, and local governments developed

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[1] B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790-1920* (New York, 2005).

[2] Merritt Roe Smith, "Army Ordnance and the 'American system' of Manufacturing, 1815-1861," in *Military Enterprise and Technological Change*, ed. Merritt Roe Smith (Cambridge, Mass., 1985), 39-86; David A. Hounshell, *From the American System to Mass Production, 1800-1932* (Baltimore, Md., 1984).

[3] Vernon W. Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development* (New York, 2006).

[4] Alan L. Olmstead and Paul W. Rhode, *Creating Abundance: Biological Innovation and American Agricultural Development* (New York, 2008); Louis Ferleger and William Lazonick, "The Managerial Revolution and the Developmental State: The Case of U.S. Agriculture," Business and Economic History 22 (Winter 1993): 67-98.

[5] Paul A. David and Gavin Wright, "Increasing Returns and the Genesis of American Resource Abundance," *Industrial and Corporate Change* 6 (March 1997): 203-45.

[6] David F. Noble, *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (New York, 1977).

means to acquire and spread technological knowledge that shaped technologies across wide ranges of the economy. Governments proved significant through two mechanisms: funding and organizing colleges, and employing workers and contractors. As biographies of major innovators demonstrate, innovators throughout the economy learned from, built on, or participated in government organizations over the entire period, and such learning was critical to many, and important for most, innovators.

Innovators and Innovations

Appropriately structured studies of biographical dictionaries have provided significant insight into the conditions supporting or undercutting technological innovation. Though including only a modest share of the individuals who generated innovations, certain biographical dictionaries provide detailed information about a set of innovators, chosen by scholars, from across the economy regardless of whether they patented. I use dictionaries to identify innovators' education, occupations, major innovation, employment by or contracting to governments, and publication record. A separate survey identified whether innovators patented their innovations.[7]

But who was an innovator? Studies of biographies of technological innovators often focus on those classified as inventors, but other groups also innovated. I add two other kinds of technological innovators: engineers of all sorts and agricultural experts. Engineers generated knowledge that laid out canals and railways, designed engines and other machinery, discovered and utilized minerals, processed chemicals, formed alloys, and built electrical utilities. Agriculturalists developed plants and animals that could thrive in a particular climate and identified sources of diseases and strategies for mitigating them. Each developed new useful knowledge of the natural world, and in that broad sense each

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[7] Studies of major innovators, virtually by definition, cannot characterize the full distribution of innovators, and one would like comparable data for wider ranges of innovators. Broader studies suggest that, while major innovators were more highly educated than others, they participated in similar organizations and networks and had similar relations to government agencies. Indeed, innovators often became material for biographies when they were centers of networks through which they learned from other network members. Studies of particular industries show that a great many lesser innovators also learned from government agencies. Hence I expect that the conclusions of the essay apply to wider groups of innovators, though the share with government involvement will probably differ. For examples of studies of major innovators, see Zorina Khan and Kenneth L. Sokoloff, " 'Schemes of Practical Utility': Entrepreneurship and Innovation Among 'Great Inventors' in the United States, 1790-1865," *Journal of Economic History* 53 (June 1993): 289-307, and Ross Thomson, *Structures of Change in the Mechanical Age: Technological Innovation in the United States, 1790-1865* (Baltimore, Md., 2009), ch. 4.

advanced technology.[8] Doubtlessly technological innovators were wider yet, including many classified as manufacturers, farmers, and scientists. But because their activity was not as directly focused on innovation, they will not be considered here.[9] I studied each biography of those classified as inventors, engineers, and agriculturalists in the *American National Biography* and the *Dictionary of American Biography*.[10] Those who undertook no significant innovation or for whom the innovation occurred before 1820 or after 1929 were eliminated. The resulting study included 1,123 major innovators. Those classified as inventors formed 40 percent of these innovators (see Table 1). Engineers (including metallurgists) made up 46 percent; civil engineers, including sanitary engineers, construction engineers, and military engineers (who typically engaged in construction) constituted almost half of the engineers. Agriculturalists, which included horticulturalists, agronomists, and soil scientists, made up 14 percent of innovators.

The addition of engineers and agriculturalists greatly changes the composition of innovations. Inventors dominated in developing instruments (including firearms, clocks, musical instruments, measurement devices, and scientific instruments) and machinery (including agricultural, textile, sewing, metalworking, woodworking, printing, business, and other nonelectrical machines). Mechanical engineers made up most of the rest in these sectors. The same was true of power (steam and water power, along with related equipment) and transportation equipment

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[8] In practice, these groups are similar to those called “technological and applied sciences” in the *American National Biography,* which includes the three groups studied here. The major difference is that I omit groups using technologies, including farmers, ranchers, aviators, scientific instrument makers, and surveyors. Many innovators fell into more than one group, such as those classified as “electrical engineer and inventor” or “engineer and metallurgist.” In such cases, I picked the group that better characterized the person’s innovative activities.

[9] Physicians also advanced useful knowledge; a good case could be made that they too were innovators. Geologists, chemists, physicists, and biologists directly or indirectly shaped innovations; many learned from government-supported colleges and in government jobs. On the other hand, innovations by many manufacturers depended less on the government. That scientists may well have had greater government involvement but manufacturers less suggests that the inventors, engineers, and agriculturalists studied here were not extreme in their government dependence.

[10] These two dictionaries were both constructed under the auspices of the American Council of Learned Societies, and entries were chosen and written by scholars, giving them more objectivity and scholarly research than dictionaries in which the individual (or close relatives) self-reported, such as the *National Cyclopedia of American Biography*. The *American National Biography* was a successor to the *Dictionary of American Biography* and chose a somewhat different and smaller set of subjects. The *ANB* omits many fundamentally important innovators, so that using both sources provides fuller coverage.

Table 1 Content of Innovation by Type of Innovator
(%)

Innovation Type	Inventors	Mechanical Engineers	Chemical & Electrical Engineers	Civil Engineers	Mining Engineers & Metallurgists	Agriculturalists
All	40.0	8.5	8.5	21.7	7.5	13.8
Instruments	96.7	3.3	0.0	0.0	0.0	0.0
Machinery	88.1	10.7	1.3	0.0	0.0	0.0
Chemical	65.0	3.3	18.3	5.0	3.3	5.0
Transportation	56.4	33.6	7.3	1.8	0.9	0.0
Power	60.8	31.4	3.9	3.9	0.0	0.0
Electrical	37.0	5.9	57.1	0.0	0.0	0.0
Metallurgy	32.9	8.6	7.1	1.4	50.0	0.0
Mining	14.8	3.7	0.0	1.9	79.6	0.0
Construction	4.0	2.0	0.0	92.8	1.2	0.0
Biological	2.5	0.0	0.0	2.5	0.0	95.0

Sources and notes: 1,123 biographies from *American National Biography* and the *Dictionary of American Biography*. All later tables draw on these data. See text for definitions of innovation types.

(steamboats, railroads, automobile, and aircraft) innovations, where those two groups took out nine-tenths of inventions. Inventors also led in chemical invention, but chemical engineers and others contributed three-tenths of the innovations. Inventors took out only a third of electrical and metallurgical innovations; electrical engineers led in the former and metallurgists in the latter. Mining engineers led in mining innovations (which includes mineral extraction, initial mineral refining, and petroleum extraction but not petroleum refining). Finally, civil engineers and agriculturalists dominated innovations in, respectively, construction (mostly civil engineering on transportation, water and sewage, along with construction equipment) and biology (plant type, disease control, and animal husbandry). Including engineers and agriculturalists changes the composition of all innovations. Instruments, machinery, chemicals, transportation, and power, which made up 80 percent of inventors' innovations, fell to 42 percent for all innovators. Electrical and metallurgy innovations rose from 15 percent of inventors' innovations to 17 percent for all innovators. The biggest change occurred among mining, construction, and biological innovations; only 5 percent of inventor's innovations, they grew to 42 percent for all innovators. Considering innovations from all these occupations better reflects the breadth of advances in useful knowledge.

Innovators and Government-Funded College Education

From early on, governments in the United States supported college education, and that support deepened over the period studied here. Public colleges developed through three channels. First, the federal government established military colleges. The U.S. Military Academy, the most important early public institution, trained its Army graduates in military and civil engineering, including the relevant mathematics and science. Especially after the steam navigation innovations of the 1850s, the Naval Academy offered training in the physical sciences and developed a focus on steam power, iron and steel construction, and armaments. Second, various states supported colleges from early in the nineteenth century. State liberal arts colleges typically included science and mathematics. Some colleges had special purposes, including normal schools to train teachers, agricultural schools, and mining schools. Michigan led the way in creating a land-grant college for agricultural education in 1855; Pennsylvania soon followed. Finally, in 1862 the Morrill Act granted federal land to states to support agricultural and mechanical education. Some states designated existing institutions to receive the support (led by Iowa), and others created new institutions (led by Kansas). Many of these initially were agricultural colleges, but over time they typically added various engineering disciplines. Dozens of other land-grant institutions formed over the next sixty years, and by 1880 many were offering high-quality, inexpensive educations that garnered support from federal and state appropriations.[11]

Government-supported colleges supplied knowledge critical to many kinds of innovation. Science and mathematics played an increasing role in private universities before 1860, and publics followed. As the research university arose, graduate programs in the sciences and mathematics arose at leading private colleges. From the 1880s, leading publics followed suit, though only Cornell could rival the privates in the numbers of Ph.D.'s granted in the early twentieth century. Government-funded colleges took the lead in applied education. The civil engineering curriculum formed at the Military Academy and refined at Rensselaer Polytechnic became a model for such programs at land grants and state colleges. Mechanical engineering, informally taught at the Naval Institute, became the centerpiece of education at the Stevens Institute of Technology, led by the one-time Naval Academy professor Robert Thurston, who then formed the leading department at Cornell. Public

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[11] Roger L. Geiger, *To Advance Knowledge: The Growth of American Research Universities, 1900-1940* (New York, 1986); Daniel Hovey Calhoun, *The American Civil Engineer: Origins and Conflict* (Cambridge, Mass., 1960).

universities set up effective mechanical engineering programs from the 1880s, utilizing European engineering and mathematical advances and the loan of Navy engineers. By the 1880s leading land grants and state colleges such as Cornell and the universities of Michigan, California, and Wisconsin set up agricultural curricula that incorporated European advances in agricultural chemistry and entomology. The Hatch Act of 1887 accelerated agricultural education by funding state research and experiment stations housed at land-grant colleges. Mining programs at Columbia and later at the land grants formed in the same period. From the late 1880s, Columbia, Massachusetts Institute of Technology (MIT), and Cornell established electrical engineering programs that trained students in science, mathematics, mechanical engineering, and—usually late in the undergraduate curriculum—electrical theory and applications. Chemical engineering developed early in the twentieth century, also led by MIT.[12] Graduates of engineering colleges increased from about 100 per year in 1870 to 4,300 on the eve of World War I. In New York state, for which precise information exists, annual engineering degrees grew from about 80 in the 1870s (excluding the Military Academy) to 210 in the 1890s and to 830 in the 1920s, with over one-third issued to Cornell graduates from 1890 on. Civil engineers dominated initially, but by the 1920s, civil, mechanical, and electrical engineers graduated in broadly similar numbers.[13]

Innovators made good use of the knowledge that colleges provided. Over the whole period, 55 percent of innovators received a college education (Table 2). A large majority concentrated on science, engineering, agriculture, or mathematics, so that their education could have directly informed their innovation. One-seventh had graduate training. About one-tenth of innovators attended foreign colleges, but half of all innovators had at least some college education in the United States.

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[12] Stanley M. Guralnick, *Science and the Ante-bellum College* (Philadelphia, 1975); Calhoun, *The American Civil Engineer*; Geiger, *To Advance Knowledge;* Raymond H. Merritt, *Engineering in American Society, 1850-1875* (Lexington, Ky., 1969); Richard R. Nelson, *The Sources of Economic Growth* (Cambridge, Mass., 1996), 189-206; Monte A. Calvert, *The Mechanical Engineer in America: 1830-1910* (Baltimore, Md., 1967); Allan Nevins, *The State Universities and Democracy* (Urbana, Ill., 1962); Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, Md., 1983), 140-74; Olmstead and Rhode, *Creating Abundance,* 243, 257; Clark C. Spence, *Mining Engineers and the American West: The Lace-Boot Brigade, 1849-1933* (New Haven, Conn., 1970), 18-53; Robert V. Bruce, *The Launching of Modern American Science, 1846-1876* (New York, 1987), 326-38.

[13] Noble, *America by Design,* 24; Michael Edelstein, "The Production of Engineers in New York Colleges and Universities, 1800-1950: Some New Data," in *Human Capital and Institutions: A Long Run View,* ed. David Eltis, Frank D. Lewis, and Kenneth L. Sokoloff (New York, 2009), 179-217.

Government-supported colleges, including federal military academies, federal land grants, and state-funded colleges, educated 26 percent of innovators at the undergraduate level, half of the total with some U.S. college education. Government-supported graduate programs educated 10 percent of those with a college education over the whole period.

Table 2 College Education by Birth Cohort
(%)

	All	Early	Middle	Late
College-Educated	54.8	32.9	56.8	82.7
Graduate Education	14.3	0.7	13.6	34.3
Some U.S. College	50.0	30.5	52.0	74.7
Government-Supported college	26.3	12.2	24.4	48.3
Shares of College-Educated				
All Government-Supported	48.0	37.2	42.9	58.5
Military Colleges	13.7	32.8	11.9	4.8
Land Grants	27.0	0.0	22.1	46.4
State-Supported	9.2	5.1	9.3	11.3
Government-Supported Graduate	10.3	0.0	7.1	19.0

Notes: Those with at least two years in college qualify as college-educated (though the vast majority got their degree or an equivalent). Graduate education is confined to technological fields, and excludes law. Government-supported includes U.S. military colleges, state-funded colleges, and land grants. Shares of types of government-supported college can add up to more than the total because some innovators attended more than one type. Some attended colleges supported by foreign governments. Early innovators were born before 1831; middle between 1831 and 1860, and late after 1860. There were 416 early innovators, 397 middle-period innovators, and 310 late innovators.

College education became more prevalent over time, as a comparison of birth cohorts shows. Innovators are divided into three groups, those born before 1831, between 1831 and 1860, and after 1860. The share with a college education increased from 33 percent for early innovators to 83 percent for those born after 1860. The share with post-baccalaureate education increased dramatically from one percent for early inventors to 34 percent for the last cohort. Government-supported colleges played a progressively greater role, increasing from 36 percent of the college educated in the first period to 58 percent in the last period. These colleges increasingly provided graduate as well as undergraduate education; 19

percent of the college-educated in the last cohort received graduate degrees in government-supported colleges. The two land grants most attended by innovators, MIT and Cornell, were private colleges with federal support born in the early 1860s. Both established leading science departments and mechanical engineering programs, and Cornell added a leading agricultural college.[14] The steady growth of government-sponsored education masks a major shift from military to civilian education. Innovators educated at the U.S. Military Academy and U.S. Naval Academy formed 88 percent of those educated with government support for the first cohort, but only 8 percent in the last cohort. State colleges grew significantly, but the greatest change came in federal land-grant colleges, which taught nearly half of all the college-educated in the last period.[15]

Government-funded colleges varied in their importance among types of innovation (see Table 3). The share with college-educated innovators varied from one-quarter for machinery to above two-thirds for construction, metallurgy, mining, and electricity. Graduate education was most common in electricity, chemistry, metallurgy, mining, and biology. Government-supported colleges were especially important for biological, chemical, electrical, and construction innovations. Innovators from government-supported colleges made up most of the college-educated in instruments, chemicals, construction, transportation, and biology. They were less significant for machinery improvements and for changes in metallurgy and mining, which relied more on foreign universities and the Columbia School of Mines. Military college graduates concentrated their efforts on construction, transportation equipment, and instruments (especially armaments); after resigning their commissions, many officers trained at military academies became prominent civilian civil and mechanical engineers. State colleges and land grants educated innovators of all types, but they were especially significant where military colleges had little impact: in chemical and biological innovations.

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[14] Though MIT was a land-grant school and hence was included as a government-supported college, its later funding was largely private. Cornell was a hybrid; its engineering and agriculture programs received substantial state and federal funding. Much the same was true of the University of Vermont. Yale and Brown were land grants through 1893 and 1892, respectively. Thirteen innovators receiving technical degrees from these colleges between the early 1860s and the early 1890s are classified as having attended a land grant, but earlier and later students with technical degrees are not.

[15] It is of course true that college education increased for everyone, not just major innovators, and that the share educated in government-supported institutions grew for major innovators and for others. The similarity suggests that major innovators were not an elite group, removed from others, and therefore that conclusions drawn from major innovators cannot be invalidated for all innovators because of differing educational trends.

Though college education was more important for some types of innovation than others, it grew in each type over time. By the last period, seven-eighths or more of the biological, chemical, electrical, construction, and metallurgy innovators had college training, and an increasing share came from government-funded colleges. Even in machinery, two-fifths of innovators were college educated.

Table 3 College Education by Innovation Type
(%)

Innovation Type	College	Graduate	Gov't Supported	Gov't-Supported/ College	Military/ College	Civilian Publics/ College
Construction	68.3	8.8	37.8	55.3	30.6	26.5
Biological	60.6	21.3	33.1	54.6	2.1	52.6
Transportation	45.5	10.9	24.5	54.0	22.0	40.0
Mining	72.2	24.1	29.6	41.0	2.6	38.5
Power	45.1	11.8	15.7	34.8	8.7	26.1
Electrical	68.9	28.6	30.3	43.9	3.7	40.2
Instruments	31.9	5.5	19.8	62.1	31.0	31.0
Chemical	56.7	21.7	33.3	58.8	2.9	55.9
Metallurgy	68.6	27.1	18.6	27.1	2.1	25.0
Machinery	24.5	1.3	5.0	20.5	5.1	15.4

Notes: Types of innovation are listed from that with the most government involvement in education, employment, or contracts (construction) to the least (machinery).

Of course, most innovations did not result only from learning in colleges; they typically relied on learning on the job. Yet college learning affected the kinds of jobs and hence the on-the-job learning that graduates got. The occupational differences of the college-educated and others were stark, as evidenced by a comparison of the first post-degree jobs of the college-educated with the occupations of those without college education at a comparable age. Among those educated in government-supported colleges, 56 percent took jobs in engineering and scientific occupations after graduating, and 24 percent became professors, while only 5 percent made machinery or other manufactured goods. Graduates of private colleges were similar; 64 percent found engineering, scientific, or college occupations, while 14 percent took manufacturing jobs. By contrast, only 26 percent of those without college education became engineers, scientists, or professors, often early in the period, whereas 48 percent entered manufacturing occupations. And a much higher share of the college-educated got jobs in the government, so that the government helped shape both the supply of and demand for technologically sophisticated labor.

Learning from Government Employment and Contracting

From their inception, federal, state, and local governments sought improvements to better meet their needs. Military objectives were central for the federal government from its inception, and remained so episodically through the 1930s (and more persistently since then). Governments at every level addressed infrastructural needs throughout the period. State and federal governments exploited the great agricultural and mining potential of the country. In the process, innovators learned from governments. Governments often invested in response to large positive externalities, where free benefits for many thwarted private investment. They also invested where the scale of research was too great for typical entrepreneurs, which was particularly true of farmers, and targeted innovations where uncertainty was high. Where externalities, scale, or uncertainty were higher than private firms could accept, government contracts or jobs were needed to promote innovation.

Many innovators learned from their involvement in government initiatives. Government employees could use learning from government occupations to innovate while they held government jobs or afterward. Contractors could learn from interactions with government officials in ways that contributed to current or later innovation. Biographies, at times supplemented from other sources, document whether innovators had employment or contracts with government agencies from which they gained knowledge that contributed to their innovations. Employment and contracting understates the role of governments in learning, because many others learned from government publications and forums.

Learning from interactions with the government prior to or at the time of innovating was common. Over the whole period, 54 percent of the major innovators secured such learning (Table 4).[16] Two-fifths worked for government agencies on projects in which their technological learning contributed to their innovations. Another 16 percent learned from interactions around government contracts. Indeed, 19 percent of innovators learned from multiple government agencies, such as when Army engineers became city engineers or public university professors worked at

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[16] In addition to those with government learning, nearly 10 percent of innovators had employment or contracts that did not contribute knowledge relevant for their innovation (such as when a machine inventor had been employed as a surveyor) or that occurred after their innovation. I considered only interactions with U.S. governments; a dozen innovators learned from interactions with foreign governments.

agricultural research stations. Government interactions usually were not their only source of learning; employees also learned from private employment and professional organizations, and contractors typically had enough privately acquired knowledge that they could negotiate and complete contracts. But the government did contribute to their learning.[17]

Table 4 Learning from Government Employment or Contracting by Cohort
(%)

	All	Early	Middle	Late
Government Learning	54.3	49.0	56.2	59.0
Employment	40.8	36.1	44.6	42.3
Contracting	16.1	14.9	13.9	20.6
Multiple Gov't Learning	19.0	14.9	20.2	22.9
State and Local	27.8	21.2	33.5	29.4
Federal	36.3	35.3	35.3	39.0

Notes: Agricultural experiment stations were considered to be a state activity, because experiment stations were organized at the state level. Experiment work done at the national level was categorized as federal learning. The sums of employment and contracting and of state and local and federal add up to more than the total government learning because some innovators were involved both types of interactions or levels of government.

All levels of governments were sources of learning. Nearly three-tenths learned from state and local government interactions, and over one-third learned from federal government interactions. Learning was common from the beginning through the end of the period, though government-mediated learning did increase over time. For the cohort born before 1831, 49 percent learned from government employment or contracting; this share rose to 59 percent for the cohort born after 1860. Interactions with state and local governments rose especially rapidly. The share who learned from more than one government agency rose significantly; from 15 percent of all innovators among the earliest cohort, it rose to 23 percent among the last cohort.

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[17] One significance of the inclusion of engineers, metallurgists, and agriculturalists among innovators is that the role of government learning is more accurately estimated. Only one-third of those classified as inventors learned through governments, but two-thirds of other innovators learned through government employment or contracting.

Types of innovation differed greatly in their dependence on government learning. Whereas 90 percent of construction innovators benefited from government learning, only 24 percent of machinery innovators did so (see Table 5). Construction innovators learned from employment in civil engineering projects at federal, state, and local levels. Almost three-fifths of biological innovators learned from government employment, but more through states than the federal government (although after 1887 the federal Hatch Act funded state experiment stations). Most transportation equipment innovators learned from government, principally from the federal government through both employment and contracting. Almost half of mining and power innovators learned from government employment at all levels, while instrument and electrical innovators learned principally from the federal government. Metallurgy and machinery innovators were least government-connected, but two-fifths and a quarter, respectively, did learn, principally from the federal government. Unsurprisingly, sectors leading in government learning also had the largest share of innovators who learned from multiple government agencies. More interestingly, those with multiple learning sources were a larger share of all those with government learning where that learning was greatest: in construction, biology, and mining. Though shares with government learning differed among sectors, it is important to note that such learning was significant for all types of innovation. Government learning was more the norm than the exception.

Table 5 Government-Mediated Learning by Type of Innovation

Innovation Type	Government Learning	Employment	Contracting	Multiple Government Learning	State & Local	Federal
Construction	90.4	77.1	17.3	33.3	56.6	53.0
Biological	60.0	58.1	2.5	31.3	50.6	25.6
Transportation	57.3	32.7	27.3	14.5	8.2	50.9
Mining	44.4	40.7	3.7	22.2	29.6	31.5
Power	45.1	21.6	29.4	9.8	19.6	29.4
Electrical	40.3	26.9	17.6	10.9	16.8	27.7
Instruments	46.2	25.3	24.2	9.9	7.7	42.9
Chemical	38.3	26.7	13.3	13.3	16.7	30.0
Metallurgy	40.0	22.9	18.6	12.9	8.6	37.1
Machinery	23.9	10.7	14.5	5.0	7.5	19.5

The agencies through which innovators learned varied enormously by innovation type and over time. Indeed, institutional innovation within the government preceded and supported innovation. Table 6 lists the government agency or level through which innovators learned in the order of their incidence. For example the largest number of early construction innovators learned from states, then from cities, the Corps of Topographical Engineers, and the Corps of Engineers. Construction innovations were shaped by new federal, state, and city institutions. The U.S. Army Corps of Engineers was formed during the Revolutionary War to construct fortifications. It took its modern form in 1802 when the U.S. Military Academy was formed and charged with training military engineers. Such training readily applied to civil engineering. The Corps of Topographical Engineers, a body of Army officers formed in 1838 and merged with the Corps of Engineers in 1863, conducted surveys, constructed maps, and undertook internal improvements, mostly in the West. Before the Civil War, the innovations of both Army groups, usually undertaken as part of their military duties, involved topographical discoveries distributed in maps and reports, studies of rivers and coasts, river clearance, flood control, and the construction of roads, harbors, bridges, railroads, and aqueducts. For example, William McNeill joined the Corps of Engineers after graduating from the U.S. Military Academy; he surveyed railroad lines, was part of an important delegation to examine English railroads, designed eight eastern railroad lines, and wrote extensively about railroad engineering.

After the war Army engineers concentrated on large-scale water control projects, including levees, canals at Sault Saint Marie, Panama, and elsewhere, and, along with the civilian U.S. Reclamation Service established in 1902, dams and water storage and delivery systems for irrigation, water supplies, flood control, and electric power. After getting a civil engineering degree at the University of Wisconsin, John Savage became chief designing engineer for the Reclamation service and developed methods to design and build forty major dams in the West, including the Hoover Dam in the early 1930s. Innovators with federal government learning often also learned from city governments—often after Army engineers left the services—and also learned through jobs in college civil engineering departments.[18]

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[18] Calhoun, *The American Civil Engineer;* William H. Goetzmann, *Army Exploration in the American West, 1803-1863* (New Haven, Conn., 1959); Laurence J. Malone, *Opening the West: Federal Internal Improvements before 1860* (Westport, Conn., 1998); Merritt, *Engineering in American Society;* Bruce E. Seely, *Building the American Highway System: Engineers as Policy Makers* (Philadelphia, 1987). Unless otherwise noted, biographical information on William McNeill, John Savage, and all later examples come from their entries in the two surveyed biographical dictionaries.

Table 6 Agencies of Government Learning by Innovation and Period

Innovation Type	Early	Middle	Late	Others
Construction	states; cities; Corps of Topographical Engineers; Corps of Engineers	cities; Corps of Engineers; other US; states; colleges	cities; US Reclamation Service; Corps of Engineers, colleges	Bureau of Public Roads; Navy; US Coast and Lake surveys; US Geological Survey
Biological	state agriculture boards; US Department of Agriculture; colleges	state experiment stations; USDA; colleges	state experiment stations; USDA; colleges	state boards of health; US Patent Office
Transportation	Navy; other US agencies; states	Navy; other US agencies; cities	Navy; Army Air Service; cities	US Signal Corps
Mining	states	US Geological Survey; states; colleges	US Bureau of Mines; states	Navy; US Mint
Power	city waterworks; various US agencies	Navy; city utilities; colleges	Navy; Ordnance Department; cities	US Corps of Engineers; US Patent Office
Electrical	Navy; cities	Navy; other US agencies; colleges	Navy; colleges; Army Signal Corps	US Bureau of Standards; US Bureau of Weights and Measures; US Patent Office
Instruments	Ordnance Department;US Coast Survey; Navy	Navy; Ordnance Department	Navy; other US	US Bureau of Standards
Chemical	Ordnance Department	Navy; colleges; state experiment stations	US Bureau of Mines; colleges	cities; US forest and meteorology services
Metallurgy	Navy; Ordnance Department	Army; colleges; US Geological Survey	US Bureau of Mines; US Bureau of Standards; colleges	US Mint; states
Machinery	Ordnance Department; other US agencies	Navy; Ordnance Department; other US agencies; colleges	colleges	US Patent Office; US Census Office; USDA

Spurred by the great success of the Erie Canal, many state governments constructed canals, and many innovators concentrated on canal innovations. Canvass White, for instance, was employed by New York state to survey British canal technology, became chief engineer in constructing the Erie Canal, and later worked for a series of public and private canals and waterworks. States also employed innovators to build bridges and roads. Cities, at times working with county and state governments, became the biggest employers of civil engineering innovators. City engineers designed public works and hired other engineers for specific projects. Innovators developed water delivery and purification systems and sanitation and sewage improvements that had major effects on public health. One German-educated civil engineer, Rudolph Hering, surveyed Brooklyn's Prospect Park, became assistant city engineer of Philadelphia working on bridges and sewers, and, in response to epidemics in American cities, wrote on European sewage disposal methods and consulted with hundreds of cities on sanitation issues. City engineers also designed and built bridges, subways, roads, and, fostered by federal legislation in 1916 and 1921, highways. Those engaged in city construction often also learned from federal organizations, state governments, and colleges. Civil engineers also worked for railroads and other private engineering projects, but their public employment created topographical knowledge, infrastructural improvements, and public health advances that each contributed vitally to U.S. economic development.

Biological innovators did not learn as much from the federal government before the Civil War, though the U.S. Patent Office funded the collection and distribution of seeds, conducted agricultural investigations, and published on agricultural developments. Innovators on state boards of agriculture developed new types of crops, analyzed the chemistry of soil, controlled pests, imported and bred superior types of animals, and studied pests and diseases. Agricultural societies and publications provided alternative modes of developing and disseminating innovations. Only two-fifths of the first cohort learned through the government. This proportion would rise to four-fifths in the second two cohorts, led by the development of the U.S. Department of Agriculture (USDA), state experiment stations, and agricultural extension programs. Established in 1862, the USDA established divisions to undertake research in chemistry, entomology, botany, and later, animal husbandry. USDA innovators had major effects in introducing new types of fruits, grains, and flowers, advancing agricultural chemistry, adapting plants to different climates, identifying and controlling pests, improving animal husbandry methods, and understanding and controlling animal diseases. After having studied plant pathology at three land grants, David Fairchild joined the USDA Office of Plant Pathology where he studied and publicized early pesticides and later headed the Office of Foreign Plant Introduction, where he imported thousands of plant types.[19]

Agricultural experiment stations began within states, led by Connecticut and California, before being federally funded by the Hatch Act of 1887 and extended by later legislation. State experiment stations were associated with land-grant colleges and coordinated by the federal Office of Experiment Stations. Personnel in the state and federal agencies undertook innovations in soil chemistry, microbiology, entomology, and animal husbandry, which fought disease and pests, developed new products, and improved public health. Like many others, Stephen Babcock combined affiliations. After studying chemistry at Cornell and abroad, he became a professor of agricultural chemistry at Wisconsin and chief chemist at the state's agricultural experiment station. He devised a simple test to measure the butterfat content of milk, which increased purity (a USDA goal), reduced adulteration, and enabled selective breeding to increase the milk and butterfat productivity of herds. He later improved pasteurization methods and discovered the importance of vitamins in animal diet. Babcock illustrates a more general characteristic; over half of the biological innovators learned from multiple government institutions, typically combining the USDA, state experiment stations, and colleges. Government networks transferred knowledge in an organized way through publications and offices of cooperative extension. Such diffusion differed from the informal diffusion of most private networks; innovations almost surely spread more rapidly as a result. Government-mediated innovation was an essential reason why agriculture was one of the great successes of post–Civil War economic development.

Mining followed a quite similar trajectory, with states leading the way before the Civil War and the federal government forming national organizations afterward. Before the war, states organized geological surveys attempting to discover mineral wealth. For instance, John Carll, working with the Pennsylvania Geological Survey, identified and published definitive accounts of the geological structure of the oil regions. The U.S. Geological Survey (USGS), formed in 1879, undertook to survey the geology and resources of the West. Innovators in its employ identified locations of mineral and petroleum deposits, developed methods of deep level mining, and improved the smelting of iron, lead, copper, silver, and gold. One USGS worker, Samuel Emmons, completed valuable work on the geological determinants of the distribution of metal ores. Innovators at the U.S. Bureau of Mines, formed in 1910 to explore mining technology and safety, developed testing methods and techniques to mine phos-

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[19] Olmstead and Rhode, *Creating Abundance*; Ferleger and Lazonick, "The Managerial Revolution and the Developmental State"; Wayne D. Rasmussen, *Taking the University to the People: Seventy-five Years of Cooperative Extension* (Ames, Iowa, 1989); Vernon W. Ruttan, *Agricultural Research Policy* (Minneapolis, Minn., 1982).

phates, potash, and coal. Others developed rock-drilling and refining equipment without government support. Half of the mining innovators with government learning combined multiple organizations, including state surveys, colleges, the USGS, and the Bureau of Mines. The USGS became a leading applied science organization vital to the postbellum emergence of the United States as a mineral-rich country.[20]

The Geological Survey and Bureau of Mines also trained metallurgical innovators who applied microscopic and other techniques to develop alloy steels and smelt various metals. They were joined by innovators trained at the National Bureau of Standards, formed in 1901, such as Paul Merica, who used microscopes to study the crystalline structure of alloys and who developed new alloys. A metallurgist of the U.S. Mint generated new methods to analyze gold and silver. The military played a bigger role than it had in mining. From the Civil War, the Navy sought to develop superior armor plating methods, and innovators responded. The Navy required means to fabricate large machinery with precision, which fostered innovation in heavy metalworking methods, including Frederick Taylor’s development of high-speed steel. Army contracts in the Civil War led to improvements in iron and zinc manufacturing. Later Army contracts led innovators to develop new alloys and casting and welding methods.[21]

The Navy was the key government agency in transportation equipment innovation. Many naval officers and private firms developed steam-driven, iron ships around the Civil War. When the Navy produced new warships from the 1880s, Navy and civilian innovators developed engines, boilers, propellers, and submarines. About half of the twenty-eight ship innovators educated through Navy interactions were Navy officers, including Charles Loring, who led the transitions from wood to iron to steel construction powered by simple and then compound steam engines. Those trained in the Navy also invented aircraft and electric

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[20] David and Wright, “Increasing Returns and the Genesis of American Resource Abundance;” Karen Clay and Gavin Wright, “Gold Rush Legacy: American Minerals and the Knowledge Economy,” in *Property in Land and Other Resources*, ed. Daniel H. Cole and Elinor Ostrom (2011); Spence, *Mining Engineers and the American West;* Thomas G. Manning, *Government in Science: The U.S. Geological Survey, 1967-1894* (Lexington, Ky., 1967); Ronald H. Limbaugh, “Making Old Tools Work Better: Pragmatic Adaptation and Innovation in Gold-Rush Technology,” in *A Golden State: Mining and Economic Development in Gold Rush California,* ed. James J. Rawls and Richard J. Orsi (Berkeley, Calif., 1999), 24-51; Harold F. Williamson, Ralph L. Andreano, Arnold R. Daum, and Gilbert C. C. Klose, *The American Petroleum Industry: The Age of Energy, 1899-1959* (Evanston, Ill., 1963), 44-48.

[21] Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865-1925* (Baltimore, Md., 1995), 91-132; Benjamin Franklin Cooling, *Gray Steel and Blue Water Navy: The Formative Years of America’s Military-Industrial Complex* (Hamden, Conn., 1979).

railways. The Army advanced aircraft and tank development. Civilian wings of governments also improved transportation. The federal government employed innovators who developed life-saving equipment and snag-removing boats. City governments worked on subway design. However, government learning played only a modest role in railroad and automobile equipment innovations. Power innovations often were linked to transportation improvements. Naval officers and contractors developed marine engines, boilers, and governors; their ranks included Francis Parkinson, the Westinghouse worker who adapted steam turbines to power naval vessels. Henry Worthington and Edwin Reynolds applied their steam engineering prowess to pumps for urban waterworks.[22]

The military also provided sources of learning for electrical, chemical, instrument, and machinery innovations. Both the Navy and the Army Signal Corps invested heavily in radio technologies and undertook experiments in their own labs, fostering innovations for public and private use. Radio and vacuum tube companies commonly had Navy links. The Navy also trained innovators through submarine detection research. Chemical innovators learned by supplying gunpowder and other explosives, ammonia, nitrogen, acetone, and gas masks and by conducting research on aluminum production and aerial torpedoes. The military was central to instrument innovations, largely firearms and other weaponry. The Army Ordnance Department developed some weapons and contracted with innovators for others. The Navy and its contractors developed torpedoes, range finders, and gyrostabilizers for ships. The military also purchased goods ranging from condensed milk to artificial limbs and developed methods for deep sea sounding. Finally, the military had basic effects on machine tool and metalworking machinery. The system of federal armories and contracting established by the Ordnance Bureau early in the nineteenth century was essential in developing interchangeable parts metalworking and woodworking machines, and Civil War contracting spread that system. These methods led to the interchangeable parts mass production system made famous by Henry Ford in the early twentieth century.[23]

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[22] Calvert, *The Mechanical Engineer in America,* 19-23; 245-62; Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York, 1989), 96-137; Louis C. Hunter, *A History of Industrial Power in the United States, 1780-1930,* vol. 2: *Steam Power* (Charlottesville, Va., 1985), 509-93.

[23] Calvert, *The Mechanical Engineer in America;* Hughes, *American Genesis;* Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y., 1977); Merritt Roe Smith, “Army Ordnance and the ‘American System’ of Manufacturing”; Hounshell, *From the American System to Mass Production;* Hugh G. J. Aitken, *The Continuous Wave: Technology and the American Radio, 1900-1932* (Princeton, N.J., 1985).

But the civil arms of government also contributed to innovator learning in these fields. Federal contracts fostered Samuel Morse's telegraph and the transcontinental telegraph. Scores of professors learned through their teaching and research in land-grant and state colleges in ways that informed innovation of every type; they were especially important in chemical and electrical innovations, often also working with federal military or civilian agencies. For example, Arthur D. Little explored paper manufacturing for the Forest Service, and Melville Scovell advanced fertilizer chemistry for the Department of Agriculture and state experiment stations. The U.S. Coast survey, formed in 1807 and renamed the U.S. Coast and Geodetic Survey in 1878, used its broad responsibilities to train a dozen innovators who developed methods of deep sea sounding, longitude measurement, hydrometers, cameras, pyrometers and other scientific instruments. When working for the Patent Office after compiling statistics and writing an essay for the Census of 1880, the Columbia School of Mines graduate Herman Hollerith developed his tabulating machine for use in the Census Department; International Business Machines would develop out of his efforts. State and local governments occasioned other changes. Municipal lighting experience trained innovators. Chemical engineers sold nitroglycerin for state construction projects and developed chlorination methods for city water supplies. City work on aqueducts led to innovations in pipe manufacturing.

The importance of military learning in many sectors raises the question of whether the military led the innovation process. Biographical dictionaries illuminate three dimensions of the issue: whether innovators held military occupations when they learned from government interactions, whether military learning acquired by interacting with military agencies contributed to innovation, and whether innovation was occasioned by wartime conditions, whether or not innovators learned from the military. In each dimension military and war-related innovators were a distinct minority among those with government-mediated learning, and much more so among all innovators. Civilians dominated government learning; they made up 87 percent of those learning from government-mediated interactions, while 19 percent had military occupations (and 6 percent had both; see Table 7). Military occupations were most significant for construction, where the Corps of Engineers and the Corps of Topographical Engineers led the way. They were almost as important in transportation, led by Navy officers, and in instruments, dominated by Army and Navy armament innovators. At the other extreme, only one plant and livestock innovator and no mining innovator had learned in the military. Because virtually all those who did not learn from the government were civilians, those with military occupations made up only 11 percent of all innovators. Nonmilitary occupations clearly led learning among innovators.

Table 7 Military and Civilian Learning by Type of Innovation
(shares of inventors with government learning, %)

Innovation Type	Military Occupation	Civilian Occupation	Military Learning	Nonmilitary Learning	War-Related	Not War-Related
All	19.3	87.0	28.2	81.0	17.9	90.0
Construction	30.7	77.8	9.3	98.2	9.8	93.8
Biological	1.0	100.0	0.0	100.0	0.0	100.0
Transportation	28.6	84.1	74.6	38.1	38.1	85.7
Mining	0.0	100.0	4.2	95.8	4.2	100.0
Power	13.0	95.7	43.5	65.2	17.4	91.3
Electrical	12.5	93.8	50.0	66.7	16.7	95.8
Instruments	26.2	81.0	66.7	47.6	33.3	73.8
Chemical	17.4	87.0	26.1	91.3	43.5	69.6
Metallurgy	7.1	96.4	50.0	71.4	39.3	75.0
Machinery	10.5	92.1	55.3	57.9	39.5	76.3

But the military still could have led if military learning, defined to be learning about military matters gained in military agencies, resulted in innovations.[24] Innovators with military learning made up 28 percent of those with government-mediated learning, led by innovators in machinery, instruments, and transportation equipment, in each case typically involving the design of military equipment. But 81 percent of innovators acquired nonmilitary knowledge in their government interactions. Moreover, only one percent of innovators with government learning learned solely from military interactions; all the rest learned from civilian government or private interactions. Interestingly, only about half of the innovators in the military had their innovations affected by military-related learning; many more concentrated on infrastructure, led by the army engineers and topographers. In this way, one major contribution of the military was civil, its goal to foster economic and political development. About 18 percent learned from government inter-

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[24] By this definition, Corps of Engineering officers could gain military learning relevant to their innovations if they interacted with officers in building fortifications but not when interacting with civilians laying out a railroad line. Dual-use technologies developed for the military, such as aircraft, radios, and ships, were classified as involving military learning but not non-military learning, even though the learning had civilian spillovers, because the initial purpose was military.

actions about war-related issues, principally in the Civil War and World War I. These wartime interactions included military provisions, but also the supply of chemicals, shoes, and knapsacks. But the vast majority interacted with the government around issues unrelated to wars. At least in terms of the frequency of its interactions with major innovators, the government's greatest contribution to innovation came outside wars and military uses.

By some measures, government learning became less military over time. The share of those with military occupations fell from 29 percent for the earliest cohort to 9 percent for the last (see Table 8). Military learning did increase over time, growing from 27 percent for the earliest cohort to 36 percent for the latest. The trend reflected an upsurge after 1890 not only of armaments but also of three dual-use technologies—radio, aircraft, and ships—technologies in which innovators also learned outside the government. Also reflecting the growth of dual-use technologies, those with nonmilitary government learning fell modestly. Innovations occasioned by wars fell from 23 percent of innovators in the first cohort (dominated by the Civil War) to 17 percent for the last cohort (dominated by World War I).

Table 8 Military and Civilian Learning by Cohort (%)

	Early	Middle	Late
Military Occupation	28.9	18.8	9.3
Civilian Occupation	80.9	87.0	94.0
Military Learning	27.0	22.9	36.1
Nonmilitary Learning	82.4	83.9	76.0
War-Related	22.5	14.3	16.9
Not War-Related	86.3	92.4	91.3

The development of some dozens of federal agencies, scores of state universities and land grants, and hundreds of city engineering departments were institutional innovations of the first order. These agencies pursued different goals—agricultural expansion, mineral discovery, infrastructural improvement, public health, public safety, national security, and more—but they all supplied organization that shaped the generation and spread of knowledge. Some agencies were linked to others, notably the USDA, state experiment stations, and land-grant colleges. Though most agencies were independent, they did learn from each other. Cities and states emulated the successes of their peers. The federal government often expanded on state precedents. These institutional innovations, like those in college education, had very large effects on economic development.

Government-Mediated Paths of Innovation

Governments structured quite distinctive paths of innovation. They had some degree of centralized direction; even in the case of experiment stations, to which the USDA delegated decision-making powers, the USDA reviewed the activities of the stations, limited the kinds of expenditures of federal funds, and established its own regional research stations. Civil wings of governments often made their innovations public through publication and demonstration; this was an expressed goal of the USDA, the USGS, and other bodies. Of course, private paths also shared knowledge through cross-firm cooperation (railroads), patent pooling (sewing and electrical machines), patent licensing, trade associations, and most generally worker mobility. But firms typically retained a competitive rationale to limit knowledge diffusion.[25]

The distinctiveness of government-mediated paths of innovation led to different patenting and publication behavior between those employed by governments and those employed privately. Thirty-seven percent of innovators learned from government jobs over the course of their innovation, though over half of them also learned from private jobs (see Table 9). Innovators learning from government jobs rose from 33 percent for the first cohort to 37 percent for the last. The large and increasing role of government innovators at least qualifies the common view of the preeminence of private innovation.

Public innovators differed from their private counterparts in the manner in which spread knowledge of and gained returns to their innovations. They relied much less on patenting. Only 41 percent received any patents in their innovation, compared to 79 percent for private innovators. Private innovators who secured government learning, most of whom were contractors, patented at similar rates to other private innovators, so that working for the government seems to have been the differentiating factor. Whereas the share of private innovators taking patents increased from 72 percent of the earliest cohort to 85 percent of the last, the share of public innovators patenting remained basically constant throughout the period.

Moreover, public innovators were much more active publishers. Sixty-six percent of them published books or articles containing technological knowledge related to their innovation, far above the 42 percent of others with government learning who published and the 37

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[25] On paths of private innovation, see Thomson, *Structures of Change in the Mechanical Age;* Steven W. Usselman, *Regulating Railroad Innovation: Business, Technology, and Politics in America, 1840-1920* (New York, 2002); Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (Princeton, N.J., 1997); Petra Moser and Ryan Lampe, "Do Patent Pools Encourage Innovation? Evidence from the 19th-Century Sewing Machine Industry," *Journal of Economic History* 70 (Dec. 2010): 898-920.

Table 9 Employment, Patents and Publications by Cohort (%)

	All	Early	Middle	Late
Share of Innovators				
Public Employment at Innovation	36.7	33.4	39.8	37.1
Others with Government Learning	17.6	15.6	16.4	21.9
Without Government Learning	45.7	51.0	43.8	41.0
Share with Patents				
All	65.3	61.9	65.8	69.4
Public Employment at Innovation	41.0	41.7	38.9	43.2
Others with Government Learning	83.6	79.7	81.3	90.2
Without Government Learning	78.0	69.8	84.5	82.8
Share with Technical Publications				
All	48.4	38.5	52.4	56.8
Public Employment at Innovation	65.5	54.7	72.8	68.7
Others with Government Learning	42.4	26.2	43.1	57.4
Without Government Learning	37.0	31.6	37.4	45.7

Sources and notes: Patent data is for 1,104 innovators; 19 were excluded because identification was ambiguous or because patenting began after 1929. For publication sources, see Table 1. Patents were surveyed from Google Patents, LexisNexis Academic, and the annual reports of the U.S. Commissioner of Patents.

percent of those without government learning. Innovators with public employment were more like scientists spreading knowledge through open sources. This was particularly true of professor-innovators at land grants and state colleges; 79 percent of them published and 42 percent patented in their innovation. But this was also true of other public employees; 58 percent of them published and 40 percent patented. Both public and private innovators published more over time.[26]

The patenting and publication behavior of public innovators is partly attributable to the kind of innovations they undertook. Two-thirds of the

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[26] Because 58 percent of innovators with public jobs also learned from private employment, their innovations were not the results of public learning alone. Government workers who also learned from private jobs over the course of the innovation had somewhat higher patenting rates than those who learned only from public jobs—48 to 32 percent—but virtually identical publication rates. The differences in patenting rates resulted from two factors. Among construction innovators with government employment, higher patenting rates are explained in part because bridge and construction equipment innovators, who had higher patenting rates than other civil engineering innovators, were more likely to have also worked privately. Outside construction, innovators with both public and private learning concentrated in sectors with high patenting rates.

public innovators concentrated on construction and biological innovations. These two types had the lowest shares of innovators with patents in their innovation; only 40 percent of construction innovators and 11 percent of biological innovators received patents (see Table 10).[27] Innovators in these sectors and in mining were the only groups for which under four-fifths received patents. Where patenting was limited, publication was strong.[28] Biological innovators, with the lowest patenting share, had the highest publication share. Construction and mining innovators also published extensively; only electrical innovators published more.

Table 10 Employment, Patents, and Publication by Type of Innovation (%)

Innovation Type	Patentee Share	Patentees, Public Jobs	Patentees, Other Gov't Learning	Patentees, No Gov't Learning	Technical Authors	Authors, Public Jobs	Authors, Other Gov't Learning	Authors, No Gov't Learning
Construction	40.4	34.6	52.8	66.7	53.8	56.9	51.4	33.3
Biological	10.6	11.5	11.1	9.4	78.8	85.1	77.8	70.3
Transportation	86.4	53.8	100.0	95.7	33.6	48.1	36.1	23.4
Mining	45.3	31.6	50.0	53.3	63.0	84.2	40.0	53.3
Power	98.0	100.0	100.0	96.4	37.3	50.0	33.3	35.7
Electrical	94.9	90.9	96.0	95.7	66.4	68.2	73.1	63.4
Instruments	92.3	95.0	100.0	87.8	27.5	60.0	18.2	18.4
Chemical	79.3	50.0	81.8	88.6	43.3	66.7	54.5	32.4
Metallurgy	84.1	75.0	93.3	83.3	51.4	84.6	40.0	45.2
Machinery	91.1	68.8	100.0	92.5	17.6	62.5	13.6	12.4

Why did patenting shares vary so much? Biological, mining, and construction innovators had lower patenting shares among public employees, among others with government learning, and among those without government learning, suggesting that it is an attribute associated with the technology. These three types of technology each involved

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[27] Moreover those biological innovators who patented did so infrequently, averaging only three patents. Collectively biological patentees had one-fifteenth as many patents as Thomas Edison had.

[28] The uneven incidence of patenting among innovations does suggest that patents cannot be taken as the sole measure of innovation; to do so would overemphasize mechanical technologies and underestimate biological, construction, and mining technologies. On the relation of patents and innovations, see Petra Moser, "How Do Patent Laws Influence Innovation? Evidence from Nineteenth-Century World's Fairs," *American Economic Review* 95 (Sept. 2005): 1214-36, and Olmstead and Rhode, *Creating Abundance*.

geographically specific factors: local soil types and climate, local geological features, and local features shaping construction such as the terrain, geological composition, and the breadth, depth, and flow of rivers. Much innovation had to do with adapting general knowledge to these specific conditions. Such innovations were hard to patent or, in the case of new plant types, impossible to patent until the Plant Patent Act in 1930. In such cases, innovators gained returns through their reputations, which were bolstered by their publishing. The point can be reinforced by comparing types of innovations used by the same people. Whereas only 11 percent of biological innovators patented, 91 percent of agricultural machinery innovators patented, and only 9 percent published. Construction innovators can be divided into those undertaking civil engineering improvements and others designing more readily patentable construction equipment such as bridges, elevators, and concrete-making methods. Only 27 percent of the former patented, whereas 76 percent of those developing equipment patented.

However, the public or private character of the job still mattered. Within all but one innovation type, those with public jobs published more than others, and within seven of the ten types, the share patenting among innovators with public jobs was smaller than among than those with private jobs. Public employment generated innovations, the results of which were published more and patented less. Such innovators with public employment provided research used in government-supported colleges, which increased the value of and demand for college education.

Education, Government Learning, and Innovation

Government-sponsored colleges and government jobs or contracting were important avenues to learning throughout the nineteenth and early twentieth century and became more significant over time. Over the whole period, 60 percent of major innovators either attended a government-supported college or learned from government contracts. The share with either kind of government learning increased over time from 50 percent of the innovators born through 1830 to 61 percent for those born between 1831 and 1860 to 73 percent for those born after 1860. Indeed, many innovators followed both avenues; 20 percent learned from government-supported colleges and from public jobs or contracts, and the share rose from 11 percent of the earliest cohort to 33 percent of the latest. The growth of government-mediated learning derived in considerable part from the flourishing of land-grant and state universities from the 1880s, the development of the Department of Agriculture and experiment stations, the research of the U.S. Geological Survey, and the infrastructural efforts of cities and the Corps of Engineers. Government-mediated learning was important in the period when the U.S. caught up with England, and it was even more vital when the U.S. diverged from England after 1890.

Learning in public colleges and in public jobs complemented and reinforced each other. Learning in colleges led to occupations that disproportionately involved government learning and innovation. Of those educated in land-grant, military, and state colleges, 77 percent learned from post-college government interactions in ways that affected their innovation (see Table 11). Ninety-five percent of those educated in military institutes later learned from government interactions, because most were commissioned as Army Engineers, Topographical Engineers, or as naval engineers or designers. But upon resigning their commissions, they often continued to learn from government interactions and contracts. Seventy percent of those who learned in land-grants and state universities took occupations and contracts in which they learned from government interactions. Furthermore, three-eighths of graduates of government-sponsored colleges—and half of those with government learning—secured useful knowledge from more than one kind of government agency, and this density of government learning contributed to their innovation. Private learning also contributed. Some five-eighths of government-sponsored college graduates learned through private occupations, which frequently generated knowledge that led to public employment. Three-eighths combined government and private learning in their innovation, whereas about the same share did not rely on private learning.[29]

Public university graduates were more likely than other innovators to gain innovation-supporting government learning, and among those gaining such learning, the share of learning from more than one government agency was higher. Of those educated in private colleges, 57 percent came to learn from government agencies before innovating, and 33 percent of those with government learning acquired knowledge through multiple government channels. By contrast, only 39 percent of those without a college education learned though government interactions, and 20 percent of them learned through multiple channels. That so many without college did secure later government learning, and did so throughout the period, implies that there were other ways to acquire government jobs or contracts. Private learning supplied knowledge that could lead to government learning. For example, the Navy made a practice of hiring engineers from those who had made machines or worked on engines in the private sector.[30] The share with private learning was highest for those without college, for whom all but 5 percent acquired knowledge informing their innovation in private occupations. In addition, many learned in mechanics' institutes, engineering societies, and other civil organizations.

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[29] In addition to government and private learning, innovators could also learn through not-for-profit jobs. About 4 percent of innovators had such jobs, mainly in private colleges.

[30] Calvert, *The Mechanical Engineer in America,* 21-22.

Table 11 Government-Sponsored Education and Government Learning (%)

	Government-Sponsored College	Other College	No College
Government Learning	77.1	57.2	39.5
Multiple Government Learning	38.6	18.9	7.8
Private Learning	61.8	88.4	95.5
Both Government and Private Learning	38.9	45.9	35.0
Public Employment at Innovation	63.5	39.0	19.9
Author	62.8	62.6	31.4
Professor	38.9	26.1	3.3
Professor, Government-Supported	33.4	11.9	2.5
With Other Government Learning	77.6	71.1	61.5
Authors	79.6	84.2	69.2

Note: Data on professors in government-sponsored colleges includes one who became a professor after his innovation had been completed.

Government-sponsored colleges were especially effective at providing access to public employment. Trained at land-grants, public colleges, and military academies with scientific and, for some, agricultural and engineering programs, graduates were prepared for positions in various engineering disciplines and in agricultural research and extension. The 63 percent who held government jobs when they undertook their innovations was far above the 39 percent with public employment among other college graduates and the 20 percent with such employment for innovators without a college education. Public colleges, city and state governments, the Department of Agriculture and state experiment stations, Army engineers, the Army Ordnance Department, the Navy, and the U.S. Geological Survey were the greatest sources of learning. But graduates of government-sponsored colleges were more likely to learn from government interactions even without public employment at the time of their innovation; the 37 percent who did so exceeded the 30 percent gaining government learning among privately employed private college graduates or the 24 percent for privately employed non-college graduates.

Innovators also provided knowledge that enabled others to use innovations or innovate themselves. Their innovations were sources of learning, as firms or government agencies spread them and trained people to use them. In addition, over three-fifths of college graduates, both public and private, published articles and books on technologies connected to their innovations, and some exceeded a hundred publications. The publications included widely read texts and reference books that taught readers about state-of-the-art technologies. College mattered for publication; only three-tenths of those without a college education published.

Finally, innovators surprisingly often spread knowledge as professors. Nineteen percent of all innovators taught for at least a year in a college after completing their own education; many taught for decades. Thirteen percent taught in land-grants, military colleges, and state-supported colleges. Almost two-fifths of innovators graduating from government-sponsored colleges became professors, well above innovators who attended private colleges and far above those without a college education. Fully a third of innovators educated in government-sponsored institutions became professors in such colleges, three times the share of those educated in privates and over ten times the share without college education. Over three-quarters of professors in government-funded colleges gained other government learning related to their innovation, somewhat above the share of professors in such colleges from other backgrounds. And professors at public colleges from all backgrounds published extensively. Their learning on the job contributed to their innovations and the innovations of others.

The innovation process was propelled by positive feedbacks among government learning, education, and innovation. Just as government-supported education and government-mediated learning contributed to innovation, so innovation deepened education and government learning. Successful innovations were incorporated into educational curricula at public and private colleges, increasing the usefulness of that education. Innovators' publications and college instruction both contributed to this education, as did the research and teaching of other professors. Successful innovations also validated the agencies spreading them, often leading to their growth. Biological innovations, for example, proved so valuable that the federal government funded state experiment stations and then agricultural extension, and learning in those organizations added to innovation. At the same time, innovating firms and government agencies created a demand for educated labor, sustaining the growth of private and especially public colleges.

Of course, many innovations occurred with little government-mediated learning. The classical examples of the largely private processes developing the harvester, the sewing machine, the automobile, or the light bulb attest to the significance of these private processes. Yet the surprising breadth of government-mediated learning suggests that government activities were essential contributors to overall innovation. The government's effects were greater yet, because government-trained innovators spread knowledge to others, who hence indirectly learned from governments. The patent system itself was a mode of educating inventors through publications of patent digests and journals. Public innovation often complemented private innovation, such as when biological innovations increased returns on agricultural machinery innovations or when resource discovery supported metallurgical advances.

To get a sense of the importance of government-mediated innovation, consider several features of the U.S. economy that had propelled it to world leadership by 1900 and extended that lead by 1929. That economy was characterized by Fordist mass production with interchangeable parts in some sectors, an unmatched home market, intensive use of minerals and petroleum in production and transportation, a highly productive agriculture sector, advanced science-based industries, a healthy population, and high levels of education. Government-mediated innovation shaped each attribute: innovations utilizing government-supplied knowledge developed interchangeable parts metalworking, transportation improvements integrating the market, mineral discovery and refining, crop and livestock protection and improvement, metallurgical, electronic, and aircraft developments, public water supply and sanitation, and an unmatched educational system. These innovations proved essential, perhaps even indispensable, for the ascendance and then world leadership of the U.S. economy.