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Government-Led Innovation in a Period of Small Government: The United States, 1820 to 1941

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In conventional interpretations, U.S. technological innovation was overwhelmingly private before 1941. Building on studies of biological and mineral innovation, I utilize historical biographies to contend that from 1820 through 1941, the government targeted, structured, and undertook technological innovations across wide ranges of the economy. Fifty-six percent of 1,336 major innovators learned from government employment and contracting in ways that shaped their innovations. State and local governments were almost active as the federal government. Such innovation concentrated in civilian uses. Studies of the USDA, the USGS, urban water-supply agencies, and land-grant colleges reveal how small government generated so much innovation.

Scholars recognize that governments in capitalist economies shaped innovation in the period of Big Government and Big Science, led by the United States during and after World War 2. But the earlier role of government in the United States has received much less attention. To be sure, the antebellum case of interchangeable-parts firearms has been well documented, and other military improvements in weaponry, metallurgy, and aircraft have been noted. But in the broad realms of the civilian economy, the literature implicitly holds that inventive capabilities were largely private and the government played little role in targeting and organizing innovation. And why not, when as late as 1902 U.S. governments at all levels formed eight percent of GDP?[1]

There are good theoretical reasons for focusing on the government in analyzing innovation. In his well-known analysis, Kenneth Arrow argues that firms in a purely competitive capitalist economy will underinvest in technological change because of difficulties appropriating the returns, the uncertainty of profits from innovation, and scale economies of research that may put projects beyond firms' financial means.[2] When private firms invest too little in innovation, the government can support innovation in two ways. It can create conditions for private firms to innovate. Scholars recognize that between independence and the Depression, the federal government shaped innovational incentives through the patent system; the low cost of patenting and the thorough examination of patent claims strongly supported invention. Local governments funded primary and later secondary education, adding to the capability to innovate and diffuse innovations.[3] In the era of small government, these indirect roles of government might appear preeminent. Yet there is another possibility: the government itself could have organized and

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[1] For an earlier version of parts of the first half of this paper, see Ross Thomson, "The Government and Innovation in the United States: Insights from Major Innovators" in *Business and Economic History On-Line,* Fall 2012. Parts of the first two sections of this paper draw on that article.

[2] Kenneth Arrow, "Economic Welfare and the Allocation of Resources for Invention" *The Rate and Direction of Inventive Activity: Economic and Social Factors* (Princeton, 1962): 609-625.

[3] B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790-1920* (Cambridge, 2005); Claudia Goldin, "The Human-Capital Century and American Leadership: Virtues of the Past," *The Journal of Economic History*, Vol. 61, No. 2 (June, 2001):263-292.

conducted technological innovation. Whereas firms might not have been able to appropriate, finance, and face the uncertainty of innovation, the government could. It might directly produce or contract to produce public goods including widely usable knowledge.

There are also strong empirical reasons for focusing on governmental innovation. After 1941, the government's role in innovating has been documented. A U.S. innovation system was formed in which the government—largely the federal government—was essential to such core technologies as jet aircraft, computers, radar, the internet, and global positioning systems.[4] In these cases, military innovation and its civilian spillovers were central to the system. Contracting firms played a central role, at times the decisive role.[5]

The case is less clear before World War 2, when the government was much smaller and less science-focused. Scholars have pointed to a number of cases in which the government was active. The federal armory system developed interchangeable-parts firearms production.[6] State and federal governments were pivotal in biological innovation.[7] The U.S. Geological Survey enabled mineral production to expand quickly and widely.[8] Big businesses actively cultivated government involvement in engineering education.[9]

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[4] For the idea of an innovation system and the distinctive government role in the post-1941 system, Richard R. Nelson, ed. *National Innovation Systems: A Comparative Analysis.* New York: Oxford Univ. Press, 1993; David C. Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change in 20th Century America* (Cambridge: Cambridge University Press, 1998), chapter 2. For a good statement of the centrality of the governments to post-World War 2 innovation, see Mariana Mazzucato, *The Entrepreneurial State Debunking Public vs. Private Sector Myths* (London, 2013).

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

[6] 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, 1984).

[7] Alan L. Olmstead and Paul W. Rhode, *Creating Abundance: Biological Innovation and American Agricultural Development* (Cambridge, 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.

[8] Paul A. David and Gavin Wright, "Increasing Returns and the Genesis of American Resource Abundance," *Industrial and Corporate Change* 6 (March 1997): 203-245.

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

Yet how important were these cases? Not only was governments small, but its employees—largely federal military, postal, and clerical workers and state and local infrastructural and educational workers—had few evident inventive capabilities. The government's greatest role could have been indirect, by forming an effective patent system. The conventional wisdom would be on the mark if the private economy, supplemented by intellectual property rights and civil organizations, supplied needed knowledge and incentives for the vast majority of innovations without any learning beyond basic education from governmental bodies. The rise of large oligopolies and the growth of scientific and engineering associations after 1880 might have provided conditions for firms to fund expensive R&D labs and appropriate returns from innovations, so that government involvement in innovation could have diminished over time. And, furthermore, even if the government mattered, did it do so in the same way as during and after World War 2?

Yet even in the small government period of American history, the government was deeply involved in innovation. As biographies of 1,336 major innovators demonstrate, innovators throughout the economy learned from, and often in, governmental organizations throughout the 1820 to 1841 period, and such learning was critical for many innovators. Not only did it supply incentives and background conditions, but, as this paper contends, it helped form the technological capabilities and inventive targets of most major innovators. From 1820 through 1941, all levels of government—not only the federal government—acquired, developed, and spread technological knowledge that shaped technologies across wide ranges of the economy. Government contractors innovated, but government employees were much more common. Civilian technologies were especially important. Our understanding of technological change in an era of small government must be revised to reflect the centrality of governmental activity.

If the government was a critical source of learning for many innovators, a second question must be asked: why was it so important? Economists often turn to positive externalities and public goods to explain lagging private activity, and these factors were at work. But the presence of market failures did not ensure that governments could succeed. I will argue that the government formed hundreds of agencies that structured innovation, secured and developed inventive capabilities, and formed networks through which innovations and knowledge of them spread widely. In this way, organizational innovations by the government sustained ongoing technological innovation.[10]

Methods and Data

Biographical dictionaries comprise the primary source for examining the role of the government in innovation. Case studies are essential to understanding the generation and spread of innovations, but they offer no way to measure the extent of government involvement. Patents offer quantitative evidence, but the quality of patents vary, and—more importantly—many innovations are not patented. Appropriately structured studies of biographical dictionaries have provided significant insight into the conditions supporting or undercutting technological innovation. Leading biographical dictionaries use the judgments of scholars to select innovators from across the economy, regardless of whether they patented. As such, they offer an indicator of the quality of innovations. I use dictionaries to identify innovators' education, occupations, major innovation, employment by or contracting with governments, and publication record. A

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[10] Governments played another central role in forming innovational capabilities through establishing state colleges, land-grant colleges, and military institutes. This training will be only indirectly treated in this paper, though innovation by professors will be examined. On the role of state-supported education, see Thomson, "The Government and Innovation in the United States." Governments also affected technological change through regulatory policies.

separate survey formed a data set of over 28,500 patents issued to these innovators from 1820 through 1941.[11]

Studies of biographies of technological innovators often focus on those classified as inventors, but other groups also innovated. I add three other kinds of innovators: engineers, agricultural experts, and applied chemists. Engineers generated knowledge that laid out canals and railways, designed machinery, discovered and utilized minerals and petroleum, processed chemicals, formed alloys, and built electrical equipment and utilities. Agriculturalists developed plants and animals that could thrive in a particular climate and identified sources of diseases and strategies for mitigating them. Chemists studied soil, fertilizers, and sanitation, and developed dyes, synthetic materials, metallurgical methods and identified the composition of materials. Each developed new useful knowledge of the natural world, and in that broad sense each advanced technology.[12] I did not examine biographies of those classified as manufacturers, farmers, and scientists outside chemistry, though many of them also innovated.[13] I studied each inventor, engineer, chemist, and agriculturalist in the *American National Biography* and the

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[11] The biggest drawback of using dictionaries is that, because they identify noteworthy innovators, they do not 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. Studies of particular industries show that a great many lesser innovators also learned from government agencies. Hence I expect that the conclusions of the paper apply to wider groups of innovators, though the share with government involvement 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, 2009), ch. 4.

[12] In practice, these groups are similar to those called "technological and applied sciences" in the *American National Biography,* which includes the four groups studied here. The major difference is that I omit groups using technologies, including farmers, ranchers, aviators, scientific instrument makers, and surveyors, and added chemists. 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.

[13] Physicians also advanced useful knowledge; a good case could be made that they too were innovators. Geologists, physicists, and biologists directly or indirectly shaped innovations; many learned from government-supported colleges and in government jobs or contracts. 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 inventors, engineers and agriculturalists studied here were not extreme in their government dependence.

Dictionary of American Biography.[14] Those who undertook no significant innovation or for whom the innovation occurred before 1820 or after 1941 were eliminated. The resulting study included 1,336 major innovators. Those classified as inventors formed 35 percent of these innovators. Engineers (including metallurgists) made up 42 percent, almost half of whom were civil engineers, including sanitary engineers, construction engineers, and military engineers. Agriculturalists, which included horticulturalists, agronomists, and soil scientists, included 12 percent of innovators, and chemists formed 12 percent.

The addition of engineers, chemists, and agriculturalists greatly changes the composition of innovations. Those classified as inventors dominated in developing machinery (including agricultural, textile, sewing, metalworking, woodworking, printing, business, and other nonelectrical machines); 31 percent of them innovated in machinery, compared to 2 percent of other innovators (see Table 1). Inventors also led in instruments (including firearms, clocks, musical instruments, measurement devices, and scientific instruments); mechanical engineers made up most of the rest in these sectors. Inventors also concentrated more on power innovations (steam and water power, along with related equipment) and transportation equipment innovations (steamboats, railroads, automobile, and aircraft); once again, mechanical engineers made up most of the rest.

Inventors and others had about the same shares in chemical and electrical innovations; chemists and chemical engineers, and electrical engineers, respectively, led among other innovators. At the other extreme, inventors innovated little in construction, mining and

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[14] 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.

biological realms. Mining engineers led in mining innovations (which includes mineral extraction, initial mineral refining, and petroleum extraction but not petroleum refining). Civil engineers led in construction (mostly civil engineering improvements in transportation, water and sewage, along with construction equipment), and agriculturalists and chemists led in biological innovations (plant type, disease control, and animal husbandry).

Table 1. Content of Innovation by Type of Innovator

Innovation Type	Inventors	Other Innovators	All
Machinery	31.2%	2.2%	11.9%
Instruments	20.9%	0.8%	7.6%
Transportation	14.5%	5.9%	8.8%
Electrical	10.0%	9.5%	9.6%
Chemical	9.1%	9.5%	9.3%
Power	6.9%	2.7%	4.1%
Metallurgy	5.1%	6.1%	5.7%
Construction	2.2%	29.8%	20.3%
Mining	1.8%	7.3%	5.4%
Biological	0.9%	26.2%	17.4%

Sources and notes: Data indicate the shares to each type of innovator of the ten types of innovations; columns add to 100%. 1,336 biographies from *American National Biography* and the *Dictionary of American Biography.* All later tables draw on these data.

Including engineers, chemists, and agriculturalists changes the composition of all innovations. Instruments, machinery, transportation, and power made up almost three-quarters of inventors' innovations, but only one-third for all innovators. By contrast, mining, construction, and biological innovations, only 5 percent of inventor's innovations, grew to 43 percent for all innovators. Considering innovations from all these occupations better reflects the breadth of advances in useful knowledge.

Learning from Government Employment and Contracting

From independence, U.S. governments at every level sought technological improvements to better meet their needs and the needs of their residents. 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 improved infrastructure throughout the period. State and federal governments tried to realize the great agricultural and mining potential of the country. City governments sought growing supplies of pure water and the disposal of sewage. 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 small firms and farms. They finally targeted innovations where uncertainty was high and returns long in coming. Where externalities, scale, or uncertainty was higher than private firms could accept, government contracts or jobs were needed to promote innovation.

Many innovators learned from their involvement in government initiatives in ways that shaped their innovation by offering inventive targets or providing skills and contacts needed to meet the target. Government employees could use learning from government occupations to innovate while they held government jobs or afterwards. Contractors could learn from interactions with government officials in ways that contributed to current or later innovation. Learning from interactions with the government prior to or at the time of innovating was widespread. Over the whole period, 56 percent of major innovators secured such learning in ways that shaped their innovation (Table 2). [15] Forty-four percent worked for government

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[15] In addition to those with government learning, nearly ten percent of innovators had government employment or contracts that did not contribute knowledge relevant for their innovation (such as when a machine inventor had been

agencies on projects in which their technological learning contributed to their innovations. Another 16 percent learned from interactions around government contracts issued to firms with which they were associated. These proportions would suggest that, contrary to some interpretations of the post-1941 period, contracting did not dominate government learning before 1941, at least as a proportion of innovators. Indeed, 22 percent of innovators learned from multiple government agencies, such as when Army engineers became city engineers or public university professors worked at agricultural research stations. All levels of governments were sources of learning. Thirty percent learned from state and local government interactions, and 36 percent learned from the federal government. The similar shares suggest that scholars' emphasis on the federal government was after 1941 was less so in earlier times. The striking conclusion is that in a period of small government, most innovators learned through government employment or contracting at both the state and local governments in ways that advanced their innovation. This was hardly a laissez-faire outcome.

Table 2. Learning from Government Employment or Contracting by Cohort

	All	Early	Middle	Late
Government Learning	55.7%	51.4%	58.1%	57.9%
Employment	43.7%	41.0%	47.0%	43.1%
Contracting	15.7%	14.5%	14.1%	18.8%
Multiple Gov't Learning	21.6%	18.8%	23.8%	22.4%
State and Local	30.2%	24.4%	35.3%	31.0%
Federal	36.4%	37.1%	36.0%	36.0%

Notes: The early period includes the cohort of innovators born through 1830. The middle period includes those born from 1831 through 1860, and the later period includes those born after 1860. Agricultural experiment stations were considered to be a state activity, because though federally funded, they 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.

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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.

Government-mediated learning was common throughout the period, but it did increase over time. For the cohort born before 1831, 51 percent learned from government employment or contracting; this share rose to 58 percent for the cohort born after 1860. Both contractors and government employees shared in this growth. Learning from state and local governments rose especially rapidly. The share who learned from more than one government agency also rose from 19 percent of all innovators among the earliest cohort to 23 percent for the last two cohorts. Apparently, government learning was not a passing phenomenon useful when the country was catching up but unneeded later. The growth of government-mediated learning after 1941 may have accelerated, but the trend had been in place for a century.

It is important not to overstate the role of government learning for innovation. Over three-quarters of the innovators learned from employment in or ownership of for-profit firms—called private economic learning—and such learning was more common than government learning throughout the period (see Table 3). Innovators also learned from working for civil, not-for-profit organizations such as private colleges, engineering societies, and agricultural associations. Moreover, for those with government learning, government interactions usually were not their only source of learning; over the whole period, 36 percent of all innovators had both governmental and private economic learning—almost two-thirds of those with government learning. Civil engineers were common examples; they often worked for private companies and were employed as city engineers or contractors on public works. Hence private learning could have underpinned public, as was true of many contractors, who had typically had enough privately acquired knowledge that they could negotiate and complete government contracts.

Table 3. Learning Sources of Innovators

	All	Early	Middle	Late
Government Learning	55.7%	51.4%	58.1%	57.9%
Private Economic Learning	77.5%	85.1%	76.8%	69.8%
Civil Learning	11.2%	4.8%	11.0%	18.3%
Private Ec and Gov't Learning	35.8%	37.1%	36.6%	33.3%
Gov't Learning or Gov't College	61.8%	52.5%	62.5%	71.4%
Gov't Learning and Gov't College	21.4%	11.7%	21.2%	32.4%

Yet it is equally important not to understate the role of governmental learning. For government learning also informed private learning. For example, the government-initiated trajectory of interchangeable-parts production was later transmitted privately, so that innovators in the sewing machine, bicycle, and automobile industries were not classified as having learned from the government, even though it was government-initiated methods they were using. And the government had wider effects. Governments funded colleges that trained innovators in relevant technologies; if these are included 62 percent learned from government jobs or colleges, so that about 6 percent of inventors who did not innovate through government learning did benefit from government colleges. Moreover, 21 percent of innovators learned from both government colleges and agencies, and college networks often formed paths leading to employment, and learning, in government agencies. Employment and contracting understated the role of governments in learning, because many others learned from government publications and forums or from those who learned from government jobs or contracts. The patent system was itself a medium of learning, because the widely read Patent Office publications conveyed extensive information about the content of invention, which both allowed inventors to avoid expending time and money on already-patented inventions and provided information about solutions to technological problems that could be applied in other realms.[16] Finally, the declining share with private learning from 85 percent for the first cohort to 70 percent for the last, combined with the growing share with government college education or learning—which increased from 52 percent for the first cohort to 71 percent for the last—suggests that government became a greater source of learning over time and that the private sector declined in significance.

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 4). Construction innovators learned from employment in civil engineering projects at federal, state, and local levels. Over three-fifths of biological innovators learned from government employment, but more through states than the federal government, especially at the state experiment stations formed after the Hatch Act in 1887. Most transportation equipment innovators learned from government, principally from the federal government through both employment and contracting. Over half of mining innovators and almost half of 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 from government interactions, 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 government employment was greatest: in construction, biology, and mining. Though shares with

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[16]. On the patent system as an information system, see Thomson, *Structures of Change in the Mechanical Age,* 209-221.

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 4. Government-mediated Learning by Type of Innovation

Innovation Type	Government Learning	Employment	Contracting	Multiple Gov't Learning	State & Local	Federal
Construction	90.4%	79.3%	17.7%	36.9%	56.1%	55.4%
Biological	64.4%	61.4%	4.7%	35.6%	53.6%	27.5%
Transportation	57.3%	32.5%	29.9%	14.5%	9.4%	49.6%
Mining	55.6%	51.4%	4.2%	31.9%	38.9%	36.1%
Power	49.1%	25.5%	32.7%	10.9%	18.2%	34.5%
Electrical	41.4%	28.9%	17.2%	10.9%	18.0%	27.3%
Instruments	42.6%	22.8%	22.8%	9.9%	5.0%	40.6%
Chemical	40.3%	32.3%	11.3%	14.5%	21.8%	29.0%
Metallurgy	39.5%	23.7%	17.1%	13.2%	11.8%	34.2%
Machinery	24.5%	11.9%	14.5%	5.0%	8.2%	19.5%

How did the Government Innovate?

How did so small a government have such a big impact on innovation? One can approach this question by looking at the technologies in which it innovated or at the innovative process. Many of the novel technologies which government workers or contractors developed could not readily have been developed privately. Appropriability problems limited private innovation, though the patent system reduced these problems. Still many innovations could not be patented, such as new resource discoveries or novel seed types. Major new technologies were highly uncertain in their technological and commercial success, including novel sanitation systems, interchangeable-parts manufacturing, and topographical discoveries. Firms and individuals often could not meet the large capital costs of innovation, including many biological and construction innovations. Some innovations faced all three problems, such as the Armory system of interchangeable-parts firearms manufacturing, in which private gunsmiths were too small to innovate, returns were uncertain, and appropriability conditions weak.[17] Hence, some technologies were more likely to be developed by public bodies, including governments.

Yet limits to private innovation cannot explain the success of government innovation; the government might simply have failed to innovate. How then did the government succeed? Richard Nelson develops a useful framework for approaching this question. In an account of how firms differ in innovative success under condition of fundamental uncertainty, Nelson points to three factors. First, firms differ in their strategies. Some are first movers, others followers, yet others merely imitative. Strategies vary in choice of product and market and in pursuit of economies of scale, diversification, or takeovers. Second, firms adopt different structures or organizational forms to pursue their strategy, including managerial hierarchies, vertical integration, or R&D. Nelson refers to the Chandlerian managerial firm as adopting one structure, but smaller more networked firms adopted other structures. Structural differences can explain the rapidity of diffusion, economies of scale, and profitability. Finally, firms find or develop capabilities to solve technological problems. Organized research and development is one way to develop capabilities in-house, but firms also trained workers, and acquired knowledge from other firms through worker mobility and the purchase of inputs, from publications, and from colleges. Firms that innovated successfully combined strategies to innovate, appropriate structures, and capabilities developed internally and acquired from the outside; such firms often adopted organizational innovations to facilitate technological ones.[18]

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[17] On limits to private firearms innovation before 1840, see Smith, “Army Ordnance and the ‘American system’ of Manufacturing, 1815-1861.”

[18] Richard R. Nelson, "Why Do Firms Differ, and How Does It Matter?" *The Sources of Economic Growth* (Cambridge, Mass., 1996): 100-119; see also Chris Freeman and Luc Soete, *The Economics of Industrial Innovation*, third edition

Governmental innovation can be interpreted through a similar framework. The difference of governments from private firms might help explain the particular government success. Governments differed in strategy most evidently because they did not have to make profits. Their core goals were often mandated by legislation, though government agencies typically determine strategies to meet legislative goals and evolved in strategies through their own learning. Government agencies adopted and modified structures to realize their strategies, and because goals and strategies differed greatly and because governments were federal, state, and local, agencies structured innovation in radically different ways. Agencies differed in capability acquisition and development as well. They acquired inventive capabilities from outside, including other government agencies. They also developed their own capabilities. On top of this, agencies diffused technologies in different ways, often freely giving them away.

In such a framework, government innovation requires understanding the strategies, structures, and capabilities of government agencies. The content of government-mediated innovation varied with the goals of government agencies, and the character of these agencies varied enormously over time.[19] Indeed, institutional innovation within the government often preceded and supported innovation. Table 5 lists the government agency or level through which innovators learned in the order of their incidence for each technology group. 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. Two characteristics are immediately

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(Cambridge, Mass.: MIT Press, 1997) and Naomi Lamoreaux, Daniel M. G. Raff, and Peter Temin, "Beyond Markets and Hierarchies: Towards a New Synthesis of American Business History," *American Historical Review*, 108 (April 2003), pp. 404-33.

[19] Explaining why governments initiated certain agencies and what coalitions underpinned these choices and directed their administration are fascinating issues, but ones not pursued here. There is significant debate here about the character of the state: was it democratic and responsive to the will of the people, as much of the economics' political economy tradition holds, or responsive to the interests of large capitalists, as some of the Marxist tradition maintains? For one interpretation in the latter tradition, see Noble, *America by Design*.

evident: the great variety of government agencies involved in innovation and the difference of agencies by type of innovation.

Table 5. 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 & Topographical Engineers; other US; states; colleges	cities; colleges, states, US Reclamation Service; Corps of Engineers	Bureau of Public Roads; Navy; Army, US Coast Geodetic Survey; US Geological Survey
Biological	state agriculture boards; colleges; US Department of Agriculture (USDA)	colleges; state experiment stations; USDA; state boards of health	colleges; USDA; state experiment stations; state boards of health	US Patent Office; US Census Office; cities; state geological surveys
Transportation	Navy; other US agencies; states; cities	Navy; colleges; cities	Army Air Service and Signal Corps; Navy; cities	US Post Office; UA Lifesaving Service; US Lighthouse Board
Mining	state geological surveys; colleges	US Geological Survey; states; colleges	US Bureau of Mines; state geological surveys; colleges	Navy; cities; USDA; US Mint; US Bureau of Standards
Power	city waterworks; Navy;	Navy; city utilities; colleges	Navy; Ordnance Department; cities; colleges	US Corps of Engineers; US Patent Office; US Mint
Electrical	Navy; cities; US Patent Office	Navy; colleges; US Coast and Geodetic Survey; cities; states	Navy; colleges; Army Signal Corps; US Bureau of Standards	US Bureau of Weights and Measures; USDA; US Geological Survey
Instruments	Ordnance Department; US Coast Survey; Navy; US Geological Survey	Navy; Ordnance Department; colleges; US Coast and Geodetic Survey	Navy; Ordnance Department; cities; US Bureau of Standards; colleges	state geological surveys; US Mint; cities
Chemical	Army Ordnance Department; colleges; states	colleges; Navy; state experiment stations; Army; states	colleges; US Bureau of Mines; Army; Bureau of Standards	cities; USDA; US forest and meteorology services
Metallurgy	Navy; Ordnance Department; state geological surveys	colleges; Army; US Geological Survey; states	US Bureau of Mines; Army; colleges; US Bureau of Standards	US Mint; US Coast and Geodetic Survey
Machinery	Ordnance Department; states; Patent Office, US Mint	Ordnance Department; Navy; colleges	colleges; Navy	US Census Office; US Bureau of Standards; states

In examining the roles of government agencies, military agencies were important in most types of innovations, raising the question—central to interpretations of post-1941 innovation—of whether the military or war 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 among all innovators. Civilians dominated government learning; they made up 86 percent of those learning from government-mediated interactions, while 22 percent had military occupations (and 8 percent had both; see Table 6). Military occupations were most significant for construction, where the Corps of Engineers and the Corps of Topographical Engineers played prominent roles. They were almost as important in transportation equipment, led by Navy officers, and in instruments, dominated by Army and Navy armament innovators. At the other extreme, only four plant and livestock innovators 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 12 percent of all innovators. Nonmilitary occupations clearly led learning among innovators.

But the military still could have led if military learning, defined to be learning about military matters gained from military agencies, resulted in innovations.[20] Innovators with military learning made up 27 percent of those with government-mediated learning, led

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[20] 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.

machinery, instruments, and transportation equipment, in each case typically involving the design of military equipment. But 91 percent of innovators acquired nonmilitary knowledge in their government interactions. Moreover only 1 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 concentrated on infrastructure, led by the army engineers. In this way, one major contribution of the military was civil, its goal to foster economic and political development. About 17 percent learned from government interactions 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 this criterion, the military emphasis of some of the post-World War 2 literature would not have been the case before then.

Table 6. 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	22.4%	85.9%	26.7%	90.9%	17.2%	83.3%
Construction	37.1%	75.1%	12.7%	94.3%	9.0%	98.4%
Biological	2.7%	98.7%	1.3%	99.3%	3.3%	100.0%
Transportation	34.3%	79.1%	71.6%	83.6%	40.3%	40.3%
Mining	0.0%	100.0%	2.5%	100.0%	2.5%	97.5%
Power	22.2%	85.2%	51.9%	88.9%	22.2%	66.7%
Electrical	22.6%	92.5%	49.1%	96.2%	18.9%	67.9%
Instruments	32.6%	76.7%	67.4%	72.1%	34.9%	46.5%
Chemical	20.0%	88.0%	26.0%	82.0%	32.0%	88.0%
Metallurgy	6.7%	96.7%	46.7%	76.7%	36.7%	73.3%
Machinery	12.8%	92.3%	53.8%	76.9%	38.5%	59.0%

By some measures, government learning became less military over time. The share of those with military occupations fell from 30 percent for the earliest cohort to 14 percent for the last (see Table 7). Military learning did increase over time, growing from 26 percent for the earliest cohort to 32 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. Innovations occasioned by wars fell from 20 percent of innovators in the first cohort (dominated by the Civil War) to 17 percent for the last cohort (dominated by World War I). Hence to understand the government's role in economically important innovation, one should focus on civilian technologies and organizations because these innovators were more numerous and because while some military innovations fostered civil productivity growth, many did not.

Table 7. Military and Civilian Learning by Cohort

	All	Early	Middle	Late
Military Occupation	22.4%	29.8%	23.6%	14.0%
Civilian Occupation	85.9%	80.7%	85.2%	91.8%
Military Learning	26.7%	26.1%	22.4%	32.1%
Nonmilitary Learning	83.3%	84.5%	85.9%	79.4%
War-related	17.2%	20.2%	14.4%	17.3%
Not war-related	90.9%	88.2%	92.4%	91.8%

Civilian Government Agencies and Innovation

If civil government agencies dominated government-led innovation, why did such innovation succeed? David Mowery maintains that government programs after the onset of World War 2 varied so much that they must be considered separately.[21] The same can be said about earlier innovations; the agencies training innovators varied in strategies, structures, capabilities, and diffusion methods. Quick sketches of four different kinds of agencies—the U.S. Department of Agriculture and state experiment stations, the U.S. Geological Survey and related state surveys, urban water and sanitation agencies, and land-grant colleges and state universities—illustrates how each involved organizational innovations that mobilized inventive capabilities and diffused innovations, but they did so in quite different ways, resting on different antecedents and distinct choices. Variety is built into governments as well as among firms.

Before the U.S. Department of Agriculture, federal government activities to promote biological innovation were largely the domain of the U.S. Patent Office, which collected and distributed seeds, conducted agricultural investigations, and published on agricultural developments. Antebellum innovators on state boards of agriculture were more influential; they imported and developed new types of crops, analyzed the chemistry of soil, imported and bred animals, and studied pests and diseases. The U.S. Department of Agriculture (USDA) was established in 1862 in order to "acquire and diffuse among the people of the United States useful information on subjects connected with agriculture…and to procure, propagate, and distribute among the people new and valuable seeds and plants." The original legislation established some strategies towards this goal, including to acquire "information concerning agriculture," to conduct "practical and scientific experiments," and to collect "new and valuable seeds and

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[21] David Mowery, "Military R&D and Innovation," in *Handbook of the Economics of Innovation, edited by B.H. Hall and Nathan Rosenberg* (Amsterdam, 2010).

plants, to test, by cultivation, the value of such of them that may require such tests, to propagate such as may be worthy of propagation, and to distribute them among agriculturalists." The legislation even suggests a structure, including a "Commissioner of Agriculture, subordinates, and chemists, botanists, entomologists, and other persons skilled in the natural sciences pertaining to agriculture."[22]

The USDA would succeed only by modifying the strategies and structures of its originating legislation. Its initial divisions of chemistry, entomology, botany, and microscopy were organized by discipline, but this had little practical effect. Then it restructured divisions to be able to solve problems, bringing together disciplines to do so. Hence the Bureau of Plant Industry, the Bureau of Animal Industry, and the Bureau of Entomology each identified and addressed critical problems. The Bureau of Chemistry, finding that other bureaus had their own chemists, came to pursue a distinct set of problems surrounding food purity and adulteration. The USDA established its own experimental station in Maryland. Its early research focused on importation of seeds and plants, chemical analysis of plants, soils, and fertilizers, livestock diseases, and statistics; this evolved to more actively identify problems and structure studies using such state-of-the-art methods as genetics and bacteriology. As it succeeded in identifying causes of animal and plant disease, it took on regulatory functions such as quarantining disease-carrying animals and pest eradication. The USDA was small until it became a Cabinet department in 1889; then it grew to develop 53 field laboratories in 1913. Its research expenditures grew from $3.1 million in 1888 (in 1984 dollars) to 5.1 million in 1900, 35.6 million in 1910, 63.2 million in 1920 and 326.1 million in 1930.[23]

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[22] U.S. Department of Agriculture, "Report of the Commissioner of Agriculture for the Year 1862" (Washington, 1863): 3. The report goes on to detail the state of agriculture, largely by crop, in the whole United States.
[23] Walter E. Huffman and Robert E. Evanson, *Science for Agriculture: A Long-term Perspective* (Ames, Iowa, 1993), pp. 1-35, 94-96. Nominal prices are adjusted by a price index for agricultural research.

The USDA was soon complemented by agricultural experiment stations. States had formed agricultural experiment stations beginning with Connecticut in 1875, shortly followed by California. Partly thanks to arguments by states with such stations, the federal government passed the Hatch Act of 1887 to provide federal support for state agricultural stations, which was extended by later legislation. Their goals, according to the original legislation, included "to conduct original researches, or verify experiments, on the physiology of plants and animals; the diseases to which they are severally subject with the remedies for the same" and a host of issues including the chemical composition of plants and soil; the capacity of plants for acclimation, foraging crops, and dairy and cheese production. Stations were to publish periodic reports and make them available to their constituents and legislatures and to the USDA. State experiment stations were associated with land-grant colleges.[24] The federal government provided funding to the stations through the USDA' Office of Experiment Stations (OES). Additional funding came from USDA direct contracts with stations and from state governments; by 1910 these funds far exceeded those supplied by the OES. States and their land-grant colleges oversaw stations, limited to some extent by the USDA. Initially the OES was a source of research publications for the stations, but by the early 20th century, the OES conducted reviews of the stations, required certain accounting methods, and restricted the types of research conducted. Later legislation added supports for research and funded extension, which spread knowledge to farmers.[25] The stations were principally responsible for conducting research and diffusing knowledge. They expanded their research staffs from 250 people in 1890 to 1,032 in 1910 and 2,853 in 1930. The

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[24] United States, *The Statutes at Large of the United States of America*, XXIV, 440-442.

[25] Olmstead and Rhode, *Creating Abundance*; Ferleger and Lazonick, "The Managerial Revolution and the Developmental State;" A Hunter Dupree, *Science in the Federal Government: A History of Policies and Activities to 1940* (New York, 1957): 149-183; 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, 1982); Margaret Rossiter, "The Organization of the Agricultural Sciences," In *The Organization of Knowledge in Modern America, 1880-1920* edited by Alexandra Oleson and John Voss (Baltimore, 1979): 211-248

share whose highest degree was a Ph.D. rose slightly from 29 percent in 1890 to 31 percent in 1930, and the share whose terminal degree was a masters rose from 31 to 42 percent over the same years. Real research expenditures of the experiment stations grew from $15.2 million in 1888 to 61.5 million in 1910 and 164.1 million in 1930.[26]

The outcome was a innovating structure that included, among government agencies, the USDA, with its centralized organization, its own scientific labs and stations, and its oversight over and coordination of state experiment stations, a series of state experimentation with substantial autonomy from the USDA, but affiliated with land-grant colleges in their state. Each of these organizations related to farmers and agricultural civil organizations.

The capabilities to undertake and successfully sustain research of the USDA and the state experiment stations came from colleges, from learning abroad, and within the government-structured agricultural system. The sample of major innovators illustrates these sources. Of the 100 major innovators with USDA and experiment station backgrounds, nine-tenths obtained college education, overwhelmingly in areas related to their innovation, and the education became next to universal for the last two cohorts (see Table 8). They had considerably more college education than all innovators, whose shares increased from 38 percent for the first cohort to 83 for the last. They also had more graduate education in their fields; and the share with such education grew 70 percent in the last cohort, who worked after 1880, when the USDA and experiment stations had their major effects. The vast majority were educated in the U.S., and a key trend is that the share educated at and land-grants and state universities grew from none for the first cohort to 72 percent for the last. This is an important synergy within the public sector: the USDA and experiment stations demanded agricultural scientists, which land-grants and state

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[26] Huffman and Evanson, *Science for Agriculture, pp. 70-78, 95-97.* In addition to its agricultural activities, he USDA also came to include the Forestry Service, Weather Bureau, and Bureau of Public Roads.

universities supplied. Private U.S. colleges trained innovators throughout the period, but their share of the college-educated declined from all in the first cohort to half in the last. One-quarter were educated abroad, largely in Germany, a center of agricultural science. But this share decreased from two-fifths of the college educated in the first cohort to one-quarter in the last, when U.S. colleges developed applied-science curricula. Foreign graduate education fell from all with such education in the first cohort to three-tenths of the last cohort.

Table 8. Learning Sources and Output of USDA and State Experiment Stations Innovators

	All	Early	Middle	Late
Number	100	9	41	50
Learning Sources				
College Education	90.0%	55.6%	90.2%	96.0%
Graduate Education	57.0%	22.2%	48.8%	70.0%
US College	86.0%	55.6%	87.8%	90.0%
Land Grant or State College	58.0%	0.0%	53.7%	72.0%
Gov't-supported College	59.0%	0.0%	53.7%	74.0%
Gov't-supported Graduate School	28.0%	0.0%	17.1%	42.0%
Private US College	50.0%	55.6%	51.2%	48.0%
Private US Graduate School	27.0%	0.0%	24.4%	34.0%
Foreign College	26.0%	22.2%	29.3%	24.0%
Foreign Graduate School	24.0%	22.2%	29.3%	20.0%
Innovation via Private Learning	34.0%	66.7%	41.5%	22.0%
Innovaton via other learning	27.0%	44.4%	19.5%	30.0%
Foreign Learning	31.0%	22.2%	31.7%	32.0%
More than one Gov't Orgn	74.0%	77.8%	80.5%	68.0%
Output				
Patents in Innovation	28.3%	33.3%	22.0%	32.7%
Patents per Patentee	6.9	2.3	4.6	8.7
Technical Publications	87.0%	55.6%	92.7%	88.0%

Innovators also developed their capabilities after college. They studied German advances, including the organization of their agricultural experiment stations. When Samuel

Johnson was selected to head Connecticut's pioneering station, he modelled it after German stations. The director of the Storrs station, Wilber Atwater, also toured German stations; based on his knowledge of stations, he became the first director of the OES. Particularly after the formation of state stations, innovators learned on the job from their own work and from others. Experiments were published, and many read the results. In addition to agency publications, many met in conferences of groups like the Association of Official Agricultural Chemists.

The innovations that came out of government research were many and important. The USDA and agricultural experiment stations were the principal agencies that extended the share of government-led biological innovation from two-fifths of the first cohort to four-fifths in the second two cohorts. Over four-fifths received biological innovations, but they also developed chemical improvements, and eight made construction improvements, particularly highway innovations associated with the USDA's Bureau of Public Roads. Through innovations in soil chemistry, microbiology, entomology, and animal husbandry, personnel in the state and federal agencies 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. 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.

Innovations spread through two media. Some innovators patented, and spread their innovations through product sale or patent licensing. Yet most innovators—72 percent over the whole period—did not receive patents in their innovation. In some cases, innovations were not patentable, such as a new seed type brought from outside the U.S., but government employees often did not patent their innovations even if they could have. The share rose a bit for the last cohort, but with an interesting restriction; many patents by government employees could be used by the government or in some cases by any US resident without royalty payment.[27]

Publication was a more common means to transmit new knowledge; 88 percent of innovators published technical articles and book detailing their innovations or the field as a whole (such as textbooks). Some had as many as 200 publications. Government networks transferred knowledge in an organized way through publications and offices of cooperative extension. Moreover conferences and the mobility of workers spread such knowledge. 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.[28]

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, many

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[27] For example William Clark's 1912 humidity regulator patent was "dedicated to the public" and "may be used by the Government of the United States or any of its officers or employees in the prosecution of work for the United States or by any person in the United States without the payment of any royalty thereon." Patent number 1,042,893.

states organized geological surveys to discover mineral and petroleum deposits. These were typically one-time affairs. Some were quite successful. For instance, John Carll, working with the Pennsylvania Geological Survey, identified and published definitive accounts of the geological structure of the oil regions.

The federal government had responsibility for surveying land in the territories, and it made occasional forays into the states. The Corps of Engineers and Corps of Topographical Engineers were enduring organizations. Ad hoc, civilian studies complemented Army engineers. One of the most successful was the study of Michigan's northern peninsula, which revealed huge copper deposits. After the Civil War, the federal government financed a series of expeditions to map the West. Clarence King, a Yale graduate in geology who had served on the California Geological Survey, directed the U.S. Geological Exploration of the Fortieth Parallel with the cooperation of the Army Corps of Engineers, which from 1867 researched the geology and topography of 100 miles of land along the Central Pacific railroad lines. The mining and geology volumes were well received, and two surveys by the Department of the Interior were similarly acclaimed. When Congress asked the National Academy of Sciences for advice about surveying the territories, the Academy's recommendation included the formation of the U.S. Geological Survey, which, after convoluted legislative maneuvers, came into being in 1879.[29]

The legislation forming the U.S. Geological Survey (USGS) defined its goals to be "classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain." The first director, Clarence King, focused this wide mandate largely on identifying and analyzing mineral resources. To this end, he centered the survey's field offices in Colorado, and concentrated on mining developments there and in

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[29] Thomas G. Manning, *Government in Science: The U.S. Geological Survey, 1867-1894* (Lexington, Kentucky, 1967), pp. 1-59; Dupree, *Science in the Federal Government:* 195-231.

Nevada. The strategy changed toward more scientific goals under its second director, John Wesley Powell, and the associated USGS organization changed as well. Powell also initiated hydrographic surveys to examine the possibility of dam construction and irrigation; partly out of this work emerged the U.S. Reclamation Service to build dams and water supply mechanisms. Originally part of the USGS, it became an independent body. Late in the 19th century, the USGS's original utilitarian focus on mining and later water was reasserted. The structure also evolved in the new century, as the survey refocused from metals to other minerals and petroleum and to the role of basic science processes in predicting mineral availability. The survey increased its workers from 38 in 1879 to 401 in 1904 and 998 in 1929, while at the same spawning the U.S. Bureau of Mines.

Most USGS researchers were highly capable. The agency endeavored to hire only well-trained personnel for its researchers, and it succeeded, as exemplified by the 25 innovators for whom the USGS shaped their innovation. All but one were college-educated in areas connected to their employment. All the college-educated attended U.S. colleges, about half private and half public. The United States did not lead in mining technologies before the Civil War, but it did lead in some technologies by 1900. To acquire foreign knowledge, one-quarter attended foreign colleges, most in mining and most in Germany, and one-fifth attended foreign graduate schools. Others learned from visits abroad. U.S. colleges were central to most innovators, led by Columbia, with its School of Mines, and Yale, then a land-grant strong in geology. One-quarter learned on the job in state or federal geological surveys before joining the USGS. The USGS also educated workers for other federal jobs; half of the USGS innovators brought their talents to other agencies, led by the U.S. Reclamation Service and the U.S. Bureau of Mines. Its benefits extended to the private sector when USGS engineers joined petroleum and mining firms.

Innovators employed by the USGS had widespread effects. They 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 phosphates, potash, and coal. Others developed rock-drilling and refining equipment without government support. The USGS became a leading applied-science organization vital to the post-bellum emergence of the United States as a mineral-rich country. 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. Their innovations typically spread through publications; four-fifths of the USGS innovators detailed their innovations, mostly in USGS publications. Two-fifths patented in their innovations, but they averaged only five patents. Like the USDA, USGS innovators typically published but patented little. Their publications were widely read and diffused their innovations broadly.[30]

In the case of urban water supply and sewage, hundreds of city and state agencies tried to solve three problems. First, how could sufficient water be supplied to a rapidly expanding urban population which did not have access to private sources of water? Second, how water quality be controlled so that it did not transmit water-borne diseases? Finally, how could waste be discarded without impairing public health? These problems, scarcely acknowledged at

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[30] 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*, edited by Daniel H. Cole and Elinor Ostrom (2011); Spence, *Mining Engineers and the American West;* Manning, *Government in Science*; 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*, edited by James J. Rawls and Richard J Orsi (Berkeley, 1999), 24-51; Harold F.Williamson, Ralph L. Andreano, Arnold R. Daum, and Gilbert C. Klose, *The American Petroleum Industry: The Age of Energy, 1899-1959* (Evanston, Ill., 1963), 44-48.

independence, became central issues that state and local governments faced in the 19th and early 20th century for reasons of the economic development of cities and well-being of urban residents.[31] Cities adopted a number of strategies to solve these problems. Some chose to bring water from greater distances, while others used closer sources. Some targeted well-to-do and commercial areas, while others were city-wide. Some filtered water while others did not. Some developed chemical and later bacteriological systems to test for water purity and water-borne diseases, while others relied on smell and taste. Some adopted sewerage systems, while others relied on cesspools.[32]

Structures varied accordingly. One key trend was the growth of municipally owned waterworks; 20 percent of waterworks were publicly owned and managed in 1830, but the share rose to 70 percent in 1925, including the biggest cities. Private water supply companies were limited by the capital costs and economies of scale of infrastructural projects, limited markets until improvements were made, and uncertainty and appropriability of innovational investments. Private firms had even less interest in sewerage investments, because consumers were individually less willing to pay them. Cities could issue their own bonds, act for the collective interests of expansion and disease control, and accept greater uncertainty. Cities formed their own public works departments to administer waterworks, along with refuse collection and street maintenance. Cities also formed boards of health, which examined and tried to reduce the

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[31] The federal government played some role in health policy. It had already played roles in military hospitals by the Civil War. A temporary National Board of Health formed in 1879 in response to a yellow fever epidemic. It conducted excellent research, but, embroiled in quarantine efforts, its charter was not renewed. The Army Medical Corps had much greater success in dealing with typhoid fever. The civilian Public Health Service, formed in 1912, conducted effective research on conditions due to dietary deficiency. Dupree, *Science in the Federal Government:* 256-270.

[32] Marvin V. Melosi, *The Sanitary City; Urban Infrastructure in America from Colonial Times to the Present* (Baltimore, 2000), pp. 58-174; Nelson M. Blake, *Water for the Cities: A History of the Urban Water Supply Problem in the United States* (Syracuse, 1956). Good case studies include Louis Cain, “Raising and Watering a City: Ellis Chesbrough and Chicago’s First Sanitation System, *Technology and Culture,* 13 (July 1972), 353-372; and Cain, “Unfouling the Public’s Nest, Chicago Sanitary Diversion of Lake Michigan Water, *Technology and Culture* , I5 (October, 1974): 594-613; Joseph Ferrie and Werner Troesken, “Water and Chicago’s mortality transition, 1850-1925,” *Explorations in Economic History*, 45 (January 2008): 1-16.

incidence of infectious disease and improve the purity of water, milk, and other products. Because disease control crossed city lines, states formed boards of health and, led by Massachusetts in 1872; the same state first established the Lawrence Experiment station to study water quality and water-borne diseases in 1886. Moreover, cities learned from other cities through the publication, professional associations, and movement of engineers and chemists.[33] To take one example combining each type of linkage, George W. Fuller conducted experiments at the Lawrence Experiment Station, advised Louisville, Cincinnati, Chicago and 150 other cities and commissions on water purification and sewerage, published extensively, and was a leading force in the American Water Works Association, the American Public Health Association, and the American Society of Civil Engineers.[34]

Capabilities developed slowly. Europe led in understanding water purity and its relation to disease from the "miasmas" of the early 19th century to the bacteriological theories that dominated later in the century. It also led in the practice of water filtration and sewerage methods. Many U.S. innovators learned abroad. One-fifth of water supply and purity innovators attended foreign colleges, led by German universities (see Table 9), and two-thirds of those with graduate education attained it in foreign universities. Moreover, another one-fifth learned from abroad outside of college through visits or extensive correspondence. Some did both. For instance, after finishing his undergraduate studies at M.I.T., Fuller spent a year at the University of Berlin and worked for the chief engineer at the Berlin waterworks. More innovators learned in U.S. universities, more in privates than in land grants and state universities. The trend was towards more and higher quality college education; nine-tenths of the last cohort—who would have begun practicing from about 1890—were college-educated, and the content was much more

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[33] Melosi, *The Sanitary City*, pp. 74, 120, and passim.
[34] "George Warren Fuller," *American National Biography*.

sophisticated. Civil engineers engaged in water supply often learned from private employment in construction projects. But water supply innovators also learned in public jobs or contracts, and because they often had multiple jobs or contracts with different cities, this learning gained a national dimension. For example, Rudolph Hering was the city engineer of Philadelphia when many U.S. cities experienced yellow fever epidemics. To understand and alleviate such epidemics, he was sent abroad to study and document European sewerage practices. He then applied and developing his knowledge in studies of 250 North and South American cities, including Philadelphia, New York, and Chicago.

Table 9. Learning Sources and Output for Water Supply and Purification Innovators

	All	Early	Middle	Late
Number	81	17	43	21
Learning Sources				
College Education	71.6%	52.9%	69.8%	90.5%
Graduate Education	19.8%	0.0%	27.9%	19.0%
US College	65.4%	47.1%	62.8%	85.7%
Land Grant or State	22.2%	0.0%	20.9%	42.9%
Govt Supported Grad School	4.9%	0.0%	7.0%	4.8%
Private US College	50.6%	41.2%	53.5%	52.4%
Private US Graduate School	11.1%	0.0%	11.6%	19.0%
Foreign College	18.5%	11.8%	20.9%	19.0%
Foreign Graduate School	12.3%	0.0%	18.6%	9.5%
Innovation via Private Learning	63.0%	70.6%	62.8%	57.1%
Foreign Learning	21.0%	29.4%	18.6%	19.0%
More than one Gov't Orgn	43.2%	47.1%	39.5%	47.6%
Output				
Patents in Innovation	43.0%	41.2%	46.5%	36.8%
Patents per Patentee	14.4	16.0	11.5	24.0
Technical Publications	72.8%	52.9%	79.1%	76.2%

The result was a series of interlinked innovations that brought clean water, disposed of sewage, and reduced disease incidence. These innovations concentrated on the construction of new infrastructure and chemical or biological innovations to detect and reduce impurities and disease in water and sewage, though innovations extended to pumps and water-flow measurement devices. Water was supplied over longer distances, led by the Croton Aqueduct and the Catskill tunnels in New York and later from the Colorado River and Sierra Nevadas to supply Los Angeles. New York developed a gravity feed system, but other cities, pioneered by Philadelphia, drove water with pumps. Water purity became a fundamental issue when impurities and disease were linked. James Kirkwood studied European systems and advocated that Saint Louis adopt a slow-sand filtration system, which the city rejected but Poughkeepsie and many later cities accepted. Allen Hazen and Hiram Mills, on the Massachusetts State Board of Health, improved the slow-sand filter at the Lawrence Experiment Station; their studies and filter were credited with dramatically reducing typhoid fever deaths. Fast-sand filtering mechanisms were developed. Hazen applied the germ theory to sanitation; he and others at Lawrence were central figures in the application of bacteriological methods to sanitation and sewage. Abel Wolman of the Maryland Department of Public Health developed methods for chlorinating water. Kirkwood developed the first effective sewerage system in Brooklyn in 1857; his associates developed leading systems in Boston and Chicago.

A minority patented their innovations, though the share was higher than among USDA and experiment station innovators. Close to three-quarters published articles and books about their innovations or the wider field. These publications were widely read. Many attended conferences, such as those of the American Society of Civil Engineers, and published in the societies' journals. Civil engineers moved widely, and the national network spread best-practice techniques.

To take the final example, innovators from land-grant and state universities has particularly widespread effects, and their effects grew with time. From early on, governments in the United States supported college education, and that support deepened over the period. Public colleges developed through different channels. The federal government established military colleges.[35] Civilian public colleges gained impact not only for educating innovators, but also for offering professorial jobs leading to innovation. Various states supported colleges from early in the 19th century. State liberal arts colleges typically included science and mathematics. Some colleges had professional goals, including agricultural schools, mining schools, and normal schools to train teachers. Michigan led the way in creating a land-grant college for agricultural education in 1855; Pennsylvania soon followed. The federal government took a central role in 1862 when the Morrill Act created land-grant colleges; it was, according to its title, "An Act Donating Public Lands to the Several States and Territories which may provide Colleges for the Benefit of Agriculture and the Mechanical Arts." States were to use the lands or their sale to establish a permanent endowment the revenue from which would "promote the liberal and practical education of the industrial classes in the several pursuits and professions in life."[36]

Land-grant colleges adopted various strategies to meet these loosely administered conditions, differing in the balance of liberal and practical education and of teaching and research. After 1880, leading publics evolved in basic ways by followed private universities in establishing graduate programs and research expectations for faculty and graduate students. The Hatch Act reinforced this focus in the agricultural sciences. Here public universities moved beyond the education function of the Morrill Act by adding a research function.

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[35] The U.S. Military Academy, the most important early public institution, trained its Army graduates in military and civil engineering. 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.

[36] "Transcript of the Morrill Act (1862)," accessed at www.ourdocuments.gov.

The structures of public colleges evolved as a response to core strategies. Publics typically organized themselves around academic departments and, when venturing outside the liberal arts, into separate colleges. By the 1880s, some state and land-grant colleges, such as the University of Michigan, the University of California, M.I.T., and Cornell (and later the universities of Wisconsin and Illinois) established graduate programs taught by published professors, though only Cornell could rival the privates in the numbers of Ph.D.'s granted in the early 20th century. Faculty in such universities were expected to research, direct theses, and publish; in the applied sciences, professor's research often generated useful innovations. In response to the Morrill Act, some states designated existing institutions to receive the support (initiated by Iowa), and others created new institutions (led by Kansas). Most picked a single college, but Massachusetts divided its land-grant funding between the Massachusetts Agricultural College in Amherst and the Massachusetts Institute of Technology. Many colleges initially focused on agriculture, but over time they typically added various engineering disciplines. Dozens of other land grants formed over the next 60 years. By the 1880s many publics offered high-quality, inexpensive educations that garnered support from federal and state appropriations and also conducted research that formed new knowledge.[37]

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 of 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 universities set up effective mechanical engineering

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[37] Roger L. Geiger, *To Advance Knowledge: The Growth of American Research Universities, 1900-1940* (New York, 1986).

programs from the 1880s, utilizing European engineering and mathematical advances. 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. Mining programs at Columbia and later at several land grants formed in the same period. From the late 1880s, Columbia, M.I.T. and Cornell established electrical engineering programs. Chemical engineering developed early in the 20th century, also led by M.I.T.[38] 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 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. As the graduates multiplied, so did professors.[39]

Many professors developed considerable innovative capabilities on the job through their study, teaching, and research. Because more innovators gained college education over time and because publics grew relative to privates, government-supported colleges increased their role in innovation as the period progressed. Many students used their education to innovate later, but 179 innovators worked at public colleges in ways that contributed to their innovation. They made up 13 percent of all innovators, and their share increased from 5 percent of the first cohort to 20 percent of the last (see Table 10). Unsurprisingly, professor-innovators were

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[38] Stanley M. Guralnick, *Science and the Ante-bellum College* (Philadelphia, 1975); Daniel Hovey Calhoun, *The American Civil Engineer: Origins and Conflict* (Cambridge, Mass., 1960); Geiger, *To Advance Knowledge;* Raymond H. Merritt, *Engineering in American Society, 1850-1875* (Lexington, Kentucky, 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, 1967); Allan Nevins, *The State Universities and Democracy* (Urbana, Ill., 1962); Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, 1983), 140-174; Olmstead and Rhode, *Creating Abundance,* 243, 257; Clark C. Spence, *Mining Engineers and the American West: The Lace-Boot Brigade, 1849-1933* (New Haven, 1970), 18-53; Robert V. Bruce, *The Launching of Modern American Science, 1846-1876* (New York, 1987), 326-338.

[39] 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,* edited by David Eltis, Frank D. Lewis, and Kenneth L. Sokoloff (New York, 2009), 179-217.

overwhelmingly college educated in technical subjects, and the share so educated increased from 78 percent for the first cohort to 98 percent for the last. The share who learned in graduate schools surged from 26 to77 percent from the first to the last cohort. The vast majority received at least part of their education in the United States, and the share educated in land grants or state colleges grew from 4 to 49 to 73 percent over the three cohorts. Similarly, the share with graduate education in land grants or state colleges grew from none for the first cohort to 45 percent for the last. Private US colleges remained important in training public professor-innovators. But while they dominated among the first cohort (supplemented by the Military Academy), state colleges and land grants were much more important among the last cohort, and their predominance was just as great among those with graduate degrees.

Table 10. Learning Sources and Output of Land-Grant and State College Innovators

	All	Early	Middle	Late
Number	179	23	72	84
Learning Sources				
College Education	92.2%	78.3%	90.3%	97.6%
Graduate Education	57.5%	26.1%	44.4%	77.4%
US College	87.2%	73.9%	84.7%	92.9%
Land Grant or State College	54.2%	4.3%	48.6%	72.6%
Gov't-supported Graduate School	27.4%	0.0%	15.3%	45.2%
Private US College	47.5%	60.9%	45.8%	45.2%
Private US Graduate School	19.0%	4.3%	15.3%	26.2%
Foreign College	28.5%	21.7%	29.2%	29.8%
Foreign Graduate School	27.9%	17.4%	29.2%	29.8%
Innovation via Private Learning	41.3%	60.9%	41.7%	35.7%
Foreign Learning	29.1%	30.4%	30.6%	27.4%
More than one Gov't Orgn	64.8%	78.3%	69.4%	57.1%
Output				
Patents in Innovation	42.9%	26.1%	34.7%	55.0%
Patents per Patentee	15.3	7.6	10.5	19.4
Technical Publications	91.6%	87.0%	94.4%	90.5%

Professor-innovators also learned from abroad. From 22 to 30 percent attended foreign universities, and, more importantly, those who did concentrated on graduate education—including all the foreign-educated in the last two cohorts. Here they caught up to the knowledge frontiers in their fields, and brought this knowledge back to the U.S. Among professor-innovators with graduate degrees, two-thirds were educated abroad for the first two cohorts, but the share fell to two-fifths among the last cohort, when U.S. graduate programs had substantially caught up in applied science. Foreign education occurred overwhelmingly in Europe, where German institutions trained three times as many innovators as all other countries combined. Three-tenths of the professor-innovators also transferred techniques after working or corresponding with researchers abroad. Biological innovations for agriculture or public health led the way, but at least six innovators transferred chemical, electrical, and metallurgical and mining methods from Europe.

Finally professors learned in occupations within the U.S. At times, private occupations in the economy supplemented knowledge as professors as sources of learning, particularly when professors consulted widely. But private jobs that contributed to innovations fell from 61 percent of professor-innovators in the first cohort to 36 percent in the last. Interestingly, many more learned from other government organizations in addition to land grants and state colleges than those who learned privately in ways that affected their innovations. The large majority did so in each period, through the share fell from 78 percent for the first cohort to 57 percent for the last as professors gained some job security and income. This was most pronounced for biological innovations, where state experiment stations, the USDA, and health departments supplemented professorships, but the group extended to federal and state geological surveys, the U.S. bureaus of Mines and Standards and other federal and state agencies.

Because land-grant and state college professors spread widely among departments, their innovations were also widespread; indeed, at least two of them contributed to each of the innovation types. Professors formed the largest share of government-mediated innovations among biological improvements, largely because professors were often associated with experiment stations, the USDA, or state or city sanitation and health improvements. They were also important for mining improvements, especially associated with geological surveys or the U.S. Bureau of Mines. The two other innovation categories with high public professorial representation were in electricity and chemistry. Professors had the lowest share of government-mediated innovations in instruments, power, transportation, and construction; the military played bigger roles in the first three, and state and local governments in construction.

Similar to the USDA, USGS, and sanitation agencies, most innovators at land-grants and state colleges did not patent. Over nine-tenths of professor-innovators published technical articles and books; this was a key means of diffusion. They also attended conferences of engineering and agricultural societies, many of them national in scope. Then as now, there was considerably mobility between universities, furthering the spread of knowledge.

The USDA and state experiment stations, the USGS, city and state water and sanitation departments, and land-grants and state universities were institutional innovations of the first order. Dozens of other civil and military federal agencies and hundreds of city and state departments were the same. They all supplied organization that shaped the generation and spread of knowledge, though in very different ways. 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. But much was decentralized.

And they utilized and built capabilities to enable them to succeed. In so doing, they generated a variety of public paths that diverged from private paths of innovation.

The Distinctiveness and Success of Government-mediated Paths of Innovation

Why was government-led innovation so common and often so successful? Several factors, some differentiating it from private innovation, help to answer this question. First, limits to private innovation gave ample scope for public innovation and meant that it would not face the kinds of political opposition that would doom legislation. Governments typically targeted innovations that the private sector could not readily undertake. John Wesley Powell, in defending the USGS which he directed, articulated this principle: "the government should not undertake to promote research in those fields where private enterprise may be relied on for good and exhaustive work, especially while vast fields where private enterprise cannot work are still unoccupied by agents of the government."[40] Private innovation was limited by appropriability, uncertainty, and scale in many sectors. For the most part, where government learning was high, private innovation faced these limits. Biological and sanitation innovations were cases in point—they could not readily be appropriated, were highly uncertain in the extent and timing of the payoff and the technical problems faced, and often involved a scale beyond what private firms or farms could meet. The move from private water supply firms to public waterworks, and the domination of public sewerage exemplify the limits of private innovation, as did the USDA's efforts to control plant disease and the USGS's mapping and resource extraction functions.

Second, once legislation or administrative decision defined goals and formed government agencies, those agencies formed strategies that often (but hardly always) supported innovation. Strategies were often formed by the study of foreign precedents, such as the study of European

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[40] Quoted in Dupree, *Science in the Federal Government:*225.

universities, sanitation, agricultural research organizations, and military engineering. Similarly, some government units copied models of other units, as the cities learned from public works of other cities or federally financed land-grants and experiment stations learned one another. Copying successful strategies reduced the uncertainty of innovation. But strategies had to be chosen, were hardly self-evident, and changed over time. Many civilian innovations targeted what Powell characterized as "investigations in those fields most vitally affecting the great industries in which people engage," but exactly which investigations to conduct and how to do so were strategic choices that at times took a long time to determine.[41] The USDA took two decades to learn how to identify key problems, and not merely collect seeds and form a national herbarium, and the movement of land-grant colleges into research took just as long.

Third, government agencies often succeeded at organizing themselves to realize their strategies. Though centralized government innovation has been criticized because it can be dissociated from user needs, the decentralized structure of much innovation, complemented by federal involvement linked to local needs, meant that much civilian innovation was user-oriented. Agency structures often learned from and diffused information to users. They also learned from other agencies, as state experiment stations learned from other stations, city water works shared knowledge, and land-grant colleges formed tight networks. Cooperation became explicit and organized; unlike firms, agencies were typically not competitive.[42] But the appropriate agency structure took time to discover. It took the USDA 20 years to reorganize

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[41] Quoted in Dupree, *Science in the Federal Government:*226.

[42] 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. 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* (Cambridge, 2002); Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (Princeton, New Jersey, 1997); Petra Moser and Ryan Lampe, "Do Patent Pools Encourage Innovation? Evidence from the 19th-Century Sewing Machine Industry," *The Journal of Economic History* 70 (December 2010): 898-920.

itself around problems and not disciplines, which gave its research needed focus. When the Hatch Act was passed, the USDA undertook an oversight function to ensure that experiment stations actually solved agricultural problems, but it accepted the autonomy of state-level units.

Poor choices of strategy and structure could and did lead to failure. The National Board of Health, called the "most egregious failure in the history of government science" is a case in point. Responding to the yellow fever epidemic of 1878, the federal board was temporary and given the ambiguous mandate of researching epidemic and formulating a proposal for a permanent board. It conducted effective research, relying on the voluntary, unpaid research of leading experts, though it could not have been expected to find how to control the disease in short order. Yet the board failed, and was no permanent board was formed. Strategy and structure both played a role in the failure. The board's research mission was changed in midcourse to one of establishing and administering quarantines, which the board had originally opposed. The board had no centralized leadership, and its moving force remained a military offer with other duties. It relied on volunteer labor of researchers, and its lack of a professional staff could not coordinate and follow up on leads. Its muddled mandate brought political opposition. With better mandates, strategies and organization—which one authority believes were possible—the U.S. might have had a permanent national public health organization similar to those of other countries, which could have had beneficial long-term effects.[43]

Fourth, innovators employed by government agencies at the time of their innovation were highly capable. They were better educated than other innovators. Over the whole period, 79 percent of government-employed innovators received a college education, far above the 52 percent of others who secured government learning through contracting or earlier employment with government learning and the 46 percent of those without government learning (see Table

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[43] Dupree, *Science in the Federal Government:*258-263; quote on 262.

11). Moreover, 33 percent had graduate education, double the 16 percent for the two groups with private employment when they innovated. This gap closed a bit over time, but even for the last cohort, government-employed innovators had considerably more college education and vastly more graduate education. The technical education of government workers certainly decreased the cost and uncertainty of innovation and increased the probability of success. This does not mean that those without undergraduate or graduate college education were less skilled, but it does mean that they acquired their skills within the economy. This carries an important implication: government-employed innovators benefitted from knowledge not easily obtainable within the for-profit economy. In this sense, their innovations were more discontinuous with knowledge generated within the economy, and hence of greater uncertainty and cost to those without college backgrounds.

Table 11. Innovative Capabilities and Output by Relation to Government

	All	Gov't Jobs at Innovation	Other Gov't Learning	No Gov't Learning
Share of Innovators		39.6%	16.1%	44.3%
Learning Modes				
With College Education	60.2%	79.2%	52.1%	46.1%
With Graduate Education	22.8%	33.1%	15.8%	16.0%
With Foreign Education	15.1%	17.4%	10.2%	14.9%
Foreign Graduate Education	10.3%	15.1%	6.0%	7.6%
With U.S. College	53.7%	74.9%	45.6%	37.8%
Gov't-supported	27.1%	44.8%	20.0%	13.9%
With Foreign Learning	24.3%	23.1%	27.4%	24.3%
In Professional Association	52.5%	64.8%	46.0%	43.9%
Output				
Patentee Share	69.2%	48.7%	86.3%	81.3%
Patents in Innovation	65.5%	43.0%	83.9%	78.9%
Patents per Patentee	31.3	12.1	41.3	37.6
Technical Publications	55.8%	73.5%	45.1%	43.9%

Sources and notes: Patent data is for 1,317 innovators; 19 were excluded because identification was ambiguous or because patenting began after 1941. 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.

A larger share of government-employed innovators received foreign collegiate or graduate education; the gap was pronounced in graduate education, in which government-employed innovators doubled other innovators.   Much of this education, especially at the graduate level, overcame U.S. backwardness in chemistry, mining, and agriculture, and as such improved the chances for innovative success at any cost or reduced the cost for any level of innovative output.[44] Government-employed innovators had a large lead in U.S. collegiate education; this was especially strong among the last cohort who could benefit from the advance of the U.S. research university. Moreover, a much higher share of public employees learned in government-supported colleges (including land-grants, state colleges and federal military academies), Among the college-educated, 57 percent got their degrees in government-supported institutions, compared to 38 percent for those with other government learning and 30 percent for those without government learning. Hence government agencies were vital for both the demand for and supply of innovative labor.

After their education, public and private innovators both learned from abroad in about the same proportions, transferring techniques at the same time. They differed in that 65 percent of public employee innovators were members of professional associations in which they shared knowledge with others, compared to about 45 percent for other innovators. Some associations were for public employees alone, but more, including the major national engineering, chemical, and agricultural associations, involved public and private employees. Innovators who were government employees, in short, learned more from education, both foreign and domestic, and

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[44] Foreign education includes both U.S. residents studying abroad and foreign residents trained (usually) in their own countries. To capture U.S. efforts to learn from abroad, one can focus on U.S. residents who elected education abroad. The contrast is especially striking for graduate education; 14 percent of government-employed innovators who were U.S. residents at age 20 received foreign graduate education, compared to only 5 percent for other resident-innovators.

from professional associations. The key contrast in the mode of learning seems to be more public versus private employment than the presence or absence of government learning.

A final difference pertains to the form of diffusion of innovations. Civil wings of governments often made their employees' innovations freely available through publication and demonstration; this was an express goal of the USDA, the USGS, and other bodies. Without the same need for private appropriation, public innovators exhibited quite different patenting and publication behavior than their privately employed counterparts. Public innovators relied much less on patenting. Only 43 percent received any patents in their innovation, compared to 80 percent for private innovators. Private innovators who secured government learning, most of whom were contractors, patented at roughly similar rates to other private innovators, so that working for the government seems to have been the differentiating factor. Both public and private innovators increased their patenting rates over time, though a number of public innovators had patents that stipulated that government agencies could use them without royalties. Even if they did patent, public innovators patented less; patentees who learned from government employment averaged 12 patents, while others averaged three times as many.

Moreover public innovators were much more active publishers. Seventy-four percent of them published books or articles containing technological knowledge related to their innovation, far above the 45 percent among others with government learning and the 44 percent of those without government learning. Innovators with public employment were more like scientists spreading knowledge through open sources.[45] This was particularly true of professor-innovators at land grants and state colleges, but was also true of other public employees.[46]

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[45] Chemical and electrical innovators also had high rates of publication and high rates of college and graduate education. This suggests that college education, and not simply public employment, led to publications.

[46] Because half 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 as they innovated had

The difference of forms of innovative output affected diffusion. It was the intent of government organizations to publish their key results, as well as to transmit them in conferences and presentations. Publications were widely read; prospectors, for example, used USGS maps for years after they were issued. Agricultural extension services and land-grants also fostered diffusion. Moreover, the sharing of knowledge by many agencies, at times brought together federally by groups such as the USDA, and professional associations also spread knowledge. At the same time, the lower patenting rate, combined with the royalty-free character of some patents by government employees, reduced the cost of acquiring knowledge.

Still, the strong public-private contrast in forms of learning and output might simply reflect differences in technology types, and if so, the key issue would not be the form of employment but the kinds of technology. Public employment at the time of innovation was highest for construction, biological, and mining innovations, in which public employees received from 47 to 73 percent of innovations; in no other sector did public workers have as much as 30 percent of innovations. These three sectors were among the highest six in college education (along with electrical, chemical, and metallurgical innovators). Two—biological and mining—joined electrical and chemical as sectors in which at least one-third of innovators secured graduate education. Biological, mining, and construction innovators also had the lowest patenting shares in their innovation, and biological and mining innovators joined electrical innovators as having the highest shares with technical publications. Moreover, those who did patent in these three sectors averaged far fewer patents—in biological and construction under 10—compared to an average of 31 for all innovators who patented.   To look at the opposite extreme, machinery innovators were the lowest in college and graduate education and in

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higher patenting rates in their innovation than those who learned only from public jobs—51to 35 percent—and patentees received almost twice as many patents. A modestly smaller share authored technical publications.

publications, but among the highest in patenting.[47] Clearly, technological differences mattered in determining the role of education and the form of innovational output, so that the public or private form of employment might not have been the critical factor.

In fact, the form of employment mattered a great deal, as a contrast of public versus private employment in each technology type reveals. Within each of the three types in which public employment dominated—construction, biological and mining—public workers at the time of their innovation had far higher college education shares than private employees and higher shares with graduate education (except construction innovators, for whom the graduate share was small; see Table 12). Where public innovators were less common, they continued to have higher college and graduate education shares in virtually all sectors.

Table 12. Education by Job Type

Innovation Type	Public Jobs Share	College Education, Public Jobs	College Education, Private Jobs	Graduate Education, Public Jobs	Graduate Education, Private Jobs
Construction	73.4%	74.4%	56.9%	8.5%	9.7%
Biological	59.2%	87.7%	52.6%	57.2%	22.1%
Transportation	24.8%	69.0%	38.6%	20.7%	6.8%
Mining	47.2%	85.3%	65.8%	55.9%	21.1%
Power	20.0%	45.5%	43.2%	27.3%	9.1%
Electrical	21.1%	85.2%	67.3%	48.1%	30.7%
Instruments	19.8%	55.0%	29.6%	5.0%	7.4%
Chemical	29.8%	100.0%	65.5%	70.3%	35.6%
Metallurgy	21.1%	87.5%	65.0%	50.0%	25.0%
Machinery	11.3%	61.1%	19.9%	16.7%	0.0%

Notes: Public jobs refer to those who had government jobs over the course of their innovation, though some also had private jobs. Thus private jobs refer to those with only private jobs over the course of their innovation.

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[47] 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 (September 2005): 1214-1236, and Olmstead and Rhode, *Creating Abundance.*

Patents and publications followed a similar pattern: within any technology type, public employees patented less and published more, while private employees—with or without government learning—patented more and published less. Hence, innovators with public jobs in the sectors with most public employment—construction, biology and mining—had lower patenting rates, fewer patents, but higher publication rates than their private counterparts (see Table 13).[48] The same was largely true among technology types with fewer public employee-innovators; they typically patented less in their innovation, had fewer patents, but published more. Much of these differences difference had structural roots; the goal of many public jobs was to solve problems and freely distribute knowledge of the solutions.

Table 13. Patenting and Publication by Job Type

Innovation Type	Patent in Innovation, Public Jobs	Patents in Innovation, Private Jobs	Patents per Patentee, Public Jobs	Patents per Patentee, Private Jobs	Publications, Public Jobs	Publications, Private Jobs
Construction	33.5%	61.4%	7.0	13.8	59.8%	47.2%
Biological	21.5%	19.4%	5.3	6.4	91.3%	75.8%
Transportation	51.7%	97.7%	19.1	39.5	55.2%	29.5%
Mining	35.3%	55.3%	6.5	31.7	91.2%	52.6%
Power	90.9%	100.0%	16.4	29.9	63.6%	38.6%
Electrical	92.3%	96.0%	29.7	70.0	74.1%	71.3%
Instruments	85.0%	91.4%	13.4	39.7	60.0%	22.2%
Chemical	69.7%	86.0%	13.9	38.7	86.5%	56.3%
Metallurgy	81.3%	90.0%	8.5	25.1	87.5%	48.3%
Machinery	77.8%	94.3%	21.5	38.1	66.7%	14.2%

Hence innovators with government jobs differed in capabilities and output from their private counterparts. In virtually every broad type of technology, they were better educated, published more, but patented less. On the other hand, the type of technology also differentiated

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[48] Biological innovators were the exception; public innovators had slightly higher patenting rates, though rates were low for all inventors. Public innovators did publish more frequently.

inventive paths. Typically education was higher for both public and private innovators in some technology types—the three sectors in which public innovation was highest, and the science-based sectors of chemistry, electricity, and metallurgy. Education was lower for public and private innovators in power, instruments, machinery, and, to a lesser extent, transportation. Similarly the share receiving patents in their innovation was lower for public and private inventors in biology, mining, and construction than in other sectors. These three sectors also had high publication rates for public and private innovators, though the other three sectors with strong college training, electricity, chemistry and metallurgy, also had higher publication rates for private and public inventors.

Technological Change, Private and Public

Since independence, technological change has propelled the United States to catch up with world economic leaders and, by about 1890, take the lead. A strong narrative focuses on firms innovating for rapidly growing markets. Firms adopted some methods from abroad and initiated new ones, building on their own expertise and that of independent inventors. Institutional innovations supported technological change, including industrial firms, factories, corporations, managerial firms, R&D, industrial capital markets, and patenting services. The diversity of organizational forms gave innovation an evolutionary quality. Patenting became common early in the period; almost half of machinery and engineering firms before 1866 received patents. And though large firms grew, smaller firms took out most patents, and patents per patentee did not rise through 1929. Rapid technical change, in turn, spawned investment, growth, and rising consumption standards, which created conditions for further technological change. A highly successful innovation system originated and flourished.[49]

For all its value, this narrative is fundamentally incomplete because it radically curtails the role of government in technological change.[50] In this narrative, the government enabled innovation through patent systems, primary and later secondary education, and, more broadly, the rule of law, but with few exceptions, such as interchangeable-parts production methods, the government did not itself innovate. This narrative needs to be reconstructed, because over half of major innovators learned from government employment or contracting. Government innovation concentrated where private innovation was limited by the uncertainty, high costs, or appropriability difficulties. This involved a remarkably wide range of cases, including one-quarter or more of innovations in each of the ten major technology groups. Such innovation relied on institutional innovations that rivalled those of the private sector, including state and land-grant colleges, agricultural departments and experiment stations, geological surveys, city and state transportation and sanitation agencies, and Army and Navy organizations. Considerable variety and learning gave an evolutionary quality to these organizations. Capabilities to innovate evolved in part internally, through public universities, complemented by not-for-profit privates. Governments developed distinctive forms of innovation, with different

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[49] Research on private invention before World War 2, see Kenneth L. Sokoloff, Naomi R. Lamoreaux, and Dhanoos Sutthiphisal, "The Reorganization of Inventive Activity in the United States during the Early Twentieth Century," *Understanding Long-Run Economic Growth: Geography, Institutions, and the Knowledge Economy,* edited by Dora L. Costa and Naomi R. Lamoreaux (Chicago, 2011), 235-274; Tom Nicholas, "The Role of Independent Invention in U.S. Technological Development, 1880-1930," *Journal of Economic History* 70 (March 2010), 57-82; Naomi R. Lamoreaux and Kenneth L. Sokoloff, "The Rise and Decline of the Independent Inventor," in *The Challenge of Remaining Innovative: Insights from Twentieth-Century American Business,* edited by Sally H. Clarke, Naomi R. Lamoreaux, and Steven W. Usselman (Stanford, Calif., 2009), 43-78; Naomi R. Lamoreaux and Kenneth L. Sokoloff. "Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries." In *Learning by Doing in Markets, Firms, and Countries,* ed. Naomi Lamoreaux, Daniel M. G. Raff, and Peter Temin. Chicago, 1999), 19-57; Thomson, *Structures of Change;* Ross Thomson, "The More Things Change, the More They Stay the Same? The Maturation of the U.S. Innovation System, 1866-1929," Yale Economic History Workshop, November, 2013.

[50] It is also incomplete for other reasons, including the roles of not-for-profit civil groups, such as mechanics's and engineering associations, private colleges, and scientific societies.

organizational forms and modes of diffusion, and these forms were essential parts of the evolving innovation system. And this pre-World War 2 system differed from that the world war would initiate in its private and public sides; smaller firms, state and local governments, and civilian branches of government played stronger roles in the earlier system.

The standard narrative needs to be amended for a related reason; government innovation and private innovation affected each other, largely positively, and U.S. innovation was stronger for it. Government innovations created spillovers that reshaped private innovation directly, such as interchangeable-parts, metallurgy, and new instrumentation. Government innovations had broader effects by supporting agricultural expansion, mineral extraction, transportation cost reduction, and mortality declines. Private growth and innovation benefited, particularly in the cities in which industrial development and invention concentrated, when prices of agricultural and mineral products and transportation services declined and when urban mortality and disease fell. Private innovation, in turn, affected government innovations through the knowledge it created and the growth it engendered. In agriculture, for example, biological and mechanical innovations, the first largely public and the second private, were mutually reinforcing. A full story of innovation in capitalist economies must include governmental as well as private innovations, and the complementarity of the two will help to understand the surge of innovation from 1790 through 1940 and its particularly powerful presence in the United States.