Continuously Advancing Innovation in the Scientific Research System—Germany' s Path to Becoming a World Leader in Science and Technology (Postprint)

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Abstract

Germany' s path to becoming a technological powerhouse has not been smooth, with numerous factors playing positive roles throughout this process. Among them, continuous institutional innovation has been of paramount importance. German science has benefited from institutional innovation since its inception, with its research system undergoing fundamental transformations approximately every century. Landmark events during this period include the establishment of the University of Berlin in 1810, the founding of the Imperial Physical-Technical Institute in 1887, the creation of the Kaiser Wilhelm Society in 1911, the post-WWII expansion of the Max Planck Society as its successor, the distinct functions performed by the other three "extra-university research organizations" (the Fraunhofer Society, the Helmholtz Association, and the Leibniz Association), and the "Excellence Strategy" launched since the late 20th century. In addition to favorable timing and circumstances, the sense of urgency and foresight among German scientists and science policy makers has played an extremely crucial role. When in a position of backwardness, they humbly learned from more developed nations; when in a leading position, they took preemptive measures, overcame internal and external pressures, and constantly pursued excellence without ever being satisfied. This has enabled Germany' s scientific research system to maintain its perpetual vitality and enduring prosperity.

Full Text

Uninterrupted System Innovation —The Road to Germany' s Status as a World Science and Technology Power

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Abstract

Germany' s path to becoming a world science and technology power has not been smooth, with many factors playing positive roles along the way. Among them, uninterrupted institutional innovation has been crucial. German science has benefited from institutional innovation since its inception, with its research system undergoing fundamental transformation approximately every century. Key milestones include the establishment of the University of Berlin in 1810, the founding of the Imperial Physical Technical Institute in 1887, the creation of the Kaiser Wilhelm Society in 1911, the post-WWII expansion of the Max Planck Society as its successor, the division of labor among the three major "non-university research institutions" (the Fraunhofer Society, Helmholtz Society, and Leibniz Society), and the "Excellence Strategy" launched since the late 20th century. Beyond favorable circumstances, German scientists and science policy-makers have demonstrated remarkable awareness of potential dangers. When lagging behind, they humbly learn from more advanced nations; when leading, they take precautions, overcome internal and external pressures, and constantly strive for improvement without satisfaction. This mindset has kept Germany' s research system dynamic and thriving.

Keywords: Road to Germany' s Scientific and Technological Power, Institutional Innovation, Non-university Research, Excellence Strategy

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The First Century: The Prussian Academy of Sciences in Its Founding Era

In 1806, when Prussia was defeated by Napoleonic France, the Prussian Academy of Sciences, advocated by Leibniz, had just passed its centennial. Established in 1700, the Academy' s original purpose was to emulate the French Academy of Sciences and the Royal Society of Britain, enhancing national prestige and demonstrating that Prussia was not merely a martial northern state but also had cultural aspirations for knowledge. However, until 1809, the Prussian government provided no direct funding. To keep the Academy operational, it was granted a monopoly on calendar sales in the Brandenburg region, following Leibniz' s suggestion. Like most 18th-century institutions, the Academy' s official language was French, and its most active members were largely Huguenots fleeing religious persecution.

During Frederick the Great' s reign (1740–1786), the Prussian Academy developed considerably, funding public competitions for solutions to outstanding scientific problems and acquiring its own observatory, anatomy theater, botanical garden, and laboratory. Influenced by London and Paris, the Academy became embroiled in the Newton-Leibniz controversy. Due to Frederick' s patronage, it attracted French Enlightenment thinkers such as Voltaire, d' Alembert, and

Condillac. Internal conflicts, particularly the personal clash between Voltaire and Maupertuis, plunged the Academy into crisis by the mid-18th century. However, when Frederick invited Lagrange to succeed Euler as president in 1789, the Academy achieved tremendous international prestige while making outstanding contributions to German culture and thought. Its spirit of tolerance attracted leading intellectuals of the time, including Kant and La Mettrie, with Kant' s writings on religion published in Berlin—works that would certainly have been censored elsewhere in Europe.

Overall, during this first century, science had no substantive connection to national or social needs; scientific research was largely driven by scholars' personal interests.

Laying Solid Foundations: The Second Century Rooted in the University of Berlin

Facing Napoleon' s military might, Prussian rulers deeply felt their own inadequacies. The challenge for German intellectuals was how to restore national strength when politically, economically, and militarily far behind France. The establishment of the University of Berlin in 1810, though a move for national survival, proved to be the best gift for the Academy' s centennial and marked a strong beginning for the second century, intimately linking Germany' s research system to national destiny.

Previously, universities primarily transmitted knowledge without space for generating new knowledge. For Wilhelm von Humboldt (1767-1835), the university represented the supreme means through which Prussia could win respect in the German world and globally, achieving true enlightenment and world leadership in spiritual education. Academic research resulted from individual thinking in a state of both solitude (*Einsamkeit*) and freedom (*Freiheit*)—only in this condition could individuals concentrate fully and produce creative work. Teaching had to be closely integrated with research, allowing everyone to develop according to their own will and personality, pursuing academic research as they pleased [1]. Under this philosophy, "the institutionalization of inquiry" was first integrated into teaching, making scientific exploration and academic research core features of German universities.

The University of Berlin' s success influenced university education models in Germany and worldwide. Not only did German universities remodel themselves after Berlin, but foreign institutions also directly emulated it. This emphasis on integrating teaching and research transformed Germany' s research environment by the mid-19th century, bringing scientific prosperity that proved crucial for German industrialization and comprehensive national strength. By the late 19th century, Germany had taken the lead in all scientific fields.

The seminar emerged as a new, more intensive teaching model that valued ideas and intellectual exchange, featuring smaller class sizes and more intimate atmospheres than lectures. Considered an advanced stage of learning for those truly committed to specialized research, the seminar inspired modern research, led to the modern doctorate, and gave rise to academic, specialized "disciplines" or professions, transforming the university' s organizational structure into faculty-based units. As the new seminar spread throughout Germany and across disciplines, it powerfully promoted the new critical methodology. This era produced Germany' s brilliant scientific minds—familiar names such as Gauss, Liebig, Hofmann, Helmholtz, Clausius, Kirchhoff, Riemann, and Kekulé.

The value of laboratories also gained recognition during this period. Before the 1820s, laboratory research held low status, considered suitable only for training future pharmacists, not for universities. Liebig elevated the laboratory' s status. In 1824, as an associate professor at the University of Giessen, Liebig established his teaching laboratory with two colleagues, quickly recruiting 20 students. He designed new equipment himself, enabling faster and more accurate experimental analysis. Liebig' s Giessen chemistry laboratory became Europe' s and the world' s premier facility, attracting the most talented youth from Europe and America. Hofmann, who later laid the foundation for dye chemistry and the dye industry, and Kekulé, famous for his dream-inspired benzene ring structure, were both members. They conducted experimental research day and night with unprecedented scale and passion.

Pioneering "Non-University Research" : The Imperial Physical Technical Institute

By the 1880s, German industry was thriving in all aspects, with many sectors busy imitating and adapting technologies primarily from Britain, especially in electrical equipment and machine tool manufacturing. To improve German product quality, there was urgent need to develop relevant measurement techniques, requiring advanced talent who understood both theory and industrial needs. However, German university professors had to complete substantial teaching hours, making it difficult for those who only wanted to conduct research.

Visionaries from industry and academia, including Siemens (1816–1892) and Helmholtz (1821–1894), began advocating for a new type of academic research institution outside the university system. It had to first meet national strategic needs, be independent of universities, have no teaching obligations, and be research-oriented; simultaneously, it should be free from state constraints, receiving funding only from the central government and private enterprise donations. Their proposal received support from the German Reichstag, leading to the creation of the Imperial Physical Technical Institute (PTR), which pioneered a series of non-university research institutions. The government invested over 700,000 marks, and Siemens donated 20,000 square meters of land for the institute' s construction, with Helmholtz serving as its first director (1887–1894) [2].

Both Siemens and Helmholtz recognized the relationship between basic scientific research, technological development, and economic application. Siemens stated that science “should be introduced into technology” to improve national material welfare, and that state support for scientific and technological research must serve economic interests. He encouraged establishing chairs in electrical engineering at technical universities in Berlin, Stuttgart, Munich, Aachen, and Hanover [3].

The PTR proved crucial in guaranteeing the quality of German industrial products. Today’ s renowned German product quality is inseparable from the solid foundation laid by the PTR. The PTR established standards for science-based industries, testing and certifying scientific instruments, measurement devices, and materials. It conducted important experiments, including the famous black-body radiation experiments that laid the foundation for quantum physics, placing it at the forefront of institutional innovation in science and technology at the turn of the 20th century. Perhaps the best proof of its success was the many imitators it inspired, such as Britain’ s National Physics Laboratory and the U.S. National Bureau of Standards.

From the Kaiser Wilhelm Society to the Max Planck Society: Establishing the Research Innovation System in the Third Century

The founding of the Kaiser Wilhelm Society in 1911 came exactly one century after the University of Berlin’ s establishment. According to German science historian Dieter Hoffmann, the main reason for establishing such basic research institutions outside universities was to enable more researchers to devote themselves to cutting-edge fundamental research [4]. By the late 19th century, growing student numbers had increased professors’ teaching loads to the point where they had no time for research. Facing pressure from the United States, which far exceeded Germany in both territory and population, visionaries proposed that the government should fund a series of institutions similar to the PTR. This initiative received support from Kaiser Wilhelm II.

Due to government fiscal shortages, the Society initially only covered members’ salaries, with funding primarily from private capitalists, mainly Jewish bankers and industrialists. Although German industrialists donated substantial sums, the Kaiser Wilhelm Society always sought funds from diverse channels to avoid being controlled by any particular donor’ s wishes.

The purpose of Kaiser Wilhelm Society institutes was to provide optimal services for scientific elites to conduct basic research without worries. While each institute had its own research orientation, researchers’ personal interests were not heavily restricted. Scientists had no teaching obligations but possessed the most modern equipment and numerous staff members. Institutes were organized according to the “Harnack Principle” —first identifying an extraordinary scientist as director, then allowing him to select members. The Society’ s intention was to fully trust the director’ s scholarly and organizational abilities, giving research a noble character while ensuring continuity and flexibility. However, during politically turbulent times, this principle was ruthlessly abused.

After WWI, German research was forced into stagnation. Some enterprises that had enthusiastically supported scientific research stopped their funding due to their own financial difficulties. Many institutes' budgets fell to unsustainable levels. To continue scientific research under these difficult circumstances, the "German Science Emergency Association" was established on October 30, 1920, through the advocacy of Haber and others. This was followed by the Donors' Association for the Promotion of German Science and other foundations such as the Liebig Foundation, Fischer Foundation, and Bayer Foundation. These associations operated very similarly to the later "peer review" system, aiming to provide some assistance to German scientific research in distress.

The Kaiser Wilhelm Society institutes achieved remarkable scientific breakthroughs, most notably the discovery of uranium fission by chemists Otto Hahn (1879–1968) and Fritz Strassmann (1902–1980), explained by their former colleague Lise Meitner (1878–1968), who had fled to Sweden to escape Nazi persecution. This discovery changed the course of world history.

Undeniably, the Kaiser Wilhelm Society also conducted extremely negative research, including the "poison gas" research mentioned earlier, as well as biomedical and anthropological studies during the Nazi era. Most darkly, it cooperated with Nazi policies by conducting human experiments in concentration camps.

Pursuing Excellence: Embarking on the Fourth Century of Ceaseless Institutional Innovation

By the early 20th century, Germany had initially formed a national innovation system with self-driving mechanisms. After a century of evolution, German scientific research could be roughly divided into university-based research and research at "non-university institutions," primarily the Max Planck Society, Fraunhofer Society, Helmholtz Society, and Leibniz Society.

The positioning and role of higher education institutions in Germany' s national innovation system are clear: cultivating future talent and conducting broad research. German universities possess strong autonomy, serving as academic "ivory towers." While inheriting the Humboldt tradition, they have undergone several major transformations, most notably the mass higher education reform of the early 1960s and the "Excellence Strategy" implemented in the early 21st century.

In the late 1950s, Germany' s once-proud education system faced severe crises, even being called an "educational catastrophe" [5]. The demand for reform was urgent, with insufficient talent reserves, unreasonable age structures among scientists and professors, and university enrollment lagging behind other major developed countries. Some scholars even warned that German universities had "no future" [7]. Increasing calls emerged for higher education reform using evaluation and competition to improve efficiency and quality.

To meet the demands of equitable education and research development, Germany reformed its higher education system in the early 1960s. The primary measure was implementing an "egalitarian principle," expanding the number of institutions and students, and renovating, newly establishing, and expanding higher education institutions. Between 1965 and 1975, Germany built 24 new universities. With greater emphasis on science and engineering, former technical high schools (*TH*) were upgraded to technical universities (*TU*), enabling students in relevant fields to obtain doctoral and master' s degrees. As the number of institutions expanded rapidly, student enrollment continued to increase from over 300,000 before the reform to more than 1 million in the 1990s, with the proportion of the same-age population rising from 7% to 30% [6].

These reforms expanded the population receiving higher education, enriched talent cultivation forms, trained large numbers of professionals for all sectors, particularly science and engineering, and generally improved the quality of the labor force, solving the problem of insufficient research talent reserves.

If pre-1990s reforms in German higher education emphasized "quantity" and equity, the "Excellence Initiative" (renamed "Excellence Strategy" after 2017), launched in 2005, emphasized "quality" improvement and university elitism.

In the 1990s, German higher education faced severe challenges: (1) declining government finances made funding sometimes inadequate; (2) compared to the United States and other countries, Germany was relatively weak in international high-tech competition, with serious brain drain; (3) German universities' international influence and competitiveness declined, reflected not only in Nobel Prize numbers or rankings but more importantly in talent cultivation, particularly in doctoral training models showing obvious drawbacks, such as outdated degree-granting patterns, excessively long study durations, and uncompetitive job markets. Increasing numbers of people called for reforming higher education through evaluation and competition to improve efficiency and quality.

The "Excellence Strategy,"initiated by the Federal Ministry of Education and Research (BMBF) and the German Research Foundation (DFG), directly targets promoting scientific research and academic innovation at German universities. These two organizations also oversee the program's organization, evaluation, and monitoring. By introducing direct competition among universities, they select the best for funding. The Excellence Strategy operates in five-year funding cycles, with two phases launched for 2007-2012 and 2012-2017. Funding is shared by the federal and state governments, with 75% from the federal government and 25% from the states.

The Excellence Strategy funding operates at three levels: (1) Graduate schools provide excellent research environments for young scientists and outstanding doctoral students, improving graduate training quality and enabling their key role in cutting-edge research international competition. Graduate schools offer broad research fields, encourage graduate participation in international academic organizations, and enhance academic visibility and exchange. (2) Excellence clusters fund universities to establish necessary institutions promoting interdisciplinary collaboration between universities, research institutions, and enterprises, strengthening research and training competitiveness. Additionally, excellence clusters provide good employment conditions or vocational training for young researchers. (3) Future concepts aim to create world-class universities to maintain and enhance leading positions in international academic competition long-term, while improving German universities' international visibility and competitiveness.

After the first phase, the Excellence Strategy was considered a great success, mainly manifested in three aspects: (1) It introduced competition and differentiation, breaking the original homogeneous pattern and benefiting innovation. It accelerated stratification among universities and highlighted development priorities. (2) Universities participated in cutting-edge research, leveraging innovation advantages. Whether graduate schools, excellence clusters, or future concepts, the Excellence Strategy focused on cultivating young scientists and doctoral students—the future mainstays of innovation. Greater and better participation in research benefited high-quality talent cultivation. (3) German universities' international image and competitiveness improved significantly. Universities could better attract world-class scientists and scholars than before, contributing to improved research and teaching standards.

However, the Excellence Strategy has also faced many criticisms, mainly concentrated in five areas: (1) It undermines the established principle of educational equity. (2) Insufficient funding and rushed timelines limit effectiveness. (3) It exacerbates regional imbalance—only 3% of Excellence Strategy funds flow to eastern German universities, adversely affecting local higher education development and worsening brain drain, potentially causing long-term stagnation or regression in regional education and economic development. (4) It carries the hidden danger of overemphasizing research at the expense of teaching. (5) Debate continues over whether to emphasize disciplines or highlight universities.

In summary, the Excellence Strategy has moved forward amid controversy. The goal of German higher education reform remains clear—looking to the future and facing increasingly fierce international competition, enhancing higher education strength, and cultivating world-class talent.

Conclusion

Remaining vigilant in times of peace and never being satisfied with the status quo are hallmarks of Germany' s research system. When behind, they excel at learning from stronger neighbors—British and French technology and capital imports played crucial roles in Germany' s early modernization. When at their peak, they worry about being overtaken by newcomers. Facing different situations, German scientists and science policymakers, with a pragmatic spirit, constantly reflect and adapt. Both ambitious and far-sighted, they have conducted uninterrupted institutional innovation for over three centuries, keeping their research system forever dynamic.

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Note: Figure translations are in progress. See original paper for figures.