Research on the Dynamic Mechanisms of Science-Based Technological Innovation and Industrial Evolution: Case Studies of Semiconductor, Digital Computer, and Radio Technology (Postprint)

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Abstract

Through research on technological innovation and industrial evolution in semiconductors, digital computers, and radio, this study analyzes the pathways, conditions, and drivers of science-based technological innovation and its industrialization, and elucidates the dynamic mechanisms for establishing large-scale technological innovation and industrial evolution. The study finds that the large-scale agglomeration of research institutions and corporate laboratories accelerates the pace of technological innovation and drives its diffusion along two pathways—"research institution-to-enterprise" and "enterprise-to-enterprise"—forming a chain reaction of large-scale technological innovation; large-scale scientific engineering creates critical conditions for this chain reaction, while regional resource and talent endowments constitute the boundary conditions for innovation scale; strategic demand provides the fundamental impetus for technology industry incubation, and market demand drives the evolution of emerging technology industries toward scale industries, providing sustained momentum for large-scale industrial technological innovation. The research conclusions further refine the dynamic mechanisms of industry-university-research collaborative innovation and offer implications for China's scientific and technological innovation and industrial upgrading.

Full Text

Dynamic Mechanism of Science-Based Technological Innovation and Industrial Evolution—Take Semiconductor, Digital Computer and Radio Technologies as Examples

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Abstract

Through examining the technological innovation and industrial evolution of semiconductors, digital computers, and radio technologies, this study analyzes the pathways, conditions, and driving forces of science-based technological innovation and its industrialization, and elucidates the dynamic mechanisms underlying large-scale technological innovation and industrial evolution. The findings reveal that the massive aggregation of research institutions and corporate laboratories accelerates the pace of technological innovation and drives its diffusion along two primary paths—"research institutions to enterprises" and "enterprises to enterprises"—forming a chain reaction of large-scale technological innovation. Major scientific projects create critical conditions for this chain reaction, while the total pool of regional resources and talent constitutes the boundary condition for innovation scale. Strategic demand provides the fundamental impetus for technology industry incubation, whereas market demand drives the evolution of emerging technology industries toward scaled industries, supplying sustained momentum for large-scale industrial technological innovation. These conclusions further refine the dynamic mechanism theory of industry-university-research collaborative innovation and offer important insights for China's current scientific and technological innovation and industrial upgrading.

Keywords: science-based technological innovation, industry-university-research collaboration, large-scale innovation, chain reaction, dynamic mechanism

The large-scale integration of scientific frontiers with industrial technology has given birth to aviation, aerospace, nuclear energy, semiconductor, digital computer, wireless communication, biopharmaceutical technologies and industries, driving exponential technological development. Through science-based large-scale technological innovation, the United States has established global leadership in science and technology fields [1], particularly through major scientific projects such as the Manhattan Project and MIT's Radiation Laboratory radar program, which fostered close collaboration between research institutions and high-tech companies, catalyzing electronics and digital computer industries [2] and accelerating the transformation from scientific discovery to technological invention and industrial birth [3]. Japan and European countries similarly employed major scientific project approaches to catch up in semiconductor and wireless communication technology innovation, making technological innovation a primary driver of economic prosperity and development.

Currently, China's economy has entered a critical stage of comprehensive industrial upgrading and transformation, urgently requiring high-quality economic development driven by technological innovation. However, as a latecomer economy, China must consider how to achieve science-based industrial technological upgrading under conditions of relative scientific and technological backwardness, clarify the conditions for science-based technological innovation and industrial incubation, and seize opportunities in the new round of technological revolution. This paper investigates the technological innovation, industrialization, and diffusion processes in semiconductors, digital computers, and radio technologies, analyzes the dynamic mechanisms of science-based technological innovation and industrial evolution, further refines the theory of industry-university-research collaborative innovation, and hopes to provide new development strategies for China's technological innovation and industrial upgrading.

1. Generation and Evolution of Science-Based Technologies and Industries

1.1 Science-Based Technologies

(1) Semiconductor Technology. Although transistor patents emerged as early as 1929 [Figure 1: see original paper], the germanium transistor was not officially invented until 1947 when Bell Labs achieved a breakthrough in manufacturing technology [4], prior to which vacuum tubes were widely used in industry. In 1958, Fairchild Semiconductor and Texas Instruments invented silicon integrated circuits and germanium integrated circuits respectively, though early integrated circuits were primarily applied in strategic fields such as rockets and digital computers. As technology matured and costs declined, they became widely applied, spawning numerous integrated circuit companies including National Semiconductor, Intel, and AMD [5]. Semiconductor integration density increased exponentially, with circuit dimensions shrinking from millimeter to micron and nanometer scales, making integrated circuit design and manufacturing increasingly complex and evolving from vertical integration into distinct stages of design, manufacturing, packaging, and testing. The design stage relies primarily on various electronic design automation (EDA) tools for logic design; manufacturing implements component layout and structure on semiconductor materials according to circuit logic; packaging involves mounting manufactured integrated circuits on substrates and encapsulating them with protective materials; and testing verifies logic functionality of completed chips. Semiconductor design and manufacturing are technology-, capital-, and talent-intensive industries, particularly semiconductor manufacturing, which involves complex equipment, numerous materials, and intricate processes. Semiconductor design, EDA tools, and key manufacturing equipment and materials are monopolized primarily by U.S., European, and Japanese companies. Relative to design and manufacturing, packaging and testing have the lowest technical barriers and were the first to diffuse to developing countries.

(2) Digital Computer Technology. In 1946, the University of Pennsylvania successfully developed the first-generation electronic computer ENIAC, which contained 17,840 vacuum tubes and could perform 5,000 additions per second. Before ENIAC, Britain developed the Z1 computer using relays in 1938, which could be freely programmed using binary numbers; in 1941, Iowa State University developed the first electronic computer, the Atanasoff-Berry Computer (ABC); and in 1944, IBM developed the MARK-1 computer using relays [Figure 1: see original paper]. The invention of vacuum tubes enabled computers to transition from mechanical to semi-mechanical and electronic systems, while transistors and integrated circuits further digitized electronic computers. Early computers were primarily used for ballistic and guidance calculations in national defense and large-scale scientific research departments. During the vacuum tube and transistor eras, U.S. computers were mainly driven by strategic demand, with technological levels and industrial scale comparable to the Soviet Union and Britain. In the 1950s, the Soviet Union's "Strela" computer achieved performance comparable to large U.S. computers using fewer vacuum tubes. It was not until 1965, when IBM developed the world's first large-scale integrated circuit-based general-purpose digital computer series, the S/360, and applied it in national defense, finance, aviation, and other fields, that U.S. computer technology and industry began leading other countries [5]. With the invention of various operating systems and software, digital computers further evolved toward miniaturization and micro-miniaturization and became widely applied across industries and consumer markets.

(3) Radio Technology. In the 1860s, Maxwell proposed electromagnetic wave theory, establishing the theoretical foundation for radio technology. In 1896, Marconi invented the wireless telegraph. During World War II, the application of radar and walkie-talkies marked the beginning of large-scale radio technology application, nearly 100 years after the establishment of radio theory. Subsequently, radio technology accelerated its development from directional and measurement applications to wireless communication, television broadcasting, and other fields, forming technologies and industries including wireless communication, satellite communication, Global Positioning System (GPS), radio telescopes, phased array radar, and radio and television broadcasting, with wireless communication having the most profound industrial scale and technological impact. The United States held an absolutely dominant position in first-generation (1G) mobile communication technology, with Motorola commanding over 70% market share in the wireless communication field. With extensive integrated circuit adoption, second-generation (2G) mobile communication technology drove rapid market growth through digitalization and miniaturization. In the 1980s, the Global System for Mobile Communications (GSM), led by Sweden's Ericsson and Finland's Nokia, became the most widely used 2G technology, while Code Division Multiple Access (CDMA) technology introduced by U.S. companies Qualcomm, Motorola, and Lucent lagged in competition. China's wireless communication industry fully imported foreign technology during the 2G era and continued catching up during 3G, 4G, and 5G eras, with China now achieving a leading position in global communications.

1.2 Generation and Evolution Pathways of Technology

The invention and innovation processes of science-based technologies such as semiconductors, digital computers, and radio reveal that these technologies are primarily based on modern scientific theories including solid-state physics, mathematical logic, and electromagnetism, diffusing earliest from research institutions such as the University of Chicago, Harvard University, and MIT to industry, with numerous corporate laboratories simultaneously participating. Research and development based on scientific theory, combined with industrial needs, optimizes and updates existing technologies, with different technologies combining in applications to achieve better results [6]: semiconductors combined with electronic computers form digital computers; semiconductors combined with wireless communication form digital communications; communication combined with digital computers forms the Internet; mobile communication combined with the Internet forms mobile Internet; digital computers combined with operating systems and communication terminals form smartphones, etc. As integrated circuit performance improves and intelligent operating systems become widespread, mobile phones have integrated functions including communication, music, video, gaming, office work, e-commerce, and learning, making the communication equipment industry far exceed digital computers in scale—the ratio of communication equipment to digital computer industry scale grew from 3:1 in 1980 to 38:1 in 2000. Additionally, combinatorial relationships among technologies form tree-like topological structures, with innovative technologies generated through combinations of foundational technologies such as semiconductors, operating systems, and communication networks. These combinatorial relationships simultaneously create technical dependencies, while foundational technologies realize value through newly combined technologies. Meanwhile, the number of technology combinations grows geometrically, whereas markets grow at a relatively slower power function rate, causing numerous new technologies to exit market competition, with only a few surviving and developing by adapting to market demand [6-8].

2. Strategic Demand, Resource Aggregation, and Technology Diffusion

2.1 Strategic Demand

U.S. national strategy provided early market environments for emerging technologies such as semiconductors, digital computers, and radio. The U.S. government simultaneously funded enterprises and research institutions, with government R&D investment accounting for over 50% of total U.S. R&D expenditures in 1980, and strategic defense accounting for over 50% of government R&D funding [Figure 2: see original paper]. After integrated circuit invention, primary applications were in missile and aircraft guidance systems, not entering commercial computer systems until 1965; consequently, NASA and the U.S. military were important early customers for semiconductor companies [10]. From the late

1950s to early 1970s, the U.S. Department of Defense undertook nearly 50% of semiconductor R&D funding. In 1959, the government funded 85% of electronic R&D expenses in the U.S. [5]; from 1949-1958, 25% of Bell Labs' semiconductor R&D expenses were funded by the U.S. military [10]; and due to surging defense orders, Fairchild Semiconductor's sales reached $1.3 billion in 1963 [10]. Computer R&D demand primarily came from missile guidance, airborne navigation, and nuclear weapons simulation calculations. In the 1950s, nearly 50% of IBM's revenue came from two projects concerning guidance calculation programs for the B-52 strategic bomber and air defense systems [9]. Radar and communication technologies based on radio technology were critical for guidance and communication, finding extensive application in large-scale scientific projects such as the Semi-Automatic Ground Environment (SAGE) and manned spaceflight, with wireless communication achieving large-scale market application and conducting massive technological innovation through enormous communication market profits. Motorola achieved huge success in mobile communication markets and subsequently entered semiconductor, space communication, and satellite communication fields, while Bell Labs became the largest R&D laboratory in the U.S. through massive R&D investment by AT&T, inventing transformative technologies including the transistor, UNIX operating system, C language, and optical fiber communication. Evidently, national strategic demand can provide market space for frontier technologies, with urgent demand for technological advancement accelerating the transformation from science to technology and driving it toward marketization.

2.2 Resource Aggregation

Large-scale U.S. strategic demand drove massive aggregation of scientific and technological resources, including total R&D investment, major scientific projects, large-scale corporate R&D investment, and regional clustering. First, **total R&D investment**. In 1969, U.S. R&D investment reached $25.6 billion, consistently maintaining the world's highest level, while the combined investment of Germany, France, Britain, and Japan totaled only $11.3 billion [5]. Second, **major scientific projects**. Through massive, cost-is-no-object investment in projects such as MIT's Radiation Laboratory radar program, SAGE, and the Apollo program, large-scale clustering of universities, research institutions, and corporate laboratories, along with close industry-university-research collaboration, promoted the integration of science and technology. MIT's Radiation Laboratory radar program and SAGE project drove R&D in electronics, semiconductors, and digital computers at companies including Raytheon, IBM, Bell Labs, and Fairchild Semiconductor. In 1955, IBM had approximately 8,000 employees working on the SAGE project [9]. Major scientific projects played a central role in knowledge exploration and strategic opportunity discovery beyond organizational and disciplinary boundaries, while extreme technical demands of these projects drove corporate R&D investment [11]. Thus, major scientific projects promoted scientific theory discovery, technological invention, and industrial birth [3]. Third, **large-scale**

corporate R&D investment. Massive R&D investment drove continuous innovation at U.S. technology companies, enabling rapid rise and sustained scale expansion. Bell Labs' R&D expenses for transistors and semiconductor equipment grew rapidly from £2.7 million in 1953 to £28 million in 1960 and £57 million in 1964, while only German Siemens and Dutch Philips in Europe could match this scale [5]. U.S. companies such as Fairchild Semiconductor, Texas Instruments, Motorola, and IBM also made enormous semiconductor R&D investments. The birth of digital computers was also a process of intensive resource investment, with total R&D costs for the S/360 general-purpose digital computer series reaching $500 million; although the U.S. government covered nearly 50% of R&D expenses, the massive investment nearly bankrupted IBM, requiring emergency loans to sustain operations in the final development stages [9]. Fourth, **regional clustering**. Large-scale strategic demand promoted integration of scientific research and industry, with major scientific projects further promoting clustering of high-tech industries and university research institutions. U.S. semiconductor and digital computer industries primarily clustered in Boston's Route 128 and Silicon Valley regions [10], with major scientific projects further enhancing regional resource concentration [8]. Evidently, large-scale, high-density innovation resources concentrated near university research institutions created necessary conditions for sufficient exchange and collision of different technological elements.

2.3 Human Capital

Driven by strategic demand, the large-scale expansion of major U.S. research institutions and corporate laboratories also required abundant talent resources [Figure 3: see original paper], with universities such as MIT and Stanford serving as important talent sources beyond technical talent immigration. MIT's Radiation Laboratory radar program had only 12 researchers in October 1940, increasing to 30 physicists in November 1940 and 4,000 personnel by 1945 [4]. Industrial research scale also grew rapidly, with corporate laboratories at General Electric, ITT, DuPont, Kodak, IBM, and Xerox employing between 500 and 30,000 R&D personnel [12,13]. Semiconductor and digital computer talent in Boston's Route 128 and Silicon Valley regions grew rapidly: various researchers in these two regions numbered approximately 80,000 in 1959, reaching 210,000 in 1975 and 420,000 in 1990 [10], accounting for 12.7% of total U.S. scientific and technical talent. Corporate participation in major scientific projects continuously increased R&D investment, establishing corporate laboratories for basic research and scientific innovation that profoundly changed research and talent cultivation models. In the 1950s, through participation in high-performance digital computer development tasks at MIT's Lincoln Laboratory and Los Alamos National Laboratory, IBM continuously expanded its R&D scale, establishing 12 research centers across 10 countries and extending research into basic science. By 2000, over 21 individuals from IBM's laboratories had received Nobel Prizes, U.S. National Science Awards, Turing Awards, and top condensed matter physics awards [10,13,14]. Bell Labs already employed 2,000 technical experts and 300 basic researchers in 1925, growing to 4,600 researchers by 1940 and approximately 9,000 during World War II. Bell Labs' basic research achieved revolutionary results, making fundamental inventions in information and communication technology (ICT) industries including transistors, optical fibers, and the UNIX operating system, earning 13 Nobel Prizes [4]. Stanford University and other institutions also absorbed substantial corporate technology during large-scale R&D participation, rapidly rising to become the most influential universities.

2.4 Technology Diffusion

After strategic demand aggregated resources and achieved technological innovation in semiconductors, digital computers, and radio, new technologies diffused through talent mobility along two primary pathways [Figure 4: see original paper]: First, **research institutions to enterprises**. Universities and research institutes function as scientific institutions cultivating talent. Universities diffuse scientific knowledge to enterprises through talent supply, with scientific knowledge combining with existing technology to form technological innovation. Early semiconductor, digital computer, and radio technologies diffused from the University of Chicago, MIT, and other institutions, combining with industrial technology and continuously evolving. During industry-university-research collaborative innovation in major scientific projects, science and technology diffused rapidly between collaborating organizations, while accelerating talent mobility between large research institutions and corporate laboratories and incubating new enterprises. In the 1960s, MIT incubated at least 175 new enterprises, 50 from Lincoln Laboratory and 30 from the Instrumentation Laboratory [10]. Second, **enterprises to enterprises**. Technology further diffused from high-tech enterprises and underwent re-innovation. Raytheon incubated 150 startups including Digital Equipment Corporation, while Sylvania's electronics division incubated 39 enterprises [10]. In 1956, Bell Labs engineer Shockley left to establish the Shockley Semiconductor Laboratory; later, key employees left to form Fairchild Semiconductor, which simultaneously invented integrated circuits with Texas Instruments. Fairchild Semiconductor subsequently spawned National Semiconductor, Intel, AMD, Altera, and other renowned semiconductor companies. In the 1960s, 31 semiconductor companies established in Silicon Valley were essentially all traceable to Fairchild Semiconductor [4,10]. Evidently, talent serves as both the subject of technological innovation and the carrier of technology diffusion, with human capital continuously appreciating through technological innovation and diffusion. Talent mobility and innovation collaboration constitute the primary modes of technology diffusion, with science diffusing mainly from research institutions to enterprises and technology diffusing continuously through research institutions-to-enterprises and enterprises-to-derived enterprises pathways.

2.5 Critical Conditions

U.S. strategic demand provided powerful market momentum for science-based technological innovation and industrial incubation, creating conditions for large-scale cooperation among science, technology, and industry. Revolutionary technologies and industries continuously diffused through the two main paths of research institutions-to-enterprises and enterprises-to-enterprises, forming new resource aggregation and technological innovation—that is, large-scale, intensive investment of basic science, industrial technology, capital, and talent elements generates large-scale technological innovation through sufficient exchange and aggregation, and through talent and technology diffusion and re-aggregation, forms scale growth similar to a chain reaction. However, this chain reaction does not occur naturally. U.S. institutions and enterprises conducting large-scale innovation basically had talent scales above 1,000 personnel, while regionally aggregated talent numbered at least 10,000, with both research institutions and enterprises possessing adequate technology and talent accumulation—meaning talent quantity and quality are prerequisites for any large-scale innovation project. Additionally, despite large-scale resource investment by the U.S. and Europe after the Cold War, they have been unable to reproduce revolutionary technological innovation and industry-university-research prosperity [2]. Science-based large-scale technological innovation chain reactions require not only large-scale aggregation of different innovation elements such as science, technology, and industry, but also effective cooperation among these differently backgrounded elements to achieve transformation from science to technology and large-scale combinatorial innovation. Major scientific projects provide both adequate resource support and pressure conditions for large-scale innovation in science, technology, and industry, forming critical conditions for the chain reaction of large-scale technological innovation.

3. Scale Expansion and Evolution of Science-Based Technology Industries

3.1 Chain Reaction of Technological Innovation

U.S. national strategic demand for advanced technology drove large-scale aggregation of universities, research institutions, and enterprises, forming external momentum for the chain reaction [Figure 5: see original paper]. Major scientific projects further aggregated resources and created powerful external pressure, enabling large-scale innovation to reach critical conditions and generating revolutionary technological innovations. After revolutionary innovations in semiconductors, digital computers, and radio technologies, talent and technology diffused from major scientific projects to research institutions and enterprises, continuing to aggregate resources and innovate technology in new organizations and driving continuous technology upgrading. Talent mobility and technology cooperation constitute the two primary technology diffusion modes in this chain reaction. Large-scale innovation achieves technological innovation, industrial incubation, and human capital appreciation, with both research institutions and enterprises enhancing innovation capabilities and receiving effective incentives. However, as the chain reaction continuously aggregates and diffuses, total resource requirements grow geometrically, and a country or region's total talent and innovation resources become boundary conditions for chain reaction scale—even the U.S. formed only two aggregation regions near Boston's Route 128 and Silicon Valley. Resource limitations also cause intense competition among large organizations and regions, requiring U.S. research institutions and enterprises to increase R&D and innovation investment to compete, with competition among companies such as Fairchild Semiconductor, Texas Instruments, Intel, AMD, and Motorola in semiconductors; IBM, Digital Equipment Corporation, General Electric, Bell Labs, and RCA in digital computers; and MIT, Bell Labs, Motorola, and RCA in wireless communications.

3.2 Scale Expansion of Technology Industries

The continuous expansion and exponential growth of technological innovation in semiconductors, digital computers, and radio drove increased technology integration and product miniaturization, while competitive innovation among enterprises further reduced technology product prices, accelerated new market formation, and expanded market scale. As semiconductor manufacturing processes evolved from millimeter to micron and nanometer scales, computer speed measurement increased from thousands to hundreds of millions of operations per second, and processor integrated transistor quantities grew exponentially [Figure 6: see original paper]. Computers evolved from massive volumes to compact cabinet and box forms, while wireless communications evolved from vehicle-mounted and backpack styles to handheld devices. Meanwhile, since technology supply far exceeded market growth, intense competition among enterprises drove exponential price declines for semiconductor, digital computer, and radio technology products [Figure 6: see original paper]. Declining prices, enriched functions, and miniaturized volumes drove the emergence of new markets and substantial market scale increases. Computers diffused from ballistic calculations and nuclear weapons simulation to industrial control, data processing, computer-aided design, and consumer markets, successively forming mainframe, minicomputer, microcomputer, and laptop markets, with market scale growing from \$3.2 billion in 1970 and \$20.1 billion in 1980 to \$178.7 billion in 2000 [Figure 7: see original paper]. Radio technology evolved from communications and radar to telescopes, radio and television broadcasting, entertainment, and office applications, with wireless communications evolving from communication tools to intelligent terminals. Semiconductor applications spread across various fields, with global market scale growing from \$2.4 billion in 1974 to \$317 billion in 2010, an increase of approximately 132 times [Figure 7: see original paper]. Consumer markets surpassed strategic markets as the dominant driving force for semiconductor, digital computer, and radio technology innovation, further expanding innovation scale and accelerating innovation speed. In 1980, industry R&D expenditure in the U.S. began exceeding government expenditure, reaching 70% of total R&D investment by 2000. From 1955-2015, defense accounted for over 50% of U.S. government R&D investment on average, with major scientific projects accounting for over 40% on average [Figure 2: see original paper]. The number of U.S. scientific researchers grew from 240,000 in 1950 to 1.8 million in 1970 and 5.19 million in 2000, a 21-fold increase over 50 years [Figure 3: see original paper].

3.3 Path Dependence in Science-Based Technological Innovation

Strategic demand drove large-scale application of science-based technologies, accelerating transformation from science to technology and products while incubating new technology industries, but also creating path dependence on strategic demand and large-scale R&D. During the Cold War, strategic demand was the primary revenue source for numerous small and medium technology companies near Silicon Valley and Route 128 [10], generating large enterprises such as IBM and Raytheon. Continuous development of semiconductor and digital computer technology created civilian product markets including microcomputers, the Internet, and smartphones, which rapidly grew into dominant markets. During the digital computer industry's transition to miniaturization, Silicon Valley's greater market orientation enabled sustained prosperity after the 1970s, while Route 128 enterprises, over-dependent on strategic demand and failing to transform in time, gradually declined in competition with Silicon Valley firms [10]. In the 1980s, Europe organized and coordinated Ericsson, Nokia, and other companies through major scientific projects (such as advanced communication technology development), successfully catching up to U.S. companies Motorola, Qualcomm, and Lucent in 2G development [1]. Japan's semiconductor industry primarily relied on consumer electronics markets such as radios, televisions, and game consoles, gradually developing into a scaled industry. Japanese semiconductor and digital computer industries conducted technological innovation according to market demand, using major scientific project approaches to accelerate technology catch-up, causing devastating blows to Silicon Valley. During 1985-1986, the U.S. semiconductor industry laid off large numbers and closed operations, with 25% unemployment [10], IBM forced to lay off 50% of its workforce [9], and high-tech companies such as Intel and AMD also making large-scale layoffs. Ultimately, the U.S. intervened with aggressive trade suppression policies against Japan, including "Section 301 investigations" and forcing Japan to sign the U.S.-Japan Semiconductor Agreement, gradually eliminating Japan's competitive threat [1].

3.4 Comparison of Large-Scale Technological Innovation Drivers

Both strategic demand-based and market-based large-scale technological innovation models can accelerate technological innovation, but they differ significantly in innovation pathways, conditions, and dynamic mechanisms. First, **innovation pathways**. Strategic demand-driven innovation promotes large-scale cooperation among universities, research institutions, and enterprises, forming innovation and diffusion pathways from scientific frontiers to basic research, technology industries, and product markets. Combinatorial innovation and evolution form technical network systems with relatively complete industrial technology accumulation. Conversely, market-based innovation faces insufficient motivation and longer innovation cycles due to complex technical networks and indirect technical dependencies. For example, after U.S. suppression, Japan's semiconductor and digital computer industries gradually lost competitive advantages. Second, **innovation conditions**. Strategic demand-driven large-scale innovation requires high levels of talent, research institutions, and industrial technology investment, with major scientific projects forming critical conditions for the chain reaction. For market-based technological innovation, enterprises expand R&D scale through market forces to achieve technology accumulation and increase market share. Third, **dynamic mechanisms**. Strategic demand-based technological innovation requires substantial resource input before industrial incubation, with incubated high-tech industries initially small-scale and limited in economic impact. Market-based technological innovation and economic growth form reinforcing loops, thus possessing stronger momentum. For example, after high-tech industry incubation in Silicon Valley, market forces expanded industrial scale, first surpassing Route 128 regions dependent on strategic demand innovation, then facing catch-up from Japan and the EU.

4. Conclusions and Policy Recommendations

4.1 Main Conclusions

This paper proposes a chain reaction model of large-scale technological innovation through analysis of science-based technological innovation and industrial evolution, examining the model's basic conditions, dynamic mechanisms, critical conditions, boundary conditions, and industrial evolution drivers.

(1) **Science-based technological innovation and diffusion.** Revolutionary technologies such as semiconductors, digital computers, and radio emerge from combinations of science and basic technologies, continuously combining with and improving other technologies in applications, forming technical dependency networks through these combinatorial relationships. Large-scale innovation accelerates technological innovation speed, while technology quantity expansion and competition cause price and cost declines, promoting technology market expansion. Technology combination scale increases exponentially, while market scale grows at a power function rate, intensifying technological innovation competition, driving price declines, and enabling new market emergence.

(2) **Chain reaction of large-scale technological innovation.** Large-scale aggregation of frontier science with semiconductor, digital computer, radio technologies and industries promotes sufficient exchange between science and technology across research institutions and enterprises, accelerating transformation from science to technology and industry.

Through two primary paths of research institution-to-enterprise and enterprise-to-enterprise diffusion and re-innovation, new technologies continuously emerge and incubate related industries, forming a chain reaction of large-scale aggregation-technological innovation-diffusion among science, technology, and industry. Strategic competition generates urgent demand for advanced technology, providing initial momentum for original innovation in semiconductors, digital computers, and radio. Talent and technology accumulation in research institutions and large enterprises constitute basic conditions for large-scale technological innovation, major scientific projects form critical conditions, and total market demand and talent pool constitute boundary conditions.

(3) **Evolutionary drivers of science-based technology industries.** The U.S. achieved science-based technological innovation and industrial incubation through large-scale strategic demand, but strategic demand-driven technological innovation and industrial incubation possess emergent characteristics without forming reinforcing loops with technological innovation and industrial economy, requiring powerful external economic drivers. For market-based large-scale technological innovation, market demand replaces strategic demand to form an expanded innovation dynamic mechanism, with large-scale market demand driving corporate technological innovation and forming reinforcing loops between technological innovation and industrial economic development, thus achieving higher innovation efficiency. However, market demand-driven technological innovation and industrial incubation suffer from insufficient technological advancement, high external dependency, and difficulty solving complex core technology problems.

4.2 Policy Recommendations

(1) **From the chain reaction model perspective.** Increase major scientific project construction scale to create critical conditions for large-scale technological innovation, promoting aggregation, integration, and mutual advancement of research institutions and industries in talent-dense regions, thereby driving enterprises to expand innovation scale and form reinforcing loops among technological innovation, human capital, industry, and economic growth. Increase support for small and medium technology enterprises, introducing and incubating them within major scientific projects to promote chain reaction expansion. China is in a period of rapid development with over 8 million university graduates annually, initially forming the world's largest scientific and engineering talent pool and ultra-large-scale market, providing high boundary conditions for human capital and market-driven large-scale technological innovation.

(2) **From the technology industry evolution mechanism perspective.** Increase strategic science and technology R&D scale, accelerate science-to-technology transformation speed and technological innovation advance-

ment, increase R&D investment in strategic core technologies and supply of original innovation, cultivate and incubate emerging strategic innovation industries to compensate for innovation motivation deficiencies caused by market dependence. Increase major scientific project construction, promote establishment of large joint laboratories in large enterprises, solve industrial key technology problems, and accelerate rapid industrial scale upgrading.

(3) **From the science-based technological innovation and diffusion mechanism perspective.** For complex technical network systems formed through innovation diffusion, identify weak links according to technical dependency relationships, adopt new national systems for key technology breakthroughs, accelerate major scientific project construction to break through core technology barriers, avoid problems of insufficient technological advancement and motivation in market-based innovation, reduce technological risks in corporate large-scale innovation, improve industrial technology robustness, and achieve high-level technological innovation and independence.

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