Chapter 2
Historical Breakthrough Innovations

The first part of this report highlighted the importance of breakthrough innovation for sustaining long-run growth. As discussed in chapter 1, recent economic research has associated such breakthrough innovations with general purpose technologies (GPTs) – technologies that have a wide variety of uses and find application in many sectors. However, no consensus has emerged on which technologies fall within varying formal definitions of GPTs.[1] Notwithstanding this definitional uncertainty, studying specific breakthrough innovations and their impact on growth holds substantial promise. The diverse circumstances in which innovations flourish, the varying nature of technology and the different channels through which new technology affects economic activity often preclude drawing general conclusions about why innovation happens, how it spurs growth and which policies best support innovative activity.

The second part of the report therefore explores the linkages between innovation, intellectual property (IP) and growth performance more concretely through case studies of different breakthrough innovations. In particular, this chapter focuses on three major historical innovations – airplanes, antibiotics and semiconductors – while chapter 3 explores three innovations that hold significant future promise.

The selection of airplanes, antibiotics and semiconductors for the historical case studies is to some extent arbitrary. However, they undoubtedly represent major innovations, in light of both their technological contributions and their transformational economic impact. They feature in numerous lists and academic accounts of the most important innovations of the 20th century.[2] In addition, they showcase the diverse contexts in which innovation happens, and cut across different fields of technology. In a nutshell, the airplane is a product made of a wide array of engineering technologies, antibiotics describe a product class that emerged from a narrow set of scientific discoveries and the semiconductor is the cornerstone technology featuring in numerous information and communication technology (ICT) products.

The three case studies are presented in section 2.1 (airplanes), section 2.2 (antibiotics) and section 2.3 (semiconductors) and follow closely the conceptual framework introduced in chapter 1. Each case study is divided into three parts. The first part describes the historical origin of the innovation, how it evolved from invention to widespread commercialization and the ways in which it transformed economic activity and contributed to growth. The second part looks at the ecosystem in which the innovation flourished – who were the key innovation actors, how they were linked and how public policies shaped the path of innovation. The third part investigates the role of the IP system, asking in particular to what extent different IP rights helped secure returns on research and development (R&D) investment and how they facilitated technology markets and the diffusion of new technologies. It also describes how the IP system adapted to the evolving nature of technology and market needs.

Finally, section 2.4 seeks to distill some of the main lessons learned from the three historical cases, thus establishing a base for comparison with today's breakthrough innovations discussed in chapter 3.

1. For a recent discussion, see Ristuccia and Solomou (2014).
2. See, for example, a popular list of top innovations put together by *The Atlantic* magazine. *www.theatlantic.com/magazine/archive/2013/11/innovations-list/309536*

2.1 – Airplanes

"To invent an airplane is nothing.
To build one is something.
But to fly is everything."

Otto Lilienthal,
German aviation pioneer

The airplane took off at the beginning of the 20th century, flying in the face of 19th-century predictions that "heavier-than-air flying machines are impossible".[3] By the end of the 20th century, air travel had become a relatively common experience and air transport had revolutionized global commerce. In consequence, the world became a smaller place. The story of airplane innovation is exceptionally rich, ranging from heroic inventors sacrificing their life in their quest for glory to brilliant engineering feats that were guided by trial and error as well as the latest scientific thinking.[4]

2.1.1 – The development of the commercial airplane and its economic contribution

At the turn of the 20th century, US inventors Orville and Wilbur Wright developed a wing warping and rudder structure that would provide lateral stabilization to an aircraft, and they filed a US patent on this invention on March 23, 1903.[5] The lateral stabilization provided by the wing and rudder combination proved to be an important breakthrough in the early years of airplane development. It enabled the Wright brothers' airplane, the *Flyer*, to lift from a level surface and fly for 59 seconds over 260 meters. The *Flyer* was – arguably – the first successful heavier-than-air machine.[6] By 1905, *Flyer III*, a vastly improved version of their earlier airplane design, could be easily steered to circle and turn, and was able to fly for over 30 minutes at a time.[7]

By the time Wilbur Wright demonstrated *Flyer III* to the public in 1908, there were several competing models. Alberto Santos-Dumont (1906) of Brazil and the Frenchmen Gabriel Voisin (1907), Henri Farman (1909) and Louis Blériot (1909) were among the many who introduced successful aircraft, with varying degrees of speed, range and structural reliability.[8]

But early aircraft designs like the Wright brothers' were by no means viable for passenger transport. They were small, single-engine vehicles powered by crude piston engines yielding 25-100 horsepower. Their operating speed was about 40 miles per hour, the maximum flight duration was two to three hours and they could only carry two people.[9]

It would take almost a decade after the Wright brothers' invention before an airplane could be considered an alternative and viable mode of transportation.

Applying scientific knowledge to aviation

The Wright brothers and their contemporaries managed to fly without knowing the scientific underpinnings to why they could do so.

A second breakthrough in airplane development occurred when science provided the explanation of how heavier-than-air craft could be airborne. In particular, advances in mathematics and physics explained how air circulated around an airfoil, and provided the crucial factor in explaining and estimating how air affected the lift and drag of an airplane.[10]

3. This 1895 quote is attributed to Scottish mathematician and physicist William Thomson, Lord Kelvin.
4. This section draws on Mowery (2015) and Budrass (2015).
5. Patent US 821,393, commonly referred to as "the 393", was filed on March 23, 1903 and granted on May 22, 1906.
6. During the early years of aviation, the airplane was one of several possible alternatives for air flight; another notable option was the dirigible, a lighter-than-air craft also controllable and powered by a machine.
7. Gibbs-Smith (2003).
8. In 1906, Alberto Santos-Dumont's 14-bis aircraft was the first to be certified by the *Aéro Club de France* and the *Fédération Aéronautique International* as a powered heavier-than-air flight. A collaboration between Henri Farman and Gabriel Voisin led to the *Voisin-Farman* airplane, which won an award from the *Aéro Club de France* in 1907 for the first flight at a height of 150 meters over a distance of 771 meters.
9. Brooks (1967).
10. Wilhelm Kutta, a mathematician at the University of Munich, and Nikolai Joukowski, a Russian aerodynamicist, separately formulated the same theorem on the circulation around an airfoil – between 1902 and 1911 for Kutta and 1902 and 1909 for Joukowski. In 1904 Ludwig Prandtl, a physicist at the University of Göttingen, published an explanation of the origin of vortices in moving fluids.

Hugo Junkers, a German professor of thermodynamics, applied this theory and invented the cantilevered thick wing, for which he filed for a patent in 1910 at the German patent office, and in 1911 at the United States Patent and Trademark Office (USPTO).[11] Unlike the thin wings of prior airplane designs, which were supported by struts and bracing wires, the thick airfoil strengthened the airplane's structure through the construction of its wings and fuselage. To further improve the airframe structure, Junkers replaced the commonly used materials of plywood, cloth and spruce with duralumin, a high-strength aluminum alloy. He produced the first all-metal airplane in 1915, but it was arguably impractical.[12] Junkers developed this design further and in 1917 introduced the first all-metal military airplane, the J-7/-9. Based on this military design, Junkers debuted the first all-metal small passenger airplane in 1919, the F-13.

The understanding of aerodynamic theory and its application in airplane design helped improve the structure and performance of aircraft. Some of the numerous improvements include (see also table 2.1):

- design of the single-spar aircraft wing and stressed-skin construction, whereby the structural weight of the airplane is placed on its wings and the "skin" of its fuselage (Adolf Rohrbach, 1918; improved upon by Herbert Wagner, 1925);
- addition of wing flaps to avoid stalling in air (independently invented by the German Gustav Lachmann and British firm Handley Page *circa* 1923);
- an ideal streamlined airplane shape that would optimize the airplane's lift and minimize drag (Bennett Melvill Jones, 1927);
- the introduction of retractable takeoff and landing gear, made possible by reducing the beams and spars in the aircraft wing and adopting stressed-skin construction; and
- the cowl radial engine, which enabled cooling of the engine while maintaining the structure of the airplane (Fred Weick at the National Advisory Committee on Aeronautics (NACA), based on H.C.H. Townend's 1928 suggestion).

By the 1930s, most airplane designs were for all-metal monoplanes incorporating the incremental innovations listed above. The enhanced stability of the airplane from changes in wing thickness, all-metal construction and stressed-skin construction of the airframe allowed greater internal space to accommodate passengers and freight, engines, tanks and instruments. These changes were embodied in the construction of the Boeing 247, Douglas DC-1 to DC-3, and Lockheed passenger aircraft.

More importantly, these aircraft were more reliable and durable than their predecessors.

The next important step in airplane development was the introduction of jet engines. Use of the jet engine was conceived in the early 20th century, but it only became practical with the gradual development of aerodynamic theories and their application to airframe design. There was no pressing demand for the jet engine at first, since piston-powered engines provided a sufficiently high level of performance for the aircraft in service. In addition, further improvement of the jet engine – such as the design of high-speed turbines and compressors for turbojet engines – and the development of swept wings were required to enable the necessary operating efficiencies to include the jet engine technology into the airplane. Third, two new developments – demand for larger passenger payloads and the introduction of new airframe designs that would accommodate multiple jet engines – pushed the turbojet engine into commercial airplanes. The first jet-powered commercial aircraft, the de Havilland *Comet*, only appeared in 1952.

By the early 1970s, wide-bodied commercial airplanes such as the Boeing 747, McDonnell Douglas DC-10 and Lockheed L-1011 were introduced. These craft showed dramatic performance improvements, in particular significant increases in passenger capacity and unprecedented operating efficiency from their turbofan engines.

11. Patent DE 253 788 was filed on February 1, 1910 at the German patent office, while patent US 1,114,364 was filed on January 26, 1911 at the USPTO.
12. The German authorities argued that the J-1 was too heavy (Gibbs-Smith, 2003).

Table 2.1: A selection of important figures in aviation, 1850-1935

Year	Inventor/Experimenter	Country	Description
Pioneers of aviation*			
1866	Francis Wenham	Great Britain	Introduced the idea of superposed wings in a flying machine, patented in 1866. Illustrated the importance of the high aspect ratio multiplane in his paper "Aerial locomotion", published in 1890. This design is the basis for biplanes, triplanes and multiplanes.
1870s	Alphonse Pénaud	France	First to construct a fixed-wing aircraft model that was relatively stable, namely the twisted rubber band-powered model with dihedral wings and tilted rudder fly. Also designed a full-scale aircraft fitted with a control system.
1890s	Otto Lilienthal	Germany	Conducted and recorded field experiments using gliders. His gliding demonstrations inspired many to fly.
1890s	Lawrence Hargrave	Australia	Introduced a box kite-like design which added to aircraft's stability. In 1893, he presented his findings at the International Conference on Aerial Navigation in Chicago, US.
1890	Clément Ader	France	Took off unassisted in steam-powered aircraft *Éole* at Armainvilliers, and was airborne for about 50 meters. First flight to take off unassisted, but plane was uncontrollable in air.
1903	Orville and Wilbur Wright	US	Developed wing warping and rudder structure to provide lateral stabilization to aircraft. Filed for patent in 1903, granted in 1906.
Aerodynamic theories and their application to airframe construction			
1904	Ludwig Prandtl	Germany	Theorized how vortices form in moving fluids. This along with the Kutta-Joukowski theorem formed the basis for an aerodynamic theory of the airfoil in 1917. It was later refined by his colleagues Albert Betz and Max Munk.
1910	Hugo Junkers	Germany	Filed for patent on "bodily design of airfoils" in 1910.
1911	Theodore von Kármán	Hungary	His *vortex street* theorem explained why an airflow separates from the airfoil at a high angle of attack. Explained why airplanes would stall.
1913	Armand Deperdussin	Belgium	Received patent on the first attempt to design a single-shell or monocoque fuselage.
1918	Adolf Rohrbach	Germany	Introduced the stressed-skin structure into his design for a four-engine passenger aircraft, the *Staaken E.4/20*.
1925	Herbert Wagner	Germany	A colleague of Adolf Rohrbach, he developed a theoretical framework on diagonal-tension fields to calculate stressed-skin design. His research optimized the properties of stressed skins in aircraft fuselage and wings.
1927	Bennett M. Jones	USA	Conceptualized the ideal streamlined airplane which placed the weight of the plane on its structure instead of just the wings. The aerodynamically optimized fuselage reduced both drag on the airplane and its fuel consumption. This idea paved the way for profitable civil aviation.
1928	H.C.H. Townend	Great Britain	Suggested mounting a ring around a radial engine in order to avoid turbulence from the cylinders.
Jet engine development			
1922	Maxime Guillaume	France	Was granted the first patent for a jet engine using a turbo-supercharger.
1930	Frank Whittle	Great Britain	Patent filed on an early turbojet prototype, was not renewed in 1935 because of lack of funding.
1932	Ernst Heinkel	Germany	Presented an aerodynamically optimized airplane, HE 70. Engaged in aero-engine design and also subsidized von Ohain's work on the jet engine.
1935	Hans J.P. von Ohain	Germany	Filed for a patent on his jet engine design. It was the first operational jet-engine airplane.

* The dates corresponding to "invention" for pioneer inventors/experimenters are approximate.

Source: Crouch (2000), Gibbs-Smith (2003), Heilbron (2003), Meyer (2013), Budrass (2015) and Mowery (2015).

Increasing dependence on air transport

Improvements in airplane reliability and durability helped to make air transport a viable mode of transportation, competing with surface transportation means such as railway and ocean transport. It cut travel time over long distances. By 1930, passengers were able to travel between European cities like Berlin, London, Paris and Vienna and return on the same day, making air travel a strong rival to rail transport.

In addition, the introduction of the jet engine and higher payload capacity led to a significant decrease in airplane operating costs. This in turn led to the introduction of "economy" class in 1958, and opened air travel to a greater proportion of the population. The same year that economy class was introduced, the number of passengers traveling across the North Atlantic by sea dropped drastically.[13] Table 2.2 shows the improvements in airplane performance and passenger capacity by airplane model and over time.

The decrease in costs also contributed to an increase in the share of goods being transported by air: the average revenue per ton-kilometer of shipped goods dropped by 92 percent between 1955 and 2004.[14]

13. ICAO (1960).
14. Hummels (2007).

Table 2.2: Increase in airplane performance and passenger capacity, 1936-1974

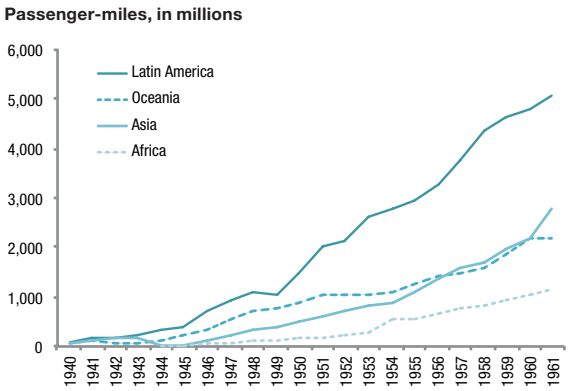
Aircraft type	Year of entry into service	Passenger payload	Mean cruising speed (mph)	Hourly productivity (capacity/ton-miles per hour)	Number built
Piston					
Douglas DC-3	1936	28	180	400	13,500
Douglas DC-4	1946*	40	205	1,000	2,300
Boeing *Stratocruiser*	1948	60	300	2,300	56
Douglas DC-6B	1951	66	315	1,950	362
Lockheed L-1049 *Super Constellation*	1951	80	310	2,800	286
Douglas DC-7	1956	112	335	2,700	338
Turboprop					
Vickers *Viscount* 700	1953	52	310	1,200	283
Bristol *Britannia* 300	1957	110	385	4,300	60
Lockheed *Electra*	1959	85	405	3,200	174
Turbojet					
Boeing 707	1958	132	570	10,500	913
Douglas DC-8	1959	142	535	9,500	208*
Sud Aviation *Carvelle*	1959	87	455	3,000	87*
Boeing 747	1969	340-493	595	30,000	1,235
Airbus A300B	1974	245	552		

* Refers to early models only.

Source: Staniland (2003).

Finally, air travel helped connect remote areas to urban areas. By the 1930s, small privately run airlines were servicing the North-South Canadian routes. There were scheduled air flights from the US, France and Germany to cities in Central and South America. Passengers from outside Europe and the US were increasingly relying on the airplane as a viable mode of transportation (see figure 2.1). Many European national airline flag carriers were founded in the 1920s, and some of them linked European cities with their colonies in parts of Asia, the Middle East, Latin America and Oceania.[15]

Figure 2.1: The number of passengers in Latin America, Asia, Africa and Oceania using air transportation increased significantly between 1940 and 1961



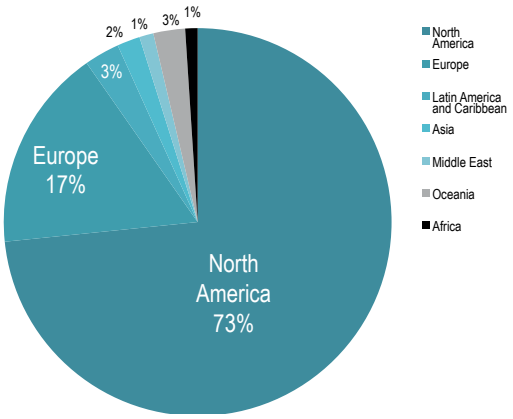
Source: Davies (1964).

15. Brooks (1967).

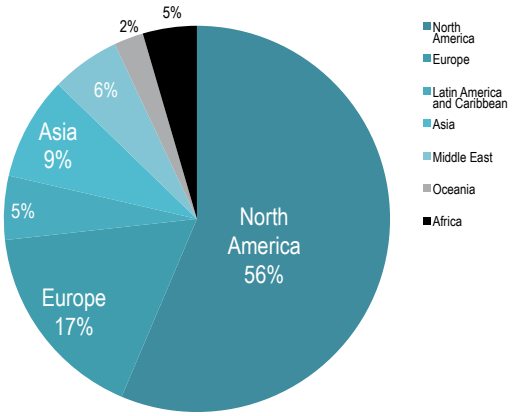
By the mid-1970s, countries outside Europe and the US were also purchasing airplanes for their own national flag carriers (see figure 2.2 below).

Figure 2.2: Comparison of the share of sales of Boeing (including McDonnell Douglas) aircraft by region, 1968 versus 1978

Total Boeing deliveries, 1968



Total Boeing deliveries, 1978



Source: Boeing (2015).

Playing an important role in economic growth

The airplane has had significant impact on economic growth since its inception.

First, the heavy capital investment required to establish a national airline flag carrier and build the necessary infrastructure to support air travel, such as airport complexes, runways, air traffic control and related service activities, has made an important contribution to economic growth. A 2006 study published by ICAO calculated that civil aviation directly contributed 370 billion United States dollars (USD) and approximately six million jobs to the world economy in 1998.[16] Another study estimated that the air transport industry accounted for between USD 11.3 billion and USD 410 billion of gross domestic product (GDP) in different regions in 2004.[17]

In addition, this investment has a multiplier effect, triggering many other economic activities that relate to growth. The same ICAO report states, "[I]n the global economy, every $100 of output produced and every 100 jobs generated by air transport trigger additional demand of some $325 and 610 jobs in other industries."[18]

Second, the combination of reliable air travel, shorter travel time and reduced cost has facilitated globalization. Both people and goods can travel longer distances in less time, thus easing the movement of both goods and services across borders. Between 1951 and 2004, growth in goods transported by air averaged 11.7 percent, as against average growth of 4.4 percent in sea shipment.[19] In addition, tourism flourished.[20]

This greater reliance on air transport has in turn contributed to the reorganization of the manufacturing supply chain and created new business models, all of which exploit countries' comparative advantages.

16. ICAO (2006).
17. USD 11.3 billion (Africa), USD 148 billion (Asia-Pacific), USD 274 billion (Europe), USD 20.6 billion (Latin America and the Caribbean) USD 16.1 billion (Middle East) and USD 410 billion (US) (ATAG, 2005). More recent estimations are available for 2014 on the ATAG site.
18. ICAO (2006).
19. Hummels (2007).
20. In 2004, 40 percent of tourists traveled by air.

2.1.2 – The airplane innovation ecosystem

The development of aviation – from the Wright brothers' breakthrough achievement of powered, controlled and unassisted flying for 56 seconds in 1903 to reliable long-distance air transportation in the 1970s – is the result of many incremental innovations and improvements from different technological fields.

These innovations were the result of interactions between many elements of the airplane innovation ecosystem, which includes the role of the inventor, academic institutions and governments and the economic environment in which innovation occurred.

Three notable factors influenced the dynamics of airplane innovation. First, there was a perceptible shift in the interaction among inventors from when attempts to fly were experimental to the emergence in the late 1910s of an industry devoted to the commercial production and sale of airframes and engines for civilian and military application. At the experimental stage, inventors shared and collaborated with one another, but this collaboration waned as the airplane industry began to form.

Second, the complexity of airplane innovation grew as advances in aviation progressed from the purely experimental application of basic mechanical engineering to heavy reliance on scientific knowledge of air circulation, and finally to today's aircraft performance optimization through the integration of complex subsystems involving electronics, hydraulics and material technology. At each stage of the development of aviation, different skills and expertise were needed for the introduction of a successful product. In addition, as newer airplane models integrated more and more systems, the innovation investment required became more expensive, and the activity became associated with a higher degree of uncertainty. In particular, the success of a new airplane product depended on optimizing the design to integrate complex systems, but how such systems will interact is often difficult to predict.

Third, governments' interest in airplane development grew as advances in aviation began to show promising avenues of application, especially for national defense purposes.

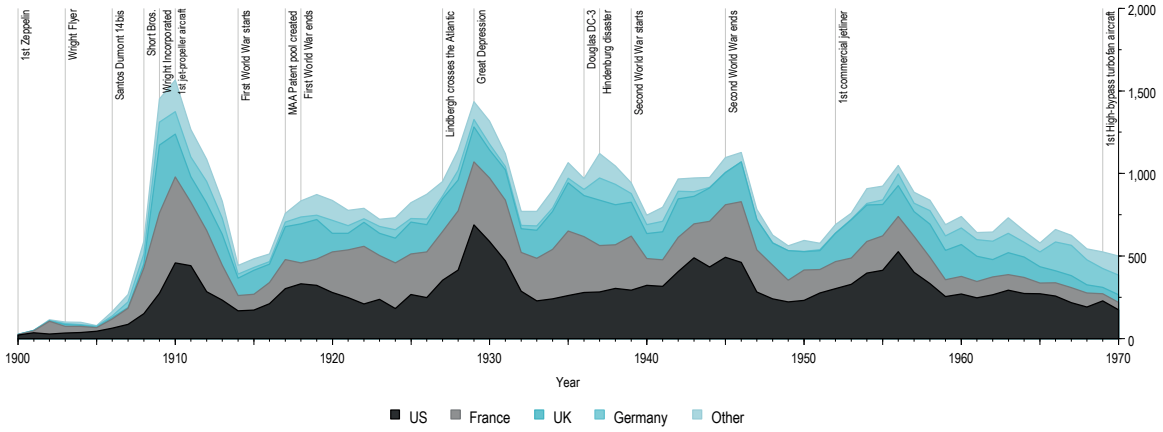
Throughout these changing dynamics in the airplane innovation ecosystem, one element seems to have held constant from 1900 to 1970: the main innovative activities in aviation were geographically concentrated in the US and Europe, in particular France, Germany and the UK, albeit with differing levels of importance among these countries over time. Global patent filing trends for that period bear out this point.

Figure 2.3 plots first avation-related patent filings by the residence of the first applicant between 1900 and 1970. There were two notable peaks in global patent filings, in 1910 and 1929. It is difficult to pinpoint the precise causes of these increases in filings. However, the earlier date corresponds to the period (1905-1910) when new airplane designs were being introduced and demonstrated in exhibition shows around Europe, while the latter coincides with the introduction of reliable passenger airplane designs such as the Douglas DC-3.[21]

21. As explained above, airplane designs of the 1930s incorporated many incremental innovations that increased aircraft performance and reliability.

Figure 2.3: Between 1900 and 1970, patent filings relating to aviation tended to be concentrated in the US, France, Germany and the UK

First patent filings by origin, 1900-1970



Source: WIPO based on PATSTAT database (see technical notes).

The changing dynamic of collaboration

In the pioneer years of flying, *circa* 1890-1905, individuals rather than governments or institutions played a critical role in advancing innovation in the field. These inventors were hobbyists and flight enthusiasts motivated primarily by curiosity; some also sought fame, but none – at least in the beginning – expected any monetary gain.

Indeed, many of them were relatively rich, having made money in other areas before beginning their experiments with flying. At this early stage, newcomers could easily participate in the community. For one thing, advances in aviation were predominantly mechanical, and could be easily imitated. Inventors would learn from previous experiments, slightly change their airplane design, then test it.

Furthermore, the latest technical developments and know-how were openly shared across the aviation community, allowing experimenters to build on the existing knowledge base.[22] There were membership-based clubs and societies on "aerial navigation" in Berlin, London and Paris. Exhibitions and conferences to showcase the latest developments in aeronautics were organized, the earliest of which was held in 1868 at Crystal Palace in London by the Aeronautical Society of Great Britain.

By 1909, there were a total of 21 aviation periodicals disseminating the latest aviation-related information. The most important of these was produced by the Frenchman Octave Chanute. In 1894, Chanute compiled and published all aviation-related experiments and their results in his book *Progress in Flying Machines*, making this knowledge accessible to the public. He was also the link that connected inventors to one another, corresponding with them and offering his ideas. At times, Chanute financed cash-strapped inventors to help them pursue their experimental work.[23]

22. Meyer (2013).
23. Among other things, he helped finance Louis Mouillard's experiments with gliders.

Before the Wright brothers' invented their wing warp design, they corresponded with and participated in this community of flying enthusiasts. During this period, government support was minimal.

As the dream of a flying machine started to become reality, the collaborative nature of aviation innovation waned.[24] It started with the Wright brothers' secrecy about their invention until they received their patent in 1906.[25] Two years after that patent was granted by the USPTO, Wilbur demonstrated their airplane model in France.[26]

Investment started pouring into the airplane industry from both the private and public sectors. Henri Deutsch de la Meurthe, a pioneer in the European oil industry, financed the development of automobile and airplane research in France until his death in 1919. Hugo Junkers funded his own aviation research, and even went so far as to build two wind tunnel facilities for his private research institute.

Airplane inventors such as the Wright brothers (1908), Gabriel Voisin (1910) and Glenn Curtiss (1916) founded their own companies to profit from their efforts. Between 1903 and 1913, approximately 200 airplane prototypes were introduced, but only a handful were manufactured.[27] Most of them were sold for government use.

Toward science-based innovation

The reliability and performance of airplanes improved significantly as innovators started understanding how a plane flies. Improvements in airplane design through the application of aerodynamic theory to airframe construction gave a technological edge to the country that could innovate in this field – Germany – over others such as the UK, France and the US.

Several elements in Germany facilitated this technological superiority. First, almost all its airplane inventors were either scientists or engineers, and could apply aerodynamic theories to produce sophisticated aircraft.[28] Even some of their pilots had engineering degrees and were able to help in calculating, measuring and testing aircraft performance. Second, several of these inventors were also university professors and benefited from their close proximity to one another. The idea for corrugated steel made with duralumin came from Junkers' colleague Hans Reissner while both were professors at the Technical University of Aachen. Third, advances in airplane design benefited from Germany's experience with the Zeppelin dirigible. Both Claude Dornier and Adolf Rohrbach worked on the Zeppelin before shifting to airplanes. The wind tunnels designed by Prandtl in 1908 – to improve the shape of Zeppelin's aircraft – were used to test the Prandtl-Betz-Munk airfoil theory up until the end of the First World War. The results of these tests informed the design and construction of airplanes in later years.

But as improvements in airplane design became more scientific, the cost of innovating in the airplane industry grew. Investment in large research and experimental facilities like wind tunnels was required to test airplane designs. In 1917, Gustave Eiffel constructed a wind tunnel capable of testing aircraft designs in Auteuil, France, but a lack of funding for aviation research reduced its potential and use.

Soon, there was an increasing gap in the aviation knowledge base among nations.[29] Inventors in other countries often lacked the skills or education needed to imitate or improve on the science-based airplane designs of their German rivals. For example, French and British designers such the Short Brothers in 1922 eagerly copied the German duralumin airplane because it was fashionable, but did not improve on it.

24. This transition is not unique to the airplane industry.
25. The brothers had disclosed that they were successful in flying in a letter to the French inventor Ferdinand Ferber on October 9, 1905, and a French article detailed their accomplishments based on their US patent application. But the European aviation community paid little attention to this announcement; it was possibly an oversight (Gibbs-Smith, 2003).
26. The Wright brothers conducted a few demonstrations in the US but failed to attract interest from the federal government.
27. Zhegu (2007).
28. Budrass (1998). Henrich Focke was a pioneer of rotating-wing aircraft; Hanns Klemm specialized in lightweight aircraft; Messerschmitt, Heinkel and Arado specialized in adaptating the aerodynamic revolution to airframe structures.
29. Constant II (1980), Crouch (2002).

In addition, there was the language barrier: The transfer of aviation knowledge across borders usually depended on translation. Hans Reissner's pioneering role in importing French knowledge on aircraft design into Germany was partly due to his proficiency in French, and it took a British scientist of German parentage, Hermann Glauert, to prepare the first translation of Prandtl's airfoil theory into English. In addition, the British journal *Engineering* translated extracts from Prandtl's contribution and reviewed them at length for its English-speaking readership.

While the latest scientific knowledge underlying advances in German airplanes was disseminated throughout the scientific community via research publications and conferences, this was not always sufficient to facilitate technological catch-up by lagging nations. In fact, one of the key channels for transmitting German knowledge was the migration of scientists and the confiscation of the country's aviation know-how after the Second World War (see box 2.1).

Box 2.1: The confiscation of German aviation know-how after the Second World War

After the end of the Second World War, the Germans were not allowed to conduct any activity in aeronautics until 1955. In addition, their patents abroad were sequestered and made available for public use. US President Truman issued an Executive Order stating "that there shall be prompt, public, free and general dissemination of enemy scientific and industrial information."[30] Thus, German patents were treated as public property and could be used by citizens of the Allied countries.

In the zones of occupation in Germany, Allied services seized an enormous amount of documents and equipment, collecting approximately 1,200 tons of technical reports, documents and patents, as well as research equipment.

Since any aeronautical activity was forbidden to Germans in Germany, a large proportion of their scientific elites migrated to Allied countries. Some 1,000 German scientists moved to the US, 40 percent of whom were considered specialists in airplane research.

Source: Budrass (2015).

Spurring airplane development through government initiative

Governments played an important role in airplane development, mainly for national defense purposes. They were crucial in facilitating the development of the airplane and disseminating knowledge, both within each country and from Germany, as the technological leader, and to the rest of the world. In addition, they became the main financiers of airplane development.

Some key government interventions include:

- supporting aviation research by creating and funding public research organizations dedicated to aviation studies, such as in France (1908), the UK (1909), Germany (1912), the US (1915) and Italy (1935);
- sponsoring prestigious international exhibitions to showcase the latest advances in flying, for example the *Salon international de l'aéronautique et de l'espace* at Paris-Le Bourget, France (1909), the RAF Air Show at Hendon, UK (1912), and the *Internationale Luftschiffahrt-Ausstellung* in Germany (1912);
- compiling the latest aviation developments and disseminating them to their researchers and manufacturers: during the First World War, the German military restricted publications related to aviation, but published the latest developments in the *Technische Berichte der Flugzeugmeisterei* for internal use; in the US, NACA regularly published translations of important aviation-related research to update its researchers on the latest European aeronautical knowledge;
- buying airplanes and subsidizing national flag carriers (see table 2.3 below).

Table 2.3: Share of airline income derived from government subsidies, in percent

	1930	1931	1932	1933
Belgium	79.8	83.0	73.5	74.8
France	79.6	81.8	79.6	79.0
Germany	63.3	68.9	69.8	64.6
Netherlands	50.9	40.4	41.0	24.0
Sweden	62.6	65.8	68.3	52.0
Switzerland	78.6	81.5	80.9	67.0
United Kingdom	69.2	48.8	35.7	39.0

Source: Miller and Sawers (1968).

30. Executive Order 9604, Providing for the Release of Scientific Information.

Two nations' innovation ecosystems and governments stood out in facilitating airplane development: Germany and the US.

Germany

Before, during and after the two World Wars, the German government made strong efforts to speed up the development and production of German warplanes.

First, it created and funded institutions that would conduct, compile and disseminate the latest aviation-related technological progress to German manufacturers.[31] One of the beneficiaries of this promotion was the aircraft manufacturer Anthony Fokker, who was the first to implement the thick airfoils developed and analyzed at the University of Göttingen during First World War. The resulting planes had a higher climb rate and better maneuverability than all Allied planes.[32]

Second, the government formed a war association of aircraft producers which included all German aircraft manufacturers and innovators. All proprietary technologies and know-how were shared among its members, greatly benefiting those that were lagging technologically.

Third, it encouraged small aircraft manufactures to form joint ventures to facilitate the faster deployment of warplanes incorporating new technologies. For example, the government initiated a joint venture between Fokker and Junkers during the First World War in an attempt to combine Fokker's experience in mass production with Junkers' latest innovation.[33]

Finally, the German government was the main purchaser of airplanes, creating constant demand. Junkers benefited from this demand. Several of his research projects applying the latest aerodynamic principles to airframe construction were financed by the government. By the Second World War, arrangements between Junkers and the German government were akin to an advance purchase commitment.

31. For example, the *Auskunfts- und Verteilungsstelle für flugwissenschaftliche Arbeiten der Flugzeugmeisterei*, the *Deutsches Forschungsinstitut für Segelflug* and the *Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren*. The German government also established research departments at a number of universities, in Aachen, Berlin, Darmstadt and Stuttgart (Trischler, 1992).
32. Anderson (1997).
33. Anderson (1997) and Budrass (1998).

US

During the First World War, the US airplane industry was so technologically backward that most of the country's warplanes were of European design. To remedy this, the government invested heavily to facilitate technology transfer from Europe and develop its own aerodynamic research capacity.

First, a federal research organization, NACA, was created in 1915 with the aim of conducting and funding R&D in airframe and propulsion technologies for both military and civilian use. It housed the first large wind tunnel that could accommodate full-scale airframes, built in 1927. A major improvement in airframe design, the NACA cowl for radial air-cooled piston engines, was developed there and later incorporated into the Douglas DC-3 design.

Second, the government funded a significant share of R&D investment for military airframes, engines and related components through defense spending. By contrast, industry financed less than 20 percent of R&D investment in the period 1945-1982. Innovation in commercial aircraft engines benefited greatly from military procurement and R&D spending. The development of the first jet engine in the US was financed entirely by the US military during the Second World War. In addition, although military R&D spending did not seek to catalyze commercial aircraft innovation, technological spillovers from military to civilian applications were an important source of innovation in commercial aircraft.

Third, the Manufacturer's Aircraft Association (MAA) was created in 1919 – under pressure from the US government – to accelerate airplane development and production. The MAA was a patent pool that would share all relevant patents pertaining to airplane designs with its members (subsection 2.1.3 discusses the MAA further).

And fourth, the government facilitated the inflow of scientific aerodynamic knowledge to the US by hiring important German scientists such as Max Munk and Theodore Kármán at NACA and US universities to build their research capacities. In addition, Ludwig Prandtl received a large contract from NACA to provide a report surveying the latest developments in aerodynamics (see table 2.1 for more on Munk, Kármán and Pradtl's contributions to aviation).[34]

34. Hanle (1982), Hansen (1987) and Anderson (1997).

2.1.3 – Airplanes and the IP system

Most scholars studying the history of the airplane assign minimal importance to patents as instruments of competitive or technical strategy. Clearly, based on the circumstances of the time, government demand for mass production of airplanes and intervention in the airplane industry played a critical role in the development of the industry. This demand reflected the military importance of aircraft and made aviation virtually unique among knowledge-intensive industries of the 20th century. It is difficult to say whether – in a counterfactual scenario – the advances in the airplane market that occurred during turbulent times of war and the threat of war would also have taken place under more "normal" circumstances.

In addition, there is little evidence of critical "blocking" patents in the breakthrough airplane innovations in the 1930s or the 1950s.[35] This is partly due to the nature of airplane innovation, which involves optimizing the integration of a complex subsystem of technologies as varied as electronics and material technology.

Nonetheless, patenting played a role in the development of the airplane industry in the early years, although it is difficult to assess how important it was. To a certain extent, patents helped early inventors to appropriate returns on their investment, and encouraged the dissemination of technologies to other countries.

Appropriating returns on investment

Patenting helped early inventors to appropriate returns on their investment. Pioneering airplane inventors filed for patents on their inventions, and built their businesses based on them. The patents prevented others from free-riding on the inventors' investments and helped sustain their competitiveness. For example, Junkers prevented the importation of Ford Trimotor airplanes into Germany on the grounds that the Ford design infringed some elements of his proprietary technology.[36]

Inventors were also able to profit from licensing their inventions. Rohrbach, for example, licensed his stressed-skin construction to British, Japanese and Italian manufacturers up to the 1930s.[37] The German ex-pilot Lachmann and the British firm Handley Page sold their slotted wing invention to governments to the tune of approximately USD 3.75 million.[38] Junkers was able to partially support his R&D investment through royalty license payments from English engineering firm William Doxford and Sons on his thick airfoil invention.[39] He also received payments of approximately two million marks from the German government for using his patented airfoil invention during the First World War.[40]

In addition, patenting facilitated the dissemination of proprietary technologies through licensing. Both Junkers and Curtiss-Wright licensed in pitch propeller technologies developed elsewhere, rather than inventing their own.[41] In 1923, the Kawasaki aircraft factory in Japan licensed Dornier's airplane design for manufacturing.

However, the disclosure element of patent documents does not appear to have proved important in disseminating innovations. The French aviation publication *L'Aérophile* published an incomplete text of the Wright brothers' 393 patent in January 1906. It described in some detail how the brothers were able to obtain lateral control, but this had little impact on aviation development in Europe.[42] In another instance, Lachmann and Handley Page independently solved the problem of airplanes stalling in the air. While Handley Page filed their patent after Lachmann, they attested that they were not aware of Lachmann's patent.

35. Mowery (2015).
36. The Ford Trimotor arguably incorporated elements of Junkers' design (Budrass, 2015).
37. Budrass (2015).
38. Miller and Sawers (1968).
39. Byers (2002).
40. Budrass (1998).
41. Miller and Sawers (1968).
42. Gibbs-Smith (2003).

To maintain their competitiveness, several of these inventors enforced their patent rights through litigation, more so at home than abroad as litigation overseas was costly. Junkers, for example, enforced his patent rights against his aircraft manufacturing rivals such Messerschmitt, Rohrbach and Dornier, to name a few. As a compromise settlement and to avoid financial trouble, Messerschmitt and Rohrbach both negotiated a partial patent exchange with Junkers. In the US, however, Junkers refrained from enforcing his patents, and chose to solicit licensing agreements with Ford Trimotor when his company was in financial difficulty.

The Wright brothers pursued litigation successfully against several of their rivals, especially at home. This was due to the US courts' generous interpretation of their invention, extending it to include "all known methods to laterally stabilize an airplane." In Europe, the German and French courts were more skeptical about their invention and applied a narrower interpretation of their claims.[43]

Extraordinary measures in times of war

The patent enforcement efforts of both Junkers and the Wright brothers underscore two points: patent litigation could be costly, and patent enforcement could have a detrimental effect on the development of the airplane. The latter point was the justification used to establish patent pools in the US, and to force Junkers into a similar patent pool-like association.

The MAA

The MAA was a patent pool established in 1917 to encourage the mass production of military airplanes. All MAA members had to grant their fellow members access to their patents relating to airplane structure – but not those covering instruments and engines. Licensing of patents to non-members was allowed as long as the terms were not more favorable than those granted to members. Any patent covering airplane design which arose from government-funded research or related activities could be used on a royalty-free basis by both members and non-members alike. Other patents that fell outside the scope of the MAA but resulted from projects for the government had to be licensed royalty free to the federal agencies. The MAA was dissolved in 1975.

The MAA had several effects on the airplane industry. First, it acknowledged the importance of the patents owned by the Wright brothers and Curtiss by granting financial concessions to both. Second, it removed the threat of litigation from either the Wright or Curtiss firms against other airplane manufacturing firms. Third, it weakened the exclusivity right of patents within the industry. In general, the MAA ensured that any airplane manufacturer had access to and could use all the technologies available in the patent pool.

The MAA's impact on airplane innovation is difficult to assess. There was a boom in terms of airplane output in the US – from 328 units in 1920 to 5,856 units in 1939, of which 256 and 2,195 units were destined for military use, respectively. But this increase in the number of US-produced aircraft also coincided with higher government spending on military as well as other initiatives to induce the mass production of aircraft during wartime.

A 1988 study found that 121 aerospace-specific patents were added to the patent pool in the period 1968-1972.[44] This figure represented only 7.8 percent of all patents in the general aerospace category for the same period, and while it probably understates the innovative activities within the industry – patentable inventions in aviation could be kept undisclosed for national interests – it suggests that the patent pool had little effect in facilitating further innovation in airplane design. But additional research on this is needed.

43. The Wright brothers applied for patents at both the French and German patent offices in March 1904. The German courts invalidated the Wright brothers' patent on the ground that they had compromised the prior art by disclosing their invention to the public before filing (Crouch, 2000). The French courts seemed in favor of the brothers' application but final decision was delayed until after their patent had expired.

44. Bittlingmayer (1988). The USPTO designates CPC code 244 for aerospace.

Box 2.2: Aviation technology transfer between the UK and the US during the Second World War

In 1941, the UK and the US signed the British-American Patent Interchange Agreement to facilitate technology exchange. Under this agreement, US and UK aircraft manufacturers were allowed to use aviation patents from either country license free for the duration of the war. It had the objective of helping the Allied forces manufacture as many aircraft as needed. At the end of the war, each patent reverted to its original owners, along with all rights and privileges.

Source: Eubank (1952).

The Association of German Aircraft Producers

In Germany, attempts were made to create a patent pool of aircraft producers during the First World War through the Association of German Aircraft Producers. This Association was established in 1917, in parallel with the *Auskunfts- und Verteilungsstelle für flugwissenschaftliche Arbeiten der Flugzeugmeisterei* to facilitate the sharing of aviation-related technologies among German aircraft producers.[45] Aircraft producers who wanted to use the distribution office had to volunteer their proprietary technologies to other members of the Association.

The Association was supposed to regulate the patent pool, but it was too weak. One of its flaws was that it was unable to convince Junkers, one of Germany's airplane pioneers, to join and share his patents.

In 1933, the Nazi government coerced Junkers into contributing his patents to the Association. From then onward, all patents in the airplane field were subject to compulsory licensing as deemed necessary. The German Air Ministry was designated the sole authority for issuing regulations for licensing and subsequent fees.[46]

While this patent pool was useful in sharing the latest developments in aviation among German manufacturers in the First World War (see the German case study in subsection 2.1.2), its effect on follow-on innovation in Germany is more difficult to establish. After the Second World War the Allied forces banned any aviation-related activities in Germany and confiscated all aviation-related technical documents. Any proprietary technology in aeronautics was made public and could be used freely (see box 2.1).

45. Office for the Distribution of Information on Airplane Research.
46. Budrass (1998), Byers (2002).

2.2 – Antibiotics

"In 1931, humans could fly across oceans and communicate instantaneously around the world. They studied quantum physics and practiced psychoanalysis, suffered mass advertising, got stuck in traffic jams, talked on the phone, erected skyscrapers, and worried about their weight. In Western nations people were cynical and ironic, greedy and thrill-happy, in love with movies and jazz, and enamored of all things new; they were, in most senses, thoroughly modern. But in at least one important way, they had advanced little more than prehistoric humans: They were almost helpless in the face of bacterial infection."

Thomas Hager
The Demon Under the Microscope, 2006

By any reckoning, the discovery of antibiotics in the 1930s revolutionized health, clinical practice and industry.[47] The development of antibiotics led to a sharp decrease in mortality and an overall increase in life expectancy within a very short time span. The decline in mortality from several infectious diseases in different regions of the world following the antibiotic revolution is remarkable. Furthermore, global diffusion of these drugs also contributed to a convergence in life expectancy among and within countries.[48]

2.2.1 – The discovery and development of antibiotics and their economic contribution

Under the broad definition of antibiotics as chemicals with microbial properties, three antibiotics stand out as the main breakthrough innovations in the historical account that follows.[49] These are the sulfa drugs in Germany in the 1930s; penicillin in the United Kingdom in the 1930s, but first mass-produced in the US later on; and streptomycin in the US in the 1940s.

There is little doubt that sulfas, penicillin and streptomycin were among the major breakthrough innovations of the 20th century. Their discovery was recognized with Nobel Prizes in Physiology or Medicine – to Gerhard Domagk in 1939, to Alexander Fleming, Ernst Chain and Howard Florey in 1945, and to Selman Waksman in 1952. Moreover, these breakthroughs also spawned a range of follow on innovations, including semi-synthetic penicillins, cephalosporins and an array of broad-spectrum antibiotics.

1930s – Sulfa drugs: the dawn of the antibiotic revolution

The development of sulfa drugs was a response to the tremendous toll that infections had on soldiers during the First World War. Streptococcal infections, in particular, were responsible for many fatalities on all sides during the war, as well as for many civilian diseases.[50]

The first effective treatments against streptococcal infections were the sulfonamides – also known as sulfa drugs – discovered in Germany after the First World War. Since the late 19th century, German chemical companies had begun to develop competencies in producing coal tar, a byproduct of coal production that became an important source of new chemicals and the basis for the synthetic dye industry. Earlier, in 1910, German chemist Paul Ehrlich had shown that compounds from dyes could be used to kill bacteria. While these compounds proved to be toxic – and were eventually replaced by penicillin – Ehrlich's work showed that synthetic chemicals could cure diseases. This led other researchers from German universities and chemical industries to search for chemicals to treat infectious diseases. Researchers from the German company Bayer – led by Gerhard Domagk, director of Pathology and Bacteriology – found a family of azo dyes with some success in killing bacteria in test tubes.

47. Mokyr (2002).
48. This section draws on Sampat (2015).
49. Bentley and Bennett (2003) and Bentley (2009).
50. Hager (2006).

By 1932, Bayer scientists had created one variation of azo dye by attaching a sulfanilamide and tested it in mice, finding strong effects in curing streptococcal infections. In the same year, patients from local hospitals were already using the first sulfa drug, Streptozon. In 1935, this was renamed Prontosil, after information from Bayer tests showed it was effective not just against streptococcal infections but others, including staphylococcal infections and gonorrhea. Soon after, researchers globally began doing laboratory and clinical testing on Prontosil using samples from Bayer. One important trait of this original development is that it became a research tool, i.e. a platform for follow-on invention. By attaching sulfa to an azo dye in the right place, Bayer researchers had the potential to make new anti-infectious medicines, starting an incredibly rich pharmaceutical field.[51]

By the end of 1935, researchers from the *Institut Pasteur* in France – directed by medical chemist Ernest Fourneau – had replicated approximate versions of Prontosil and, more importantly, discovered that pure sulfanilamide was responsible for the therapeutic effect. This discovery opened up global research on sulfa, with scientists discovering new variants against a range of infectious diseases. This in turn led to the rapid development of sulfa-related medicines. By the end of 1937, consumers could buy pure sulfa over the counter at their local drugstores under more than 20 trade names, and by 1945, thousands of new sulfa drug variants were available as well.[52]

1940s – Penicillin: the "magic bullet"

The discovery of penicillin is one of the most cited examples of "serendipitous" discovery in science. In the course of a study sponsored by the UK Medical Research Council, Alexander Fleming had laid out a dish of the bacteria *Staphylococcus* which became contaminated with a spore from what would later be identified as *Penicillium notatum*. Fleming surmised that the mold inhibited the growth of the bacteria. In 1929, he published a paper on the effects of penicillin.[53] Though this paper did not emphasize clinical or medical utility, it did note potential medical uses. In the years that followed, Fleming and his colleagues at St. Mary's Hospital in London conducted a small number of experiments in humans, but achieved only mixed results because of difficulties in producing sufficiently pure penicillin to adequately test it.[54]

Starting in the mid-1930s, a laboratory at Oxford – funded by the Rockefeller Foundation and headed by Howard Florey and Ernst Chain – had been working on antibiotics, partly based on successes with sulfa drugs.[55] In 1940, encouraged by the UK government's interest in new treatments for wartime infection, Florey, Chain and Norman Heatley succeeded in purifying penicillin for the first time. This made it possible to conduct proper clinical tests, which proved penicillin to be incredibly efficacious in treating a broad range of infections.

Following the initial tests, the next challenge was to produce penicillin on a large scale. In 1941, working with Florey and Heatley, Andrew Moyer and other US Department of Agriculture (USDA) scientists developed a medium for the mass production of penicillin. One year later, the US government convinced firms to become involved in the production. While this was initially limited to a small number of firms, eventually the US government would buy penicillin from any firm with demonstrated capabilities. Several large US firms became involved in the wartime penicillin effort, including Pfizer, Squibb and Merck. The 1940s wartime effort was a great success, making the transition from laboratory to mass production in an amazingly short period of time and attaining productivity increases of two orders of magnitude. From this time onward, companies involved in penicillin production used their newly developed capabilities to explore other opportunities, in particular the search for new antibiotics.

51. See Hager (2006), pp.137 and 143, Lesch (2007) and Bentley (2009).
52. Hager (2006, p.196).
53. A. Fleming, *Br. J. Exp. Pathol.* 10 , 226 (1929).
54. Wainwright (1990), Kingston (2000).
55. Neushul (1993).

The natural penicillins developed during the war and shortly thereafter had some drawbacks, including difficulty of administration, limited effect on certain organisms, and growing resistance. In 1957, the organic chemist John Sheehan from the Massachusetts Institute of Technology (MIT) developed the first pure chemical synthesis of penicillin with the financial support of Bristol Laboratories. This process also synthesized the intermediate compound 6-APA. Around the same time, Chain and scientists from the UK's Beecham Group found a way to isolate 6-APA from the fermentation broth. The isolation of 6-APA made possible the development of virtually any new penicillin structure that could be imagined.[56] Soon there was cooperation between Bristol and Beecham, because Beecham required Sheehan's method for making other penicillins from 6-APA and Bristol's manufacturing capability to scale up its own. This led to the production of early semi-synthetic penicillins, including phenethicillin, ampicillin and amoxicillin. Thanks to this technology, these and many other firms developed several improved variants of penicillin which are still in use today.

1950-60s – Streptomycin and other broad-spectrum antibiotics

Even before penicillin was successfully launched, other scholars had a longstanding belief that soil bacteria might be useful against other microorganisms.[57] In 1939, Merck signed a research agreement with soil chemist Selman Waksman from Rutgers University, who was already investigating a specific type of soil bacteria, the actinomycetes. The agreement gave Waksman the resources to screen soil samples and evaluate the resulting antibiotics pharmacologically, plus access to large-scale equipment for producing any promising discoveries. In 1943, Albert Schatz – one of Waksman's students – found a bacterium from soil samples and other sources that was effective against tuberculosis, naming it streptomycin. After animal and human trials in the following years, the drug was available in the market by 1950.

Streptomycin was significant for several reasons. First, neither sulfa drugs nor penicillin had much of an effect on tuberculosis, which was still a major cause of morbidity and mortality in the 1950s. Additionally, streptomycin proved useful against many other diseases, among them typhoid fever, bubonic plague and urinary tract infections. But perhaps most importantly, the discovery of streptomycin concerned not only a new medicine but also a new research tool that enabled scientists to search soil samples and other natural sources for antibiotics.[58]

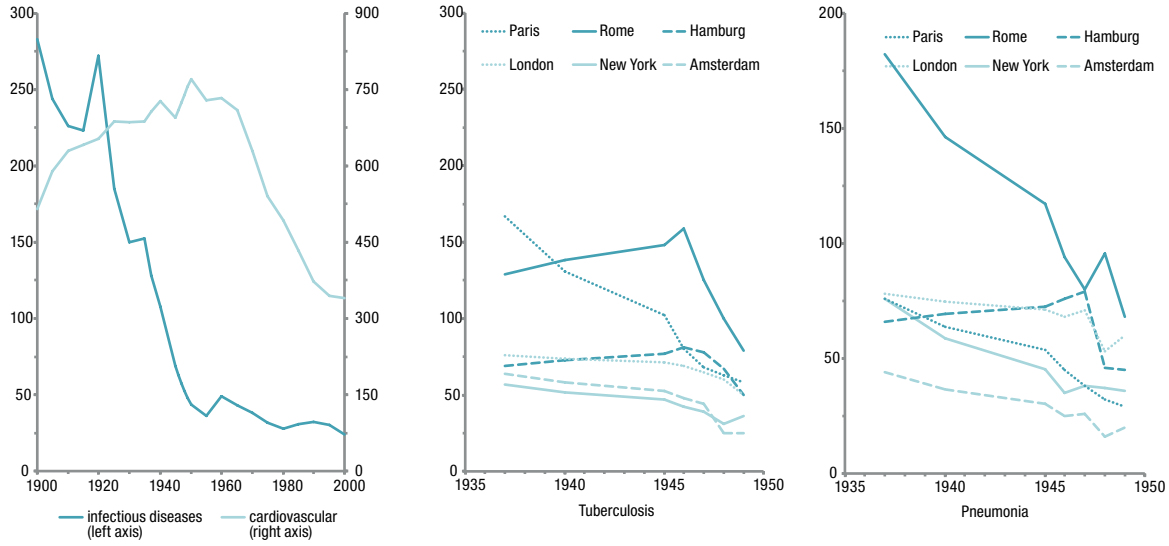
Following streptomycin, other firms also began searching soil samples for antimicrobial activity. Some of the early successes were chlortetracycline (1948), chloramphenicol (1948), oxytetracylcine (1950), and tetracycline (1955).[59] Another important early class of drugs was the cephalosporins (1964), which were based on the Italian scientist Giuseppe Brotzu's discovery of the *Cephalosporium acremonium* in a local sewer. Many of these are notable for having a broader spectrum than penicillin as well as other benefits. Still other classes of antibacterials were developed in the years that followed, such as nitroimidazoles, chloramphenicols, quinolones, monobactams, amoxicillin-clavulanic acid and imipenem-cilastatin.

In the aftermath of the antibiotics revolution, a new pharmaceutical industry was constituted which innovated in many dimensions, including developing new classes of drugs, creating new drugs effective against different types of bacteria or with better side effect profiles, and making improvements in the route and ease of administration.

56. Mann (2004).
57. Kingston (2004).
58. Temin (1980).
59. Landau *et al* (1999).

Figure 2.4: Antibiotics had a great impact on human health

Mortality from infectious diseases compared with cardiovascular diseases and in different geographical regions



Source: Cutler *et al* (2006) and Achilladelis (1993).

The economic contribution of antibiotics

There is little doubt that antibiotics have had a strong positive impact on human health. Between 1937 and 1943, sulfa drugs led to sharp decreases in mortality from a range of conditions, such as maternal mortality, pneumonia and scarlet fever. [60] Overall life expectancy in the US increased between 8 and 16 percent during this period. The discovery of sulfa and penicillin caused a marked drop in infectious disease mortality in the US; death rates from various infectious diseases had achieved their current level by 1960.[61] There is also evidence of sharp falls in tuberculosis and pneumonia mortality globally after the antibiotic revolution.[62] Certainly, other factors also contributed to this decline, including improved nutrition and public health among others. Then again, antibiotics also facilitated other forms of treatment – like surgery or cancer treatments – and so aided progress against other diseases as well.[63] In any case, the trend of declining mortality after the antibiotic revolution for several infectious diseases in different regions of the world is remarkable (see figure 2.4).

As with many new technologies, diffusion patterns were uneven. But the eventual global diffusion of these drugs helped contribute to a convergence in life expectancy.[64] Relatively soon after their discovery, the sulfa drugs diffused broadly throughout Europe and the US. Both the United Nations (UN) and the US government had programs to distribute penicillin and streptomycin globally. Similarly, the UN funded the building of new plants, including in China, Czechoslovakia, Italy, Poland, Yugoslavia and elsewhere.[65]

Generally speaking, it is difficult to place an exact economic value on the benefits of new medical technologies, but the economic contribution of antibiotics in the first half of the 20th century was surely substantial. Some estimates suggests that the value of improvements in life expectancy during this time is of the same order of magnitude as the welfare gains from per capita GDP growth over the same period.[66]

60. Jayachandran *et al* (2010).
61. Cutler *et al* (2006).
62. Achilladelis (1993).
63. Le Fanu (2011).
64. Acemoglu and Johnson (2007).
65. FTC (1958).
66. Nordhaus (2002).

The unprecedented impact of antibiotics on human health has certainly affected economic growth through labor force improvement and human capital accumulation. As mentioned, the global diffusion of antibiotics affected life expectancy, leading to a significant increase in the overall size of the workforce and probably also labor market participation.[67] In addition, the improved health conditions affected the quality of labor. Better health conditions associated with antibiotics improved employment presence in the short run, which in turn affected labor productivity. Similarly, improved childhood health must have affected schooling attendance as well as learning capabilities, so also improving labor productivity in the long run.[68]

One consequence of the outstanding diffusion and economic impact of antibiotics is the growing concern about resistant strains of bacteria related to their systematic use not only in the field of human health.

2.2.2 – The antibiotics innovation ecosystem

The innovation ecosystem surrounding each antibiotic discovery played a key role in spurring the innovations. According to all the historical accounts, strong pre-existing scientific efforts – mostly from public academic institutions – laid the grounds for the later commercial development of antibiotics. Similarly, external factors – such as war – significantly affected the public and private incentives to innovate in this industry. Correspondingly, the overall antibiotic revolution shaped the innovation ecosystem for follow-on antibiotics and medicines more generally. Not only the new discoveries themselves but also their commercial development affected the innovation environment, steering both the structure of the industry and the regulatory framework closer to those we observe nowadays.

The push from science and the disruption of war

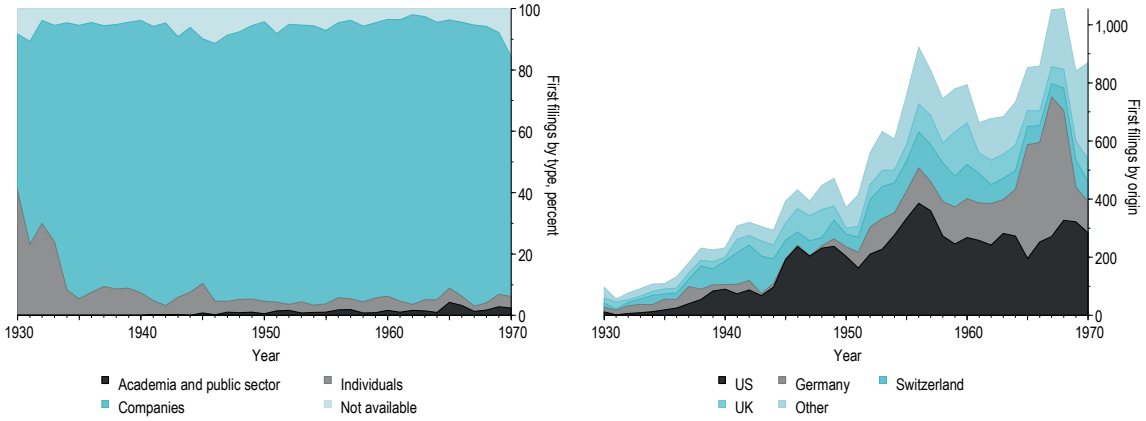
In the case of all three antibiotics, downstream innovations built on pre-existing science, demonstrating the strong links between science and industry. The channels through which academics contributed to industrial innovation varied, from "simply" doing the fundamental research to developing embryonic ideas that were further developed by industry, to working with industry support to develop a potential product. The channels through which academic research was transferred to industry were also diverse, including publication, consulting and labor mobility. Some licensing of patents to firms occurred, but in a very different way than is common today.

As with many other breakthrough innovations in history, wartime disruption was an important inducement to change, and military procurement and defense R&D played a particular role in the development of GPTs.[69] In different ways, war was crucial in the development of both sulfa- and penicillin-related drugs. In the case of sulfa, Bayer lost control of its US patents and trademarks as result of appropriations by the US government, which indirectly pushed it to search for new synthetic chemical products to replace these losses.[70] With regard to penicillin, government played a more direct role in stimulating innovation, with the urgent need for effective treatment during the Second World War fueling a massive development and production program in the US.

67. Acemoglu and Johnson (2007).
68. Bhalotra and Venkataramani (2012).
69. Rosenberg (1969) and Ruttan (2000, 2006).
70. Hager (2006).

Figure 2.5: The changing face of antibiotic innovation

First filings related to sulfas, penicillins and streptomycins by type and geographical origin of applicant, 1930-1970



Source: WIPO based on PATSTAT database (see technical notes).

What is interesting in both cases is that while wartime disruption and urgency undoubtedly contributed to the demand for innovation, both innovations built on pre-existing science. If anything, war may have spurred more rapid exploitation of existing publicly funded science. Of course, it is not an easy task to link such "scientific push" to a precise magnitude. However, a look at historical patent data suggests that one can associate about one-third of antibiotics inventions in the early 1930s with non-industry inventors (see figure 2.5). This is likely to be an underestimate, because scientific discoveries will not always have led to patentable outputs – as with Fleming – and, when they did, academic institutions may not have appeared as applicants as that practice was less common than it is today.

From discovery to mass production and commercialization

The role of the private sector in bringing antibiotics to the market was substantial. Private companies were responsible for scaling up production and establishing the commercial channels to diffuse the new drugs. This includes also mass production and distribution for the trial phase. Moreover, in many cases they provided financial support for the scientific discoveries. Sulfa is the clearest instance of such involvement, as Bayer sponsored the research and executed it within its premises.[71]

The private sector's role concerned not only the development of the discovery, but also follow-on innovation. For instance, the main stakeholders to profit from the sulfa platform – even without the azo dye – were chemical companies which had dyestuff experience, many of them from Germany and Switzerland.[72] Figure 2.5 illustrates an increasing pattern of sulfonamides-, penicillin- and streptomycin-related patents filed mainly by German, Swiss and US applicants – mostly private companies – even decades after the initial discoveries.

However, penicillin is an example of how much effort it can take to bring the benefits of a scientific discovery to end users. As mentioned before, one of the main challenges in developing related medicines was mass production of pure penicillin at a profitable yield. Interestingly, after synthesizing pure penicillin, Florey and Chain did apparently discuss the idea with a number of British pharmaceutical firms – including Glaxo and Imperial Chemical Industries – but these firms lacked the ability to mass-produce penicillin, in part because of wartime bombing and concerns about a possible German invasion.[73] Even after USDA scientists had developed the mass-production process, the US government had trouble convincing private firms to become involved in the production effort. To convince them, it had to coordinate clinical testing, fund the transfer of capabilities and equipment, support university research aiming at overcoming technical hurdles in scaling-up production, and foster the exchange of technical information.[74]

71. Hager (2006).

72. Achilladelis (1993).
73. Wainwright (1990).
74. Neushul (1993).

In the aftermath of the wartime scaling-up of penicillin, the pharmaceutical industry was completely transformed, with firms having internalized and formalized the R&D process. Companies transformed into vertically integrated firms with research, manufacturing and sales arms, focused on discovering, making and commercializing drugs. Patents and trademarks, together with aggressive marketing, became essential aspects of the business model. There were also significant economies of scale that encouraged concentration.[75] The rapid entry of firms after the initial innovation in penicillin during and after the Second World War was followed by much slower entry thereafter and, subsequently, exit of many companies.[76] The early entrants accounted for much of the production of penicillin into the 1970s, which suggests increasing returns on R&D. The development of synthetic penicillins facilitated a round of new entries, though the strongest firms were still the incumbents. Streptomycin still had a relatively large number of suppliers, but the drugs introduced later typically had just one or a few in each market.

Breakthrough innovations and the regulatory framework

At the beginning of the development of antibiotics there were still no requirements for large-scale trials. A series of deaths linked to some of the earlier sulfa drugs in the US contributed to the passage of the Food, Drug, and Cosmetic Act of 1938, which gave the US Food and Drug Administration (FDA) powers to regulate drug safety and efficacy.[77] Among other things, the Act created the need for drugs to be prescribed by doctors rather than sold over the counter. In the 1950 and 1960s, reports of birth defects from thalidomide and the rise of aggressive marketing contributed to a new wave of regulation. A particular concern in pharmaceuticals was overprescribing fixed-dose combinations of existing antibiotics such as penicillin and streptomycin. Companies were marketing these combinations widely with little evidence of effectiveness, contributing to bacterial resistance.[78] Among other fixes, the legislation aimed to create an efficacy standard at the FDA to ensure that new drugs worked, and to increase competition.[79] In 1962, the Kefauver-Harris Amendment Act helped to modernize the FDA by institutionalizing the need for randomized clinical trials before drug approval.

Most European countries have also strengthened their product approval regulation since the 1960s. The UK Medicines Act of 1971 was the closest parallel to the US, but elsewhere in Europe regulation remained weaker than in the US and UK. In Germany, even in the wake of the thalidomide tragedy, there was strong opposition to drug regulation and a belief that the pharmaceutical industry could self-regulate. France, Japan and Italy were also much less demanding than the US. There was considerable variation in national drug regulations across Europe until at least the 1990s.[80]

The regulatory changes in the late 1930s in the US helped to shut down a lot of low-quality drug retailers and spawn the search for safer and less toxic sulfa variants. The more stringent regulations from the 1960s and 1970s in the US and UK also had an effect on the industry structure, obliging weaker and less international firms to exit the market. Such changes have increased the cost of development and approval, but arguably they have also penalized the less innovative firms. In any case, they undoubtedly altered the marketing strategies of drug companies in the decades that followed. Moreover, another consequence of regulations was stronger industry-university relations, as the increasingly demanding and sophisticated clinical trials required access to hospitals able to design and implement them.[81]

2.2.3 – Antibiotics and the IP system

IP has played varying roles in the history of different antibiotics, and there is a great deal of anecdotal evidence on the potential and limits of IP protection. One can observe several cases where scientific discoveries and production methods have been patented, but many others where they have not. There has also been a systematic use of trademarks, often overlooked and underappreciated. Moreover, as with other regulatory aspects, breakthrough innovations in antibiotics have affected the IP system at least as much as the system has stimulated innovations.

75. Temin (1979, 1980).
76. Klepper and Simons (1997).
77. Temin (1979, 1980).
78. Podolsky (2015).
79. Carpenter (2014).
80. Vogel (1988), McKelvey *et al* (2004) and Carpenter (2014).
81. McKelvey *et al* (2004).

Appropriation of innovation through patents

One of the goals of the patent system is to promote innovation by means of the appropriation of inventions. This seems to have provided the necessary incentives for Bayer to develop the sulfa drugs. On December 25, 1932, Bayer filed the first patent related to a sulfa drug – entitled "Processes for the production of azo compounds" – which was issued in 1935.[82] Domagk and other scientists at Bayer immediately began not only to patent this compound, but also to discover and patent all related ones that worked. By the 1960s, they had filed more than 50 new patents related to sulfas. This active patenting practice was already widespread within the German chemical sector. Between 1905 and 1915, the German chemical company Hoechst filed no fewer than 20 patents based on Ehrlich's research. Most of these were process patents, as Germany – like most other countries at that time – did not allow product patents in pharmaceuticals.[83] In practical terms, Bayer did not patent the molecule, just the research platform for combining azo dyes and sulfonamides, which became irrelevant after the *Institut Pasteur*'s discovery.

Conversely, the penicillin story is typically viewed as one where patents did not play much of incentivizing role, given that there were no patents for the discovery or synthesis of pure penicillin.[84] While some have suggested that Fleming's non-patenting of penicillin was one reason why it took so long to get commercialized, others dismiss this claim on the grounds that there was limited scope to patent what Fleming described in his papers. Similarly, some argue that even if the Oxford team had sought patent protection, the outcome would have been uncertain for many reasons: the penicillin mold was a natural product; product patents in pharmaceuticals were not instituted in the UK until 1949; and the research team had disclosed the synthesis process in a publication before they became interested in patenting it.

In any case, some patents did protect the process for mass-producing penicillin. In 1944, Moyer and Robert Coghill filed for a patent for the "Method for production of increased yields of penicillin", which was granted in 1947 and assigned to USDA.[85] Non-acknowledgement of the British collaborators would eventually become the source of controversy in the UK, where some British researchers also alleged that the US researchers had privatized a public discovery. In any case, the belief that the UK had lost out on penicillin led British researchers to be more inclined to patent other medical discoveries later on.[86] It is also worth noting that around the same time, many UK and US firms – such as May & Baker, Glaxo, Eli Lilly and Merck – also filed for patents related to the process of producing penicillin.

The importance of patents for incentivizing the development of later antibiotics is more obvious. The search for these antibiotics was explicitly about developing new, exclusive molecules in an era when price competition on first-generation antibiotics had made the industry unprofitable. The discovery of streptomycin resulted from this new approach, although ultimately IP relating to it was protected in a relatively unrestrictive way. In particular, the research that led to the discovery was carried out under an agreement between Merck and Waksman aimed at discovering antibiotics that would be patented in exchange for support for R&D and clinical trials. In 1945, Waksman and Schatz filed the first streptomycin-related patent, which was assigned to the Rutgers Research and Endowment Foundation in 1948.[87] In practical terms, this meant that the streptomycin molecule was patent protected – although not by Merck – while the research platform was kept in the public domain. Some scholars argue this setting was fundamental for promoting follow-on innovation.[88] The possibility of patenting products of nature combined with freedom to use the methods to look for them increased the patentability prospects of many antibiotics which followed, not only for Merck but the whole industry.[89]

82. Patent DE 607 537.
83. This law did not change until 1968 in Germany. Similarly, the UK allowed product patents only in 1949, France in 1967 and Italy in 1978. See Dutfield (2009).
84. Bentley (2009).
85. Patent US 2,423,873.
86. See Wainwright (1990). For instance, Florey filed a patent in 1952 on the process to produce cephalosporin which was based on Brotzu's discovery (patent US 2,883,328).
87. Patent US 2,449,866.
88. Temin (1980) and Merges and Nelson (1990).
89. Kingston (2001).

The case of synthetic penicillin also reflects the changed role of patents in the antibiotics industry. According to Sheehan's account, the prospect of patents for synthetic pencillins after the war was much more important to drug companies than it had been for natural penicillins during the war. In 1957, Sheehan – who was already listed as an inventor in more than 10 patent applications relating to penicillin and streptomycin at Merck – filed a patent in the US for synthetic penicillin. In the same year, the Beecham Group filed a patent application relating to synthetic penicillin in the UK, which was granted in 1960.[90] The Beecham Group has stated that the original decision to expand drug research into semi-synthetic penicillins and the basic work that led to the discovery and development of the new penicillins would not have taken place without the incentives of patent protection.[91]

Trademarks – the other means of appropriation

Even without enforceable patents after the *Institut Pasteur*'s discovery, Bayer still managed to make significant revenues from sulfa drugs. Bayer secured its competitive advantage using its first-in-class status, brand name and strong sales. Brand recognition protected by trademarks proved to be a rewarding strategy for Bayer in particular, and for the industry more generally.[92] Bayer marketed its sulfa drugs first as Streptozon and later as Prontosil, Prontylin and Prontalbin.

Much as the Germans had done with sulfa drugs, firms began using brands aggressively to try to strengthen and lengthen their market positions. This was particularly important when there was significant within-class competition which exerted price pressure on early antibiotics.[93] By 1954, there were over 100 antibiotics marketed in the US under more than 600 trade names, which evidently created much confusion for physicians.[94] Related to this, firms began investing in marketing to doctors. Most major companies invested heavily in expanding their sales forces. As a result, marketing and sales became at least as important as R&D for pharmaceutical companies. Firms spent around one-third of their sales revenue on average on marketing, but less than one-sixth on R&D activities.[95]

90. Patent GB 838,974.
91. Taylor *et al* (1973), p.259.
92. Dutfield (2009).
93. Temin (1979, 1980).
94. Welch (1954).
95. Achilladelis (1993).

Disclosure, collaboration and diffusion

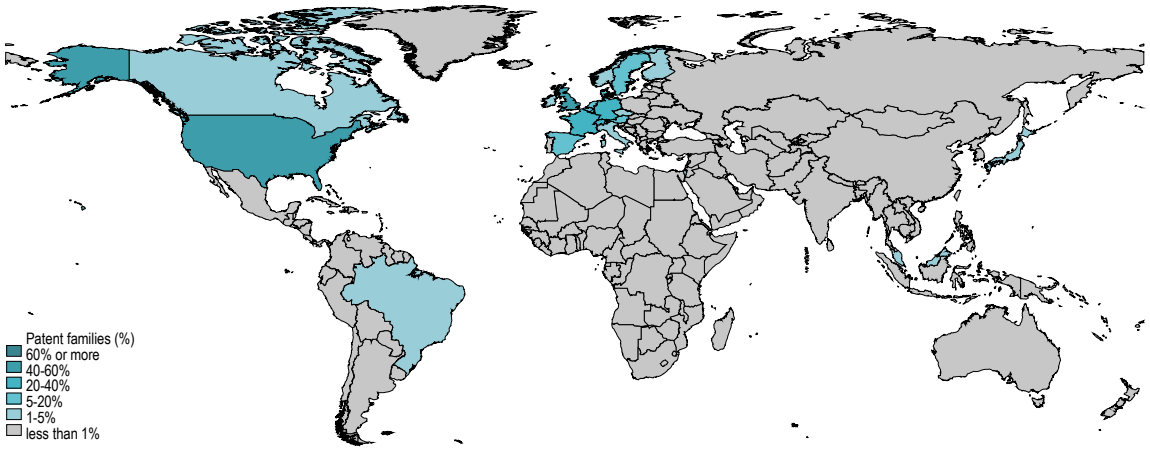
Another of the goals of a patent system is to promote disclosure. Some accounts of the development of sulfa indicate that Bayer had concerns about the effects of publicizing the invention which led it to delay applying for patent protection until other variants of sulfa had been found. There was no way to protect the area forever, because its earlier work already suggested that any number of azo-dye derivatives could be active as medicines. Bayer could not patent them all, but delaying application gave it time to find and patent the best of them.[96] Following the issuance of the first patent, Domagk published an article about the discovery and Bayer released it more broadly for trials, including to hospitals.[97] However, given its concerns about reverse engineering, Bayer apparently strove to prevent complete disclosure in the patents write-up. The publication of the main sulfa patent revealed how to replicate Streptozon at least in vague terms.[98] Regardless of whether the source was the scientific publication or the patent document, the disclosure eventually allowed researchers from the *Institut Pasteur* to experiment and identify sulfanilamide, an already-known molecule, as the key ingredient. Disclosure and subsequent inventing around the existing patents certainly incentivized the discovery, which made Bayer's patents valueless.

Providing a framework for disclosure also facilitates collaboration. By the pioneering researchers' own accounts, patents allowed academia and industry to cooperate to produce early semi-synthetic penicillins. One of Sheehan's motives for obtaining a patent was to be able to collaborate more freely with Bristol Laboratories.[99] Similarly, patent protection allowed Beecham to persuade Bristol to share their manufacturing know-how. Unfortunately, this collaborative effort broke down eventually and there was a long legal dispute about whether Sheehan or the Beecham Group had priority to 6-APA. This dispute was settled in favor of Sheehan in 1979. As already discussed, the research collaboration between Rutgers and Merck leading to streptomycin was also supported by patent rights.[100]

96. Hager (2006).
97. G. Domagk (1935) in *Dtsch. Med. Wochenschr*, 61, p.573.
98. Hager (2006).
99. Sheehan (1982).
100. However, there was controversy about whether Waksman or Schatz deserved the credit for the discovery and also the royalties. This ended in a US court ruling in 1950 in favor of compensating Schatz.

Figure 2.6: Limited patent protection for antibiotics was sought outside the US and UK

Share of patent families worldwide for which applicants have sought protection in a given country, before 1970



Source: WIPO based on PATSTAT database (see technical notes).

All of these breakthrough inventions diffused rapidly and at low cost within industrialized countries, suggesting that patents did not get in the way. As mentioned, after the French discovery, the base compound of the sulfa drugs was not patentable and the same seems also true for Fleming's penicillin discovery. This lack of patentability helped spur broad diffusion. In the case of streptomycin, Merck agreed to license it broadly under pressure from Waksman and Rutgers. In addition, product patents were not widely available even in developed countries until the late 1960s, and most developing countries did not allow for pharmaceutical product patents until after the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) in 1995.[101] Several scholars have noted that in spite of this, it took considerable time for the breakthrough antibiotics to diffuse to developing countries.[102] Moreover, many of the infectious diseases they treat remain problems even today, when patents have expired. A look at the historical series of antibiotics patents suggests that this was not only the case in developing countries (figure 2.6). A substantial proportion of patents filed before the 1970s sought protection only in the UK and US, making most of the inventions accessible in jurisdictions with many competing companies such as Germany, France, Switzerland and Japan.

Co-evolution of the patent system with science and industry

The antibiotic revolution in many ways created the pharmaceutical industry, and it also shaped dramatic changes within the industry in the years that followed. As the discussion of broad-spectrum antibiotics above suggested, the initial breakthrough innovations generated profits and created capabilities which would later be deployed in the search for other antibiotics and other drugs. Across all drug classes, this later search focused explicitly on getting patentable inventions to be produced exclusively. This was supported by large, vertically integrated firms active in research. Patent litigation and races to obtain patents became more common. Once firms obtained patents, there was heavy marketing of drugs. This growth of marketing, combined with concerns about inappropriate utilization and high prices, prompted new drug regulation, which is thought in turn to have raised the costs of drug development, and perhaps also the importance of patent protection.

101. Deere (2008).
102. Cutler *et al* (2006).

One lesson from the breakthrough innovations is that science, technology, law and firms' strategies co-evolve. This makes it very difficult to tease out the causal role patents and other intellectual property rights have on innovation. It is difficult to say how the development of the breakthrough antibiotics would have played out with weaker or stronger patents. However, it is much clearer that the antibiotic revolution helped create the modern patent-intensive pharmaceutical industry, by creating capabilities and profits that generated subsequent innovation, and by shaping patent laws, patent standards and firms' patent strategies.

Streptomycin was one of the precedents that led to changes in US patent law. Previously, a "flash of creative genius" was needed to establish patentability. This standard would bar many antibiotic patents, which were developed through well-known techniques. The Patent Act of 1952 changed the "creative genius" requirement to "non-obviousness", which may have been more amenable to obtaining patents from routinized large-scale R&D efforts.[103] Other countries followed in enacting non-obviousness or "inventive step" requirements, including Japan in 1959, Sweden in 1967, France in 1968 and the UK in 1968.[104] The granting of a composition of matter patent was an important precedent for the pharmaceutical industry, as was the emergence of the non-obviousness requirement.

Around the same time, other changes in US legislation aimed to create an efficacy standard at the FDA to ensure that new drugs worked and to eliminate patents for "me too" and fixed-dose combination drugs.[105] The original bill of the Kefauver-Harris Amendment Act also included provisions for compulsory licensing, essentially allowing market entry at three years in exchange for reasonable royalties. Arguably, such amendments to regulation had their roots in concerns about negative effects of patent monopolies on antibiotics, but they are commonly cited reasons why patent protection is more important in pharmaceuticals than other sectors. On the one hand, trials increase R&D costs significantly, making the need for long patent terms to recoup investments. On the other hand, the need for trials makes inventing around a patent harder: One can tweak a molecule, but it is costly to introduce this changed molecule to market, requiring expensive new trials.

Before the 1970s, academic institutions were reluctant to become actively involved in patenting and licensing activities, especially for health-related technologies.[106] In almost all the discussed cases, academics were somewhat nervous about patenting public health-related technologies. Academic institutions were similarly reluctant. For instance, the assignee of Sheehan's patent on synthetic penicillin was not MIT but the Research Corporation – a third-party technology transfer agent founded in 1912 – which handled academic patents for many institutions in the post-war period. Not only were academic institutions reluctant to get involved in licensing patents; when they did so, as in the case of streptomycin, they were inclined to adopt a broad approach and favor increased competition. In the US, academic institutions became less reluctant to be involved in patenting and licensing medical inventions in the decades that followed. Through a range of developments which culminated with the Bayh-Dole Act of 1980, federal policy supported patenting and exclusive licensing of the results of public medical research. Whether and how this focus on patenting and licensing has influenced the other types of university-industry interaction and channels of technology transfer that were important for breakthrough innovations remains unclear.[107]

As mentioned in subsection 2.2.1, there is growing concern about antibiotic-resistant strains of bacteria. Some argue that this will significantly impact incentives to develop new antibiotics, prompting changes to the institutional and regulatory framework related to the pharmaceutical industry, including potentially to the patent system.[108] However, it is not yet clear how these dynamics will play out.

103. Dutfield (2009) and Kingston (2004).
104. Kingston (2001).
105. Carpenter (2014).
106. Mowery and Sampat (2001a, b).
107. Mowery *et al* (2004).
108. Outterson *et al* (2007), So *et al* (2011) and Jaczynska *et al* (2015).

2.3 – Semiconductors

"Integrated circuits will lead to such wonders as home computers…automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today."

Gordon Moore,
co-founder of Intel, 1965

A semiconductor is a material that can conduct electricity only under certain conditions. This property makes it a good medium for the control of electrical current and allows semiconductor devices to switch, amplify and convert electrical current. Semiconductor technology is at the origin of the development of the ICT industry and today's digital economy. The invention of semiconductors led to the rapid rise of mainframes and later personal computers (PCs), in turn giving rise to the informatization of entire industries, and institutions such as hospitals, schools, transport and homes.[109]

2.3.1 – The development of semiconductors and their economic contribution

The word "semiconducting" was used for the first time by Alessandro Volta in 1782 as he experimented with the electrical properties of materials. The technological breakthrough behind semiconductors depended on a series of scientific discoveries and technological inventions, and culminated in the invention of the microprocessor, which is at the heart of any PC or device with processing power.

The history of the semiconductor can be divided into four historical periods: vacuum tubes, transistors, integrated circuits (ICs) and microprocessors. Put simply, microprocessors consist of a large number of ICs, which in turn are nothing more than bundles of lots of linked transistors on a chip.

Vacuum tubes (1900-1945): laying the scientific foundations for semiconductors

After more than a century of scientific research, in 1904 Jagadish Bose obtained the first patent for a device that used the properties of semiconductors to detect electromagnetic waves for use in radio.[110] In 1908, Lee De Forest patented the vacuum tube triode, a device to detect and amplify weak radio signals.[111] These devices were also used as rectifiers to convert alternating current into direct current. The First World War provided a strong stimulus to the development of new generations of amplifiers and their mass production. The growing volume of telephone traffic created additional demand for amplifiers.[112] After the war, amplifiers based on vacuum tubes fostered the development of telephony, radio and computers.

Vacuum tubes presented a number of technical issues, however. The metal in the tubes burned out and they were too big, unreliable and energy-consuming. During the Second World War, the military forces, mainly in the US, demanded large quantities of high-quality radar receivers. In the meantime, in the UK, military needs and efforts at Bletchley Park led to the development of the first electronic programmable computer, the Colossus.

Although vacuum tubes were more reliable and allowed for more applications than previous technologies, their deficiencies became increasingly evident with industrial production, posing an important research challenge.

Transistors (1945-1950s): from the Bell invention to innovation by (rival) firms

After the war, Bell Telephone Labs, a subsidiary of American Telephone & Telegraph (AT&T), became one of the leading forces for future innovation in the industry. In December 1947, Bell announced the – serendipitous – invention of the transistor by a research team led by William Shockley. Soon after, Shockley left Bell Labs to set up his own company, Shockley Semiconductor Laboratory. Transistors played a crucial role in the development of electronic devices. Their small size, low heat generation, high reliability and low power requirements allowed the miniaturizing of complex circuitry such as that needed for computers.

109. This section draws on Hoeren (2015a).

110. Patent US 755,840.
111. Patent US 879,532.
112. Levin (1982).

European researchers and firms were also sufficiently technologically advanced to be able to develop and produce transistors. In August 1948, the German physicists Herbert Mataré and Heinrich Welker from the Compagnie des Freins et Signaux Westinghouse in France filed an application for a patent on "*le transistron*". Their research was independent of and concurrent with the research by Bell Labs. Only one week after Bell's announcement, Philips in the Netherlands produced a workable transistor, followed shortly thereafter by Thomson-Houston of France, and General Electric Corporation and Standard Telephones and Cables of the UK.[113]

A succession of product and process innovations improved upon the first transistor, finally leading to the invention of the planar transistor by Jean Hoerni. Hoerni had just left Shockley Semiconductor to set up Fairchild Semiconductor.

ICs (1960s): the rise of individual startups and Moore's law

The successor to the transistor, the IC, was developed and patented independently in 1959 by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor.[114] Independent research conducted in Europe was leading scientists in a similar direction. In 1952, the British physicist G.W.A. Dummer had the same intuition as Kilby. Based on his idea, the British company Plessey produced the world´s first model of an IC.

The price of the IC was competitive compared with discrete transistors, ensuring a rapid diffusion of the technology and especially its use in mainframes for military purposes or large businesses, and much later in large computers in firms and laboratories. Further miniaturization and increased computing power of ICs became the target of the semiconductor industry. The 1965 prediction of Gordon Moore, one of the founders of Fairchild Semiconductor and Intel, that the number of transistors on a single chip would double every 12 months – which he later revised to every 24 months – proved broadly correct in the decade that followed, and is known to this day as Moore's law.

Microprocessors (1970s-1990s): the application of semiconductors to PCs

Microprocessors enabled the rise of PCs, which spread computing to households and small businesses. Microprocessors were much more complex than ICs. A single chip included more than 100,000 components and gates.

Texas Instruments and Intel both claimed to have developed the first microprocessor between 1970 and 1971. From the 1970s, Japanese producers developed and mass-produced microprocessors, becoming an important challenge to Intel and most US firms (see section 2.3.3).

In the meantime, process innovations and the development of computerized design tools enabled the task of chip product design to be split off from manufacturing. These important innovations allowed firms to specialize. They also created a market opportunity for new firms – especially in Asia – as these would mass-produce cheap chips for ICT production worldwide.

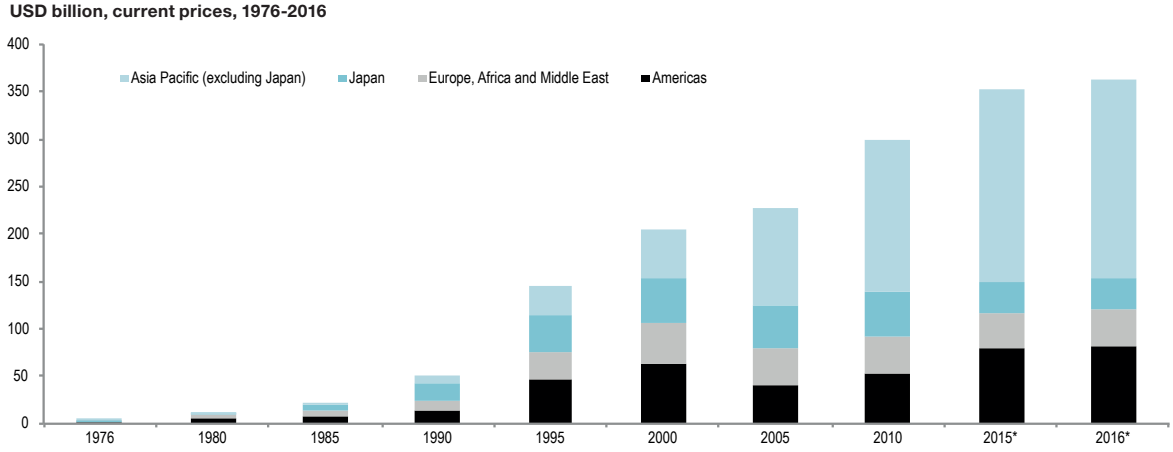
The economic contribution of semiconductors

Semiconductors have had significant economic impact which continues to the present. Until the 1970s, semiconductor devices were used to generate and control electrical current and to detect radio signals. Various industries, such as transport, chemicals and aluminum adopted semiconductor devices with huge productivity gains. Later on, semiconductors triggered the development of the ICT industry, thus also enabling growth in many other industries.

The semiconductor industry itself has been growing for more than four decades. The global semiconductor market is estimated at USD 347 billion in 2015, up from nearly USD 3 billion in 1976 (see figure 2.7). Initially, demand growth came from computers and consumer electronics. Today, automotive and wireless products drive growth.[115]

113. Malerba (1985).
114. For his breakthrough invention, Kilby won the Nobel Prize in Physics in 2005.
115. WSTS (2015).

Figure 2.7: Global semiconductor sales have increased rapidly, with strong regional variations



Notes: The regions here follow the definition of the WSTS. * estimates.

Source: WIPO based on the Historical Billings Report and the WSTS (2015).

An important geographical shift in semiconductor production has taken place during this period. In 1976, nearly 70 percent of shipments emanated from the USA, 20 percent from Europe and 5 percent from Japan. In 1990, the share of the US had fallen to about 30 percent while Japan had increased its share to 40 percent. Since then, the shares of the US, Europe and Japan have all declined, with the broader Asia Pacific region – essentially, Taiwan (Province of China) and the Republic of Korea – accounting for close to 60 percent of sales in 2015.

The use of ICTs and the Internet has transformed existing industries and created entirely new ones – including in retail, distribution, energy, finance, transportation and health; ICTs affect how people learn, travel, work and interact socially.

Economists have worked to quantify the wider contribution of ICTs to economic growth (see section 1.2 and box 1.2 in the previous chapter of this report). They identify three growth channels that have emerged over time.[116]

First, investment in ICTs contribute to overall capital deepening.[117] Second, technological progress in the ICT industry spurs TFP growth in the ICT-producing industries. The quality and speed of chips increase steadily while their cost falls, increasing their diffusion significantly.[118] Third, similarly to other GPTs and taking significant time, greater adoption of computers across all sectors of the economy raises economy-wide total factor productivity. Firms and transactions become more efficient thanks to network effects too, as long as ICT investments are paired with organizational and process innovations.

Empirical studies confirm the existence of all three growth channels, but with some caveats, in particular as far as the third channel is concerned. There is consensus that since the mid-1990s the ICT-producing sector has made a considerable contribution to productivity growth in several high-income countries.[119] In the US, the contribution of ICT to labor productivity growth was already evident from the mid-1970s (see box 1.2). Indeed, ICT investment continued to positively affect value-added growth up to the last economic crisis and beyond.[120]

116. OECD (2004) and Van Ark and Inklaar (2005).

117. Stiroh (2002).
118. Jorgenson (2001).
119. Jorgenson and Stiroh (2000) and Colecchia and Schreyer (2002).
120. Van Ark (2014).

In addition, most studies conducted in the early 2000s in the US and for some other high-income countries demonstrate the strong effect of efficiency gains in the ICT-using, as opposed to ICT-producing sectors, in particular the service sector.[121]

These rewards from ICT investment have not yet been reaped by all countries. A concern has been that the ICT-driven productivity boost is not even as widely shared in Europe or Japan as it is in the US.[122] Some studies also point out that the productivity impacts of ICT capital deepening in high-income countries may now have reached their climax (see section 1.5).[123]

Semiconductors have started to diffuse to emerging economies, sometimes rapidly. As at 2015, China is the biggest market for semiconductors, followed by India, the Russian Federation and Brazil.[124] Also, in some low- and middle-income economies, ICTs have already had important effects in making markets more efficient, for example by creating new payment services or spurring further innovation. Undoubtedly, this potential in developing economies is far from exhausted. In terms of semiconductor production, economies such as China, Malaysia, Taiwan (Province of China) and a few other Asian economies host some of the largest assembling and manufacturing activities. In terms of semiconductor innovation – and a few exceptions aside, including in China and some other Asian countries and in Latin America, notably in Argentina, Brazil and Costa Rica – most higher value-added activities such as chip design still take place in high-income countries.

2.3.2 – The semiconductor innovation ecosystem

The semiconductor innovation ecosystem evolved considerably over time, reflecting in particular the move from early-stage invention and first commercialization to mass production and diffusion. The innovation system in each of the three main geographical regions, namely the US, Europe and Japan, had a very distinct structure, adding its specific contribution to innovation and diffusion.

In the US, the Silicon Valley cluster created the conditions for specialized firms to emerge and coexist with large established firms. In Japan, large firms – initially building on technology licensed from the US – achieved large-scale and cheaper production and introduced innovations at both the technological and organizational levels. In Europe, a strong system of basic research, the dominance of large firms – and industrial policy efforts to create and maintain them – and a focus on consumer markets allowed firms to gain a strong competitive position in semiconductors for consumer industries.

All phases of semiconductor innovation, but in particular the early stage until the 1960s, relied heavily on contributions in fundamental science and linkages to public and university research. In addition, fast diffusion of knowledge spurred global innovation.

Semiconductor innovation greatly benefited from government support and policy, in the form of demand for and purchase of semiconductor devices, and industrial and trade policy.

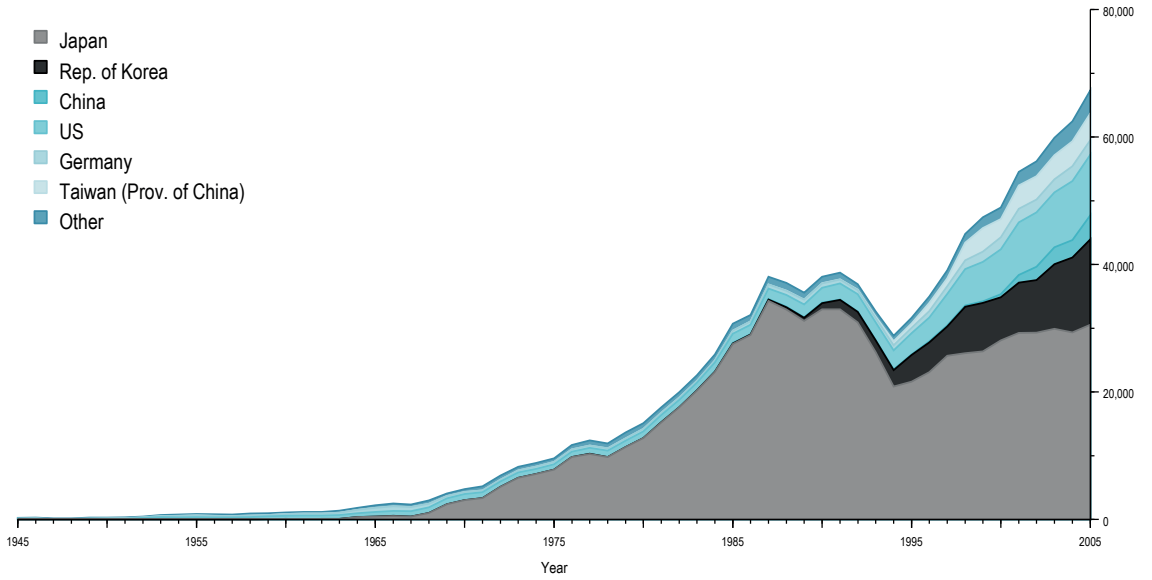
Early concentration in the US and Europe and diffusion to Asia

Most of the innovation in semiconductors has taken place in a few clusters. In the US, Silicon Valley in the San Francisco Bay area has become synonymous with ICT entrepreneurship, dynamism and innovation. In Japan, Tokyo and the Osaka-Kobe region emerged as important semiconductor clusters.[125]

121. Jorgenson and Stiroh (2000), Pilat and Wölfl (2004), Bosworth and Triplett (2007) and OECD (2015).
122. Colecchia and Schreyer (2002), Jorgenson and Motohashi (2005) and van Ark (2014).
123. Gordon (2012) and van Ark (2014).
124. PwC (2014).
125. Morris (1990).

Figure 2.8: Fast growth in semiconductor patenting, especially in the US and Japan

First patent filings by origin, 1945-2005



Source: WIPO based on the PATSTAT database (see technical notes).

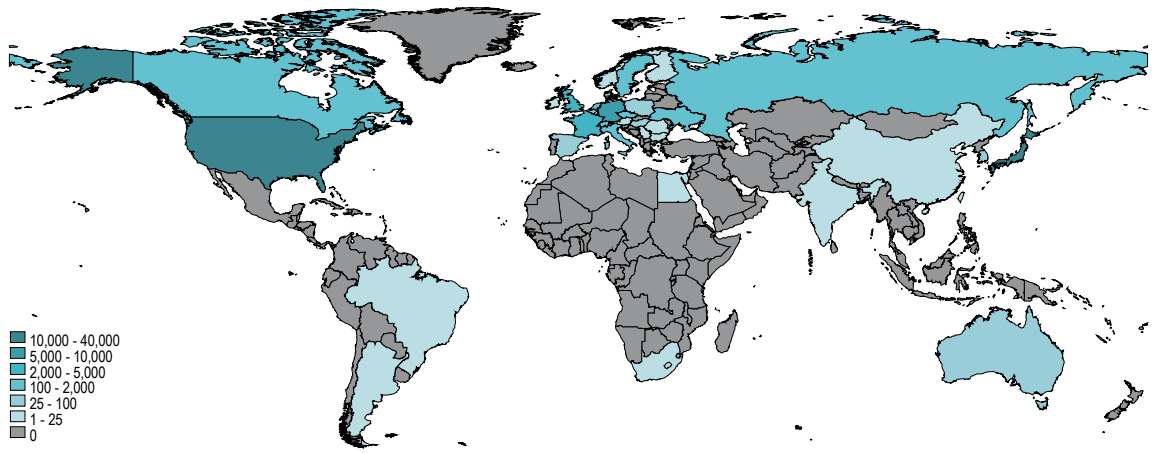
Figure 2.8 depicts the number of first patent filings worldwide in semiconductors from 1945 to 2005. This period captures the time of invention – from the transistor in 1947 to the microprocessor in 1971 – and the subsequent period of diffusion. In the first period, the US and Japan led semiconductor patenting, followed by Germany, the UK, France and the Netherlands. Until 1971, US inventors filed on average 40 percent of all patents in the industry annually. Up to the 1960s, inventors of Japanese origin filed on average one percent of all patents; but by 1980 they filed 85 percent, reaching a peak of 90 percent in 1986. Similarly, the share of patents filed by inventors from the Republic of Korea was close to zero until the late 1980s but 20 percent by 2005. The high shares of patents with Japanese origins are at least to a certain degree related to the practice of *patent flooding*, whereby Japanese firms filed many patents with minor changes on core technologies already patented by US firms. Features of the Japanese patent system allowed for this practice.[126]

Figure 2.9 depicts the origin of first patent filings in the period of invention between 1945 and 1975 (top) and contrasts this with the period from 1976 to 2005 (bottom). Three countries accounted for 89 percent of world semiconductor patents in each period: Between 1945 and 1975, these countries were Japan, the US and Germany, while in the second period they were Japan, the US and the Republic of Korea. In the second period, Taiwan (Province of China) and China joined the group of top six patent filers. Other economies such as Singapore, Israel, the Russian Federation and middle-income countries including Malaysia, India and South Africa have also shown a growth in patenting, even if patent numbers are considerably lower.

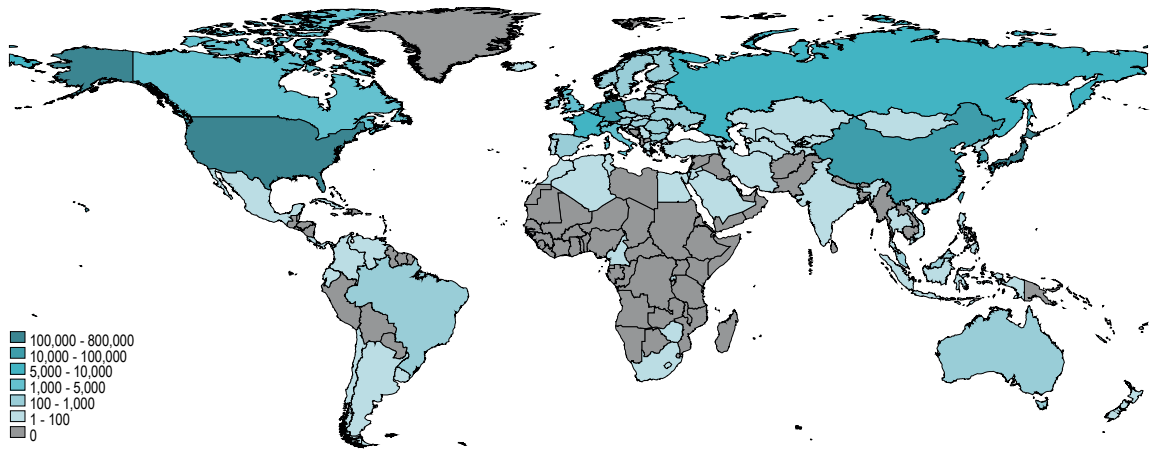
126. See, for example, Wolfson (1993).

Figure 2.9: Diffusion from the US, Germany and Japan and other Asian countries

First patent filings by origin, 1945-1975



First patent filings by origin, 1976-2005



Source: WIPO based on the PATSTAT database (see technical notes).

The evolution of the semiconductor innovation ecosystem

The semiconductor innovation ecosystem evolved over the different technological phases described in section 2.3.1. Table 2.4 summarizes its main characteristics.

Vacuum tubes: large integrated firms and strong need for basic research

Large integrated firms – mostly electrical and electronic system companies such as Western Electric in the US, Philips in the Netherlands, Siemens in Germany and Nippon Electric Company (NEC) in Japan – were the major producers of semiconductors and constituted a stable oligopoly. US and European firms relied on their strong research units and on research at universities. At this time, the innovative efforts of Japanese firms were driven by the absorption of foreign technologies.

Transistors: clustering and new entrants in the US

In this era, interactions between scientific and technological knowledge were crucial for the development of new semiconductor devices.[127] In the US, universities such as Stanford University, MIT and the University of California, Berkeley formed a pool of knowledgeable scientists and engineers who attracted firms to locate in the same area. The interactions between basic and applied research were so important that large corporations had a corporate research laboratory – in AT&T's case, Bell Labs.

In Europe and Japan, major producers were still large integrated firms in the electrical equipment business, even if in Japan actual and potential new entrants such as Sony created some rivalry. In the US, large firms coexisted with new entrants. These were of two types: firms formerly engaged in other industries, for example Hughes and Texas Instruments, and firms established to manufacture semiconductors, for example Transitron.

US firms mainly served military agencies; European and Japanese firms served the civilian market, in particular for radios and televisions. The needs of these two markets differed considerably. In Europe and Japan, costs, reliability and increased capacity to detect signals became the main focus of research, and established germanium as the material of choice for transistors. In the US, size and power consumption established clear targets for new devices and led manufacturers to prefer silicon to germanium.[128] Later on, silicon became the dominant semiconductor material for most applications.

ICs: the startup boom in the US, but still little dynamism in Europe and Japan

The divergence between the US and the European and Japanese ecosystems widened.

In the US, the IC market segment attracted the attention of many entrepreneurial scientists who left larger corporations to set up their own IC firms. Personal mobility, facilitated by clustering and the availability of risk capital, encouraged this trend.[129] By 1966, the major producers of semiconductors in the US were mainly specialized semiconductor firms – Texas Instruments, Fairchild, Motorola – followed by large electrical companies like Western Electric and General Electric.

In Europe, consumer markets remained the major user of semiconductors. As a consequence, the major producers – Philips and Siemens – which had developed considerable expertise in using germanium continued to mass-produce transistors and resisted switching to silicon and ICs. In Europe, smaller firms such as Plessey and Ferranti in the UK, COSEM in France and Allgemeine Elektricitats-Gesellschaft AEG -Telefunken in Germany switched to ICs. However, their delayed entry and limited financial resources did not allow them to grow enough. Furthermore, consumer markets drove European firms to opt for analogue rather than digital ICs. These technological choices disadvantaged European producers as silicon and digital ICs came to dominate the industry. Consequently, the European markets for computer and digital devices were largely satisfied by imports from the US or from European-based subsidiaries of US firms, while European firms maintained a strong commercial position in consumer electronics.[130] Broadly speaking, in the US startups ensured greater dynamism and a faster switch to modern ICs.

The Japanese semiconductor industry presented some commonalities with the European industry, despite being technologically less advanced. In continuity with previous periods, large integrated firms dominated the industry. In addition, firms focused on the consumer market, especially calculators, and were reluctant to move to silicon devices.

127. For example, in the late 1940s, researchers at Purdue University were remarkably close to inventing the transistor.
128. Malerba (1985) and Langlois and Steinmueller (1999).
129. The agreement that the engineers leaving Shockley Semiconductor concluded with Fairchild Camera and Instrument – the firm that financed the formation of Fairchild Semiconductor – was the first of its kind and contributed to the emergence of the venture capital business (Lécuyer and Brock, 2010).
130. Malerba (1985).

Table 2.4: The evolution of the semiconductor ecosystem (1900-1990s)

	Leading actors	Types of innovative efforts	Main users
Vacuum tubes	Integrated electrical firms (EU/US/JP)	Product innovation through scientific discoveries	Military radars (US) Consumer markets – television and radio (EU/JP) Power supply, transport and metal industries (EU)
Transistors	1. Integrated electrical firms (EU/US/JP) 2. Specialized firms (US)	Product innovation through applied research and engineering	Military uses and computers (US) Consumer markets – television and radio (EU/JP)
ICs	1. Integrated electrical firms (EU/JP) 2. Startups (US)	Product and process innovations, organizational and financial innovations	Mainframes and minicomputers (US) Consumer markets (EU/JP)
Microprocessors	1. IDMs (US/ EU/JP/ KR) 2. Fabless firms (US) 3. Foundries (TW/SG/MY/TH/CN)	Product and process innovations, organizational innovations	PCs (US) Consumer electronics, telecommunications and automotive (EU) Consumer electronics (JP)

Note: EU = Europe, JP = Japan, KR = Republic of Korea, TW = Taiwan (Province of China), SG = Singapore, MY = Malaysia, TH = Thailand and CN = China.

During this era, interactions between R&D and production were important for innovation. For instance, Texas Instruments adopted an organizational structure that fostered relations between different divisions. This was one of the success factors of the company.[131] Similarly, in Fairchild Semiconductor the invention of the planar transistor was the result of research efforts based on an intuition by a foreman in the production division.[132]

Microprocessors: toward increased division of labor between design and production

Process innovations weakened the interdependencies between R&D and production. In addition, the complexity of microprocessors meant that greater capital investment was required for their manufacture. Consequently, three types of firms emerged: firms that kept both production and design in-house, known as *integrated device manufacturers* (IDMs), firms specialized in design, called *fabless* (fabrication-less) firms, and firms specialized in manufacturing, called *foundries*. The application of semiconductors to wireless communications and consumer products such as video games also contributed to specialization. These markets were much more fragmented and their product life cycle much shorter than computer markets.

In the US, Intel, the leader in the microprocessor market, and most semiconductor firms focused on design-intensive chips, yielding higher margins. Some of these firms, such as Intel and Texas Instruments, maintained their production facilities, evolving into IDMs. Others, such as Qualcomm, chose the fabless business model and outsourced manufacturing to foundries. Most Japanese firms, such as NEC, Toshiba and Hitachi, also became IDMs, but focused on standardized semiconductor devices. Similarly, in Korea, Samsung, Hyundai and LG Electronics became among the world leaders in memory chip sales. Foundries concentrated especially in Taiwan (Province of China). In 1996, the main foundries in Taiwan (Province of China) – Taiwan Semiconductor Manufacturing, United Microelectronics and Winbond Technology – produced 40 percent of the output required by US fabless companies.[133] In the late 1990s, firms from other Asian economies, such as Singapore, Malaysia, Thailand and China, entered the foundry business.

US firms focused on computer applications, Japanese companies on consumer electronics. The size and diversified nature of Japanese firms allowed them to rely on internal capital transfers in periods of sales downturns, guaranteeing stable and high investment rates. Another characteristic of Japanese firms was their focus on quality control: the Total Quality Management practice promoted automated process control and monitoring. This had remarkable effects in improving quality and productivity. Finally, lifetime employment, prevalent in Japan, limited the diffusion of knowledge and loss of acquired know-how.

131. Morris (1990).
132. Lécuyer and Brock (2010).
133. Langlois and Steinmueller (1999).

European firms adopted a strategy of acquisitions of US firms and R&D collaborations with established producers of microprocessors. This allowed them to use the new technology in consumer electronics, telecommunications and automotive applications. Philips, Siemens and SGS-Thomson maintained their commercial position in international consumer electronics markets and spun off specialized semiconductor companies that became very successful later on.[134]

The critical role of government in financing and stimulating research and innovation

Governments spurred the development of semiconductors through various mechanisms with pronounced differences across countries.

In the US, the 1949 research grant to Bell Labs, the grants for R&D and manufacturing pilot contracts, and all other direct and indirect forms of financial support accounted for a quarter of all R&D in the industry in the late 1950s.[135] Financial support continued up to the 1987 SEMATECH project, which also induced R&D cooperation between rival firms. The government and its military agencies ensured steady demand for US semiconductors. A "Buy American" policy made foreign bids less competitive than national bids. The government also influenced the industry by spelling out technical requirements. The very logic of miniaturization was a result of this. Government programs established laboratories and networks of research organizations. Research projects supported by the government focused on applied research, were interdisciplinary, and involved close collaboration between researchers and manufacturers. In terms of the regulatory environment, a 1956 antitrust consent decree forcing AT&T to refrain from selling semiconductors commercially created a business opportunity for both large firms and startups. The US government also advanced the process of product standardization, allowing firms to enjoy a larger market and consequently benefit from economies of scale. The National Cooperative Research Act of 1984 facilitated joint research.[136]

In Europe, no military contracts were available, and when support was available, little spillover to commercial applications materialized.[137] Governments did not devote the same financial resources to support the development of the industry. Greater financial support arrived much later, when European firms were trying to catch up with US firms in microprocessors. The research laboratories set up by governments were keener on basic than applied research.[138] Subsidies, tariffs, non-tariff barriers and competition policies supported *national champions*. Their limited scale of operations, due to the fragmentation of the European market, influenced the outcomes of these policies.[139] In addition, national procurement, for example in telecommunications, further deepened the fragmentation of the market.

Military procurement also played no role in the development of the Japanese semiconductor industry. However, the government exerted strong influence on the industry via its Ministry of International Trade and Industry (MITI). Among its most far-reaching actions was the Very-Large-Scale Integration (VLSI) project (1976-1980), a consortium including Fujitsu, NEC, Hitachi, Mitsubishi and Toshiba. As in Europe, Japan's MITI favored the development of a national industry through high tariffs and non-tariff barriers and preferential treatment of national firms in public procurement. The government also hindered the formation of wholly-owned subsidiaries of foreign firms via capital controls and controlled licensing agreements between Japanese and US firms.[140] National banks, whose funds were controlled by the Bank of Japan, could hold equity shares in companies to which they were lending. Hence, banks supported national firms even when there was no return on investment, allowing firms to maintain high investment rates.

134. Malerba (1985) and Langlois and Steinmueller (1999).
135. Tilton (1971).
136. Langlois and Steinmueller (1999).
137. See, for example, the case of the Colossus computer developed during the Second World War in the UK for code breaking.
138. Malerba (1985).
139. Morris (1990).
140. Nakagawa (1985), Flamm (1996), Langlois and Steinmueller (1999) and Hoeren (2015a).

2.3.3 – Semiconductors and the IP system

Through the various stages of innovation and commercialization, appropriation and IP strategies naturally evolved. They were often specific to particular actors, and varied significantly across countries too. A few broad characterizations are possible, however.

Patents: From open to more defensive patenting strategies?

Due to the high mobility of scientists in Silicon Valley and the willingness of researchers to publish their inventions, secrecy was not considered a viable strategy in the US. In the case of Japan, by contrast, employees benefited from lifetime employment and rarely left their company, keeping information internal. Trade secrecy laws were rarely invoked.

Semiconductor innovation coincided with the intense use of patents. All the phases discussed above witnessed numerous patent filings, most for inventions that were critical for the further development of the industry. Patent filings saw notable growth from the early days (see figure 2.8). This strong use of patents is striking as legally, the layout of semiconductors is in principle not protectable via traditional patent rights. Indeed, layouts of ICs were considered obvious variations of prior layouts, and not deserving of patent protection.[141] From a business perspective too, the short commercial life of ICs also made other forms of appropriation more appealing. Indeed, lead time, first-mover advantage, design capabilities and a good reputation were more important in this respect.[142] Nevertheless, other elements of semiconductor technology were patentable. In particular, patents were used to appropriate returns on technically complex structural features of semiconductor devices and innovations in semiconductor processing.

More importantly, patents were mostly used as an effective means of sharing technology among key actors. In part due to business strategy and government policy, patents rarely needed to be enforced. Firms were aware that chip development requires access to a multitude of overlapping inventions and rights held by diverse parties.[143] Firms directly or indirectly used other parties' inventions, either explicitly through flexible large-scale cross-licensing practices or implicitly by ignoring others' patent rights.[144]

Disclosure, the sharing of technology and the lack of litigation facilitated cumulative innovation, and diffusion. Patents also facilitated specialization and helped to mobilize resources to cover the high R&D costs and to finance startups.[145] Indeed, the current build-up of large patent portfolios to block competitors or to avert the threat of litigation, is – by historical standards – a newer phenomenon in the industry. The feared negative effect on true innovation might also be more contained than initially thought by some.[146]

It is helpful to distinguish the various phases of IP strategy carefully.

Phase 1 (1900-1940): Individual academic undertakings with patents

In the early 20th century various academic inventors laid the foundations for the industry. Even at this early stage, inventions were often also filed as patents as well as being published as scientific papers. Yet these patents were not used exclusively by the inventor. In fact, they were mostly not commercially exploited at all; rather, they contributed to the pool of knowledge.

141. Hoeren (2015a).
142. Levin *et al* (1987) and Cohen *et al* (2000).
143. Grindley and Teece (1997) and Hall and Ziedonis (2007).
144. Von Hippel (1982), Appleyard (1996), Motohashi (2008) and Hoeren (2015a) .
145. Hall (2005).
146. See, for instance, Shapiro (2000), Hall and Ziedonis (2001) and Jaffe and Lerner (2004) for related concerns.

Phase 2 (1940-1980): Patent equilibrium and extensive cross-licensing

From the 1940s until the 1970s, the rapid rise of IP coincided with innovation, not only in the US, but also in Europe and Japan.[147] Patent owners did not use patents to keep technologies to themselves or fend off competition. Patents were either cross-licensed or deliberately not enforced.[148] Startups used existing semiconductor techniques for follow-on innovation.

Right holders had two reasons to abstain from enforcing patent rights.

First, the various industry players understood that enforcing individual patent rights in such a complex overlapping technology landscape would be impossible and counterproductive. Even critical patents drew on the technical disclosures of, and potentially infringed, existing patents.[149]

Filing a significant number of patents without enforcing them brought about a balance of power; various inventions were held by competing parties. Litigation was limited to a few critical initial cases. For instance, the key inventions of Noyce and Kilby were made independently of each other, leading to Fairchild and Texas Instruments having coincident patent claims for an almost identical invention. At first these two firms sued each other for patent infringement, but in a 1966 settlement each party agreed not to dispute its rival's patents; a far-reaching cross-licensing agreement was reached.[150] This type of arrangement became popular in the industry and firms increasingly opted for cross-licensing agreements rather than litigation.

In addition, the mobility of inventors and the creation of startups were rampant, leading to further diffusion of technologies. Indeed, in 1977 the US Federal Trade Commission noted: "The fact that companies can rapidly copy each other is very important. This rapid copying is the result of the mobility of personnel from firm to firm and the unwillingness of most firms to bring trade secrets or patent infringement suits".[151]

Internationally, patents were not used to fend off competition either. In fact, although Japan was quickly becoming the major semiconductor production location, few resident or non-resident patents were granted in Japan before 1962.[152] As a result, patent litigation was rare on an international basis.

Second, in an interesting parallel with airplanes (section 2.1), competition policy in the US played a role too. Following the antitrust consent decree of 1956 (see section 2.3.2), AT&T agreed to grant royalty-free licenses on existing patents and to stop operating as a semiconductor producer. Likewise, all future Bell patents were to be made available at reasonable rates. Later, antitrust policy prevented large patent holders such as AT&T and International Business Machines from enforcing their patent rights in the 1960s and 1970s. The technology leaders then set up liberal licensing policies that are widely credited with promoting the rapid pace of innovation.[153] As Hoeren (2015a) notes: "Bell had an interesting concept of sharing the new transistor technology with experts around the world […] Bell organized three conferences for other scientists to get acquainted with the new […] technology first hand […] People interested in that conference had to pay a USD 25,000 patent-licensing fee upfront deductible against future royalties […]".

147. Levin (1982)
148. Shapiro (2000).
149. The name of Shockley was left off the point contact transistor patent application in 1948 after lawyers for Bell found that his writings on transistors were "highly influenced" by an earlier 1925 patent granted to the electronic engineer Julius Edgar Lilienfeld (Shurkin, 2006).
150. Langlois and Steinmueller (1999).
151. FTC (1977).
152. An interesting case shows an implication of this. At Sony, Leo Esaki discovered (and won a Nobel Prize for) the Esaki effect, which greatly increased the speed at which semiconductors functioned. However, Esaki never asked for a patent for his invention, but shared his ideas with other researchers. In 1960, a Bell employee filed a patent application for a device utilizing the Esaki effect.
153. Levin (1982).

Starting from that point, a lot of US and international – mostly Japanese and European – companies licensed technology from Bell. The licensees were in turn requested to make their patents available at a fair price.[154] Reverse engineering allowed all semiconductor companies to check the interiors of circuits produced by their competitors. The publication of the patent applications alerted researchers to the work already being done by others and also increased the respect inventors had for each other's work.

This open approach to patented technologies did not stop at national borders. The early Japanese chip companies all thrived on technology licensed from US firms. When the cost of designing chips increased, US and Japanese firms cooperated and cross-licensed technology.[155]

Phase 3 (1980-1984): Initial closing-up as result of industrial policy and trade wars, and the creation of *sui generis* rights

The innovation and IP model described above began to erode, mostly as a result of industrial policy and the changing nature of technological leadership. In the 1980s, Japanese firms started to surpass US firms in the quality of semiconductor chips. This raised concerns in the US; accusations of IP infringement by Japanese companies were raised. Moreover, Fairchild and Texas Instruments were restricted from investing further in Japan. Moreover, in Japan full patent rights were not granted to Texas Instruments on its key integrated circuit patent until 1989 (although some limited patent rights were approved in 1977), more than 25 years after its original filing.[156]

The US and Japanese governments interfered more and more in the industry, both instituting preferential treatment for national firms. Accusations of semiconductor counterfeiting arose; US and Japanese chip firms started a patent war which lasted for a decade. The liberal cross-border licensing policies came to an end. This led to lobbying efforts to produce a *sui generis* system protecting semiconductor mask design. Corresponding laws were concluded nationally and internationally, creating a new type of IP right. Yet this *ad hoc*, technology-specific *sui generis* approach failed to see any notable uptake or impact.

154. Levin (1982).
155. Motohashi (2008).
156. Flamm (1996) and Hoeren (2015a).

Phase 4 (1984 onward): Semiconductor patent surge, defensive patenting and litigation

From the early 1980s onward, semiconductor patenting and the propensity to patent accelerated to unforeseen levels in the US and abroad.[157] According to the literature, this increase in patenting and a change in IP strategy was spurred by pro-patenting legislation in the US, namely the creation of the Court of Appeals for the Federal Circuit (CAFC) by the Federal Courts Improvement Act of 1982, a further intensification of the competitive nature of the semiconductor industry and the increasing tendency to more actively seek licensing revenues.[158] In particular, Texas Instruments' move to exploit its IP portfolio more and start earning revenue from its competitors had a ripple effect.[159] The rise of a new business model in which chip design was separated from chip production also played a role in this change in patenting strategies; chip designers earn revenues by selling IP licenses to manufacturers.

Furthermore, patents were also progressively used to block potential entrants and competitors, and to pose a barrier for follow-on innovation. A so-called patent holdup situation arose, risking – by some accounts – a slowdown in technological progress.[160] According to the literature and industry accounts, patents were increasingly filed defensively, to avoid the risk of being sued for patent infringement. The rate of litigation by US semiconductor firms as enforcers of patents is shown to have remained relatively stable over the past two decades. In contrast, there was a documented rise in active litigation by non-practicing entities.

157. As documented in Fink *et al* (2015), the steepest increase in the ratio of first patents to R&D on a global level also occurred in the "electrical machinery, computer and audiovisual technology" category, which includes semiconductors.
158. Hall and Ziedonis (2001).
159. FTC (2002).
160. FTC (2003).

Whether the above facts have fundamentally changed the relevance of patents to semiconductor R&D and the diffusion of the technology is an open question. No credible evidence exists to show that more recent concerns about patent hold-up or litigation have had a tangible impact on semiconductor innovation. Increased patenting could in fact be the result of increased efficiency in innovation among semiconductor firms – that is, more patents per unit of R&D are yielded. Indeed, the rate of innovation as measured by Moore's law is – although challenged by the limits of physics – intact.

Furthermore, it is argued that, under the surface, extensive explicit cross-licensing agreements or implicit agreements – covenants – not to sue are still in place between the major semiconductor design and production firms.[161] In addition, today these contracts contain trade secrets and confidentiality provisions.[162]

Failed attempts to create *sui generis* protection for semiconductors

As described above, in the 1980s a *sui generis* system to protect semiconductor mask design was created, but without ever achieving any notable use by innovation actors and inventors.

Business associations sought a protection regime to counter what they framed as increased semiconductor counterfeiting abroad. They argued that existing patent laws failed to give sufficient protection to their industry.[163] The US Congress finally favored the idea of *sui generis* protection. The targeted object of protection was the "mask work", that is, the pattern used to set the circuits on the silicon wafer in order to create ICs. The Semiconductor Chip Protection Act of 1984 (SCPA) in the US created a new kind of industrial property statute containing elements of patent, copyright and competition law.[164] Japan published an act similar to the SCPA as early as May 31, 1985.[165] In Europe, the EC Council adopted the Directive on the Legal Protection of Semiconductor Products in 1986.[166] The SCPA built on the notion of reciprocity. Topographies and mask works of a foreign chip producer would only be protected in the US if standards similar to the SCPA were adhered to in that foreign jurisdiction. Finally, the protection of semiconductor technology was regulated in Articles 35-38 of the TRIPS Agreement in 1994.

Interestingly, however, the *sui generis* system did not experience significant uptake or have a real impact in practice. First, as mentioned, the *sui generis* right protected the mask of the chip. However, the function of the IC is more valuable than its mask. Second, although masks are complex and hard to copy, they can be easily modified without damaging chips' functionality. Hence, masks would not be protected against altered masks obtained, for example, through reverse engineering. These technical aspects of the *sui generis* protection lowered its appeal. In addition, due to the increasingly short lifespan of chips, high production costs and customization requirements, chip piracy became practically unaffordable. Consequently, hardly any litigation to enforce mask work designs ever occurred and the industry continued to rely on patents.

161. See Hoeren (2015a) for additional references.
162. Ludlow (2014).
163. Levin (1982).
164. Title III of Public Law 98-620 of November 8, 1984, now 17 U.S.C. Section 901 *et seq.*; Industrial Property Laws and Treaties, United States of America – Text 1-001.
165. Act Concerning the Circuit Layout of a Semiconductor Integrated Circuit (Act No. 43 of May 31, 1985).
166. *OJ,* L 24/36, January 27, 1987, Directive on the Legal Protection of Semiconductor Products, 87/54/EEC.

Copyright to protect chip design: Gaining in importance recently?

While initially deemed irrelevant, the use of copyright to protect chip design has gained in importance more recently. Copyright had always been considered for the potential protection of chip designs, in particular in the US. These attempts largely failed. For instance, the US Copyright Office refused to register patterns on printed circuit boards and semiconductor chips because no separate artistic aspects had been demonstrated. The pattern was simply deemed inseparable from the utilitarian function of the chip. In the end, the *sui generis* approach outlined above was favored; copyright was dropped as a possible means of appropriation.

Nonetheless, as new business models separating chip design and manufacture have become ever more central, industry experts suggest that copyright is now an important tool for appropriating semiconductor innovation. Specifically, the netlists – the graphical descriptions of all the devices and the connections between each device given by fabless firms to foundries, which may include text, software, libraries and databases – are undoubtedly protected by copyright law insofar as they include highly valuable and creative text-format representations of chip designs.[167]

167. For an example, see *www.concept.de/img/Netlist_Debugger_Showing_Critial_Circuit_Fragment_L.gif*; and see also Hoeren (2015b).

2.4 – Lessons learned

The three case studies presented in this chapter offer diverse insights into how breakthrough innovations have spurred growth and what role the IP system played in the relevant innovation ecosystems. Many of the insights are specific to the technologies and historical context at hand and do not easily lend themselves to generalization. Indeed, innovation in airplanes, semiconductors and antibiotics is still thriving today, and the ecosystems underlying innovative activity in these fields have evolved greatly.

Notwithstanding this caveat, it is worth drawing some comparisons between the three historical cases and asking what key lessons can be learned. This final section attempts to do so. It follows the structure of the case studies, first focusing on the innovations' growth contribution, then on their ecosystems, and finally on the role of IP.

Growth contribution

Looking at how the three innovations affected growth, antibiotics stand out as having promoted growth primarily through a longer-living and healthier workforce. Their growth contribution likely goes beyond treating bacterial infections, as the commercialization of antibiotics gave rise to the research-based pharmaceutical industry and the accompanying regulatory framework that generated other pharmaceutical breakthroughs.

Airplanes and semiconductors mainly contributed to growth by spurring investment, raising the productivity of firms and transforming economic structures. Economic transformation was particularly far-reaching. Both innovations prompted radical changes in supply chains affecting a wide spectrum of sectors and were at the root of entirely new industries. These growth effects took time to materialize, but sustained growth for decades following first commercialization. They also relied on continuous follow-on innovation – both technological and organizational in nature.

How did the three innovations disseminate and spur growth in low- and middle-income countries? Although the case studies do not offer any quantitative evidence, it is interesting to note that the products due to the innovations – aircraft, antibiotic medicines and numerous information technology products – saw relatively wide adoption in developing economies. This adoption is bound to have made important growth contributions. By contrast, the manufacturing know-how associated with these innovations did not spread as widely. While some developing economies succeeded in creating manufacturing capacity in these industries, the bulk of production remains concentrated in a relatively small number of countries to this day.

Innovation ecosystems

The innovations described in the three case studies resulted from the efforts of a variety of actors at different stages of the innovation process. Governments were the main source of funding for the scientific research that was often instrumental in making inventive breakthroughs happen. In addition, in all three cases governments played a crucial role in moving innovation from the laboratory to the production stage – often motivated by a desire to enhance national defense. To the extent that individual firms and financial markets could not have absorbed the high costs and risks of product development, one may speculate that some of the innovations associated with airplanes, antibiotics and semiconductors would never have seen the light of day without government intervention – or at least not at the time they did. At the same time, the efforts of firms were equally crucial, especially in commercializing promising ideas and engaging in follow-on innovations that facilitated scaled-up production, cost reductions and wide-scale adoption of new technologies.

How far did the ecosystem shape the direction of innovation in the three historical cases? At one level, innovation resulted from individual ideas and serendipitous forces – as vividly illustrated by the first flights of airplane pioneers and the discovery of penicillin. At another level, the innovation ecosystem clearly mattered. For example, Germany's strong science base was crucial in improving the design of the airplane, as were deliberate efforts to translate and disseminate aviation knowledge. Similarly, the greater interest of the US government in using semiconductors for national defense purposes compared with Europe and Japan led firms in the latter countries to focus more on consumer electronics applications. In addition, the US innovation ecosystem was more conducive to the growth of startup firms. This explains why new market entrants were a key driver of innovation in the US, whereas in Europe innovation largely occurred within established firms.[168] Interestingly, then, initial differences in the incentives provided by national innovation ecosystems turned out to have long-lasting consequences for industrial development and specialization.

As a final observation, the three ecosystems evolved considerably as innovation unfolded over the course of years and decades. Above all, airplane innovation saw a pronounced shift from clubs of amateur inventors to an ecosystem featuring large R&D-intensive manufacturers, independent suppliers of parts and components, strong industry-university linkages and a downstream service industry. The innovation systems underlying antibiotics and semiconductors also saw significant evolution, even if its extent and nature differed. Across all three cases, two common trends stand out. First, responding to progressively more complex technological challenges, innovation actors – whether individuals, university labs, or firms – became ever more specialized. One possible exception was the vertical integration of research-based pharmaceutical companies in the case of antiobiotics. Second, as commercialization took off, innovation shifted toward optimizing technology for different uses and adapting it to the needs of the marketplace. As described above, these forms of follow-on innovation proved decisive in fully realizing each innovations' potential.[169]

168. The economic literature has formally explored differences in firms' innovation performance in relation to their size during an industry product life cycle (Klepper 1996).
169. These findings are broadly in line with studies of the product life cycle of different industries. See, for example, Klepper (1996) and Malerba (2002).

The role of IP

How important was IP protection in the history of airplanes, antibiotics and semiconductors? In the absence of a counterfactual history without IP protection, it is impossible to answer this question with any confidence. Nonetheless, the three case studies hold several lessons on the role of IP.

First, innovators frequently relied on the IP system to protect the fruits of their innovative activities. In some periods – and especially for semiconductors – they did so extensively. Their motivations for doing so varied, but available evidence suggests that IP protection contributed at least partially to R&D appropriation – thus indicating that IP rights mattered for innovation incentives.[170]

Second, the innovation ecosystems at times flourished as a result of explicit or implicit knowledge-sharing arrangements. In the case of airplanes, the first clubs of amateur inventors operated not unlike modern "open-source" communities. Later on, the first airplane manufacturers licensed patented airplane technology to other manufacturers, and formal patent pool arrangements expressly sought to promote the commercialization of new airplanes by different manufacturers. In the case of antibiotics, the free availability of new research tools proved important in stimulating follow-on innovation by a large community of researchers. Finally, in the case of semiconductors, cross-licensing agreements and tacit arrangements not to enforce patent rights were similarly important for the commercialization of new technologies and follow-on innovation. In many cases, the IP system facilitated the sharing of knowledge, along the lines described in section 1.4 of the previous chapter. However, knowledge sharing also relied on social norms and, in selected cases, government intervention. The semiconductor case is especially interesting, as litigation and industrial policy actions challenged established cross-licensing approaches; however, it is not clear to what extent these developments had a significant impact on the speed and direction of innovation.

170. The importance of IP protection as a means of appropriating returns on R&D investment is bound to have differed across the three industries studied. In particular, the production of semiconductors and airplanes requires greater upfront capital investment than the production of pharmaceuticals. The higher market entry costs in the former industries may have lessened firms' reliance on IP protection when competing in the marketplace.

Third, the IP system itself adapted to the newly emerging technologies. At the outset, patent offices and courts faced difficult questions about the patentability of founding inventions. These questions concerned whether those inventions were patentable under the legal standards prevailing at the time and how broad inventive claims could be. The first question arose in the case of early-stage antibiotics and for the layout of the semiconductor. The second question was at the center of disputes around the Wright brothers' seminal patents, where courts in the US and Europe reached different conclusions. The patent pooling arrangements described above – in which governments played some role – also served to calibrate the patent system to best support the innovation ecosystems prevailing at the time. Again, in the presence of many confounding influences, and discounting the benefit of hindsight, it is difficult to evaluate whether policymakers necessarily got it right. Interestingly, the one more radical departure from the traditional set of IP rights – the creation of a new form of IP for layout designs of ICs – proved to be a failure, in the sense that it was not much used. If any lesson can be drawn from this experience, it is that policymakers need to carefully consider the dynamic nature of technology when reforming IP policies.

Finally, looking at global IP landscapes, available data suggest that innovators in the three cases overwhelmingly sought patent protection in the high-income countries where most of the innovation took place. Only a small share of first patent filings in the relevant technological fields had equivalents in low- and middle-income economies. Overall, this suggests that patents were neither helpful for technology dissemination when it did occur, nor harmful when it did not happen (see also section 1.4). Rather, it points to the presence or lack of absorptive capacity as the main factor explaining the extent of dissemination.

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