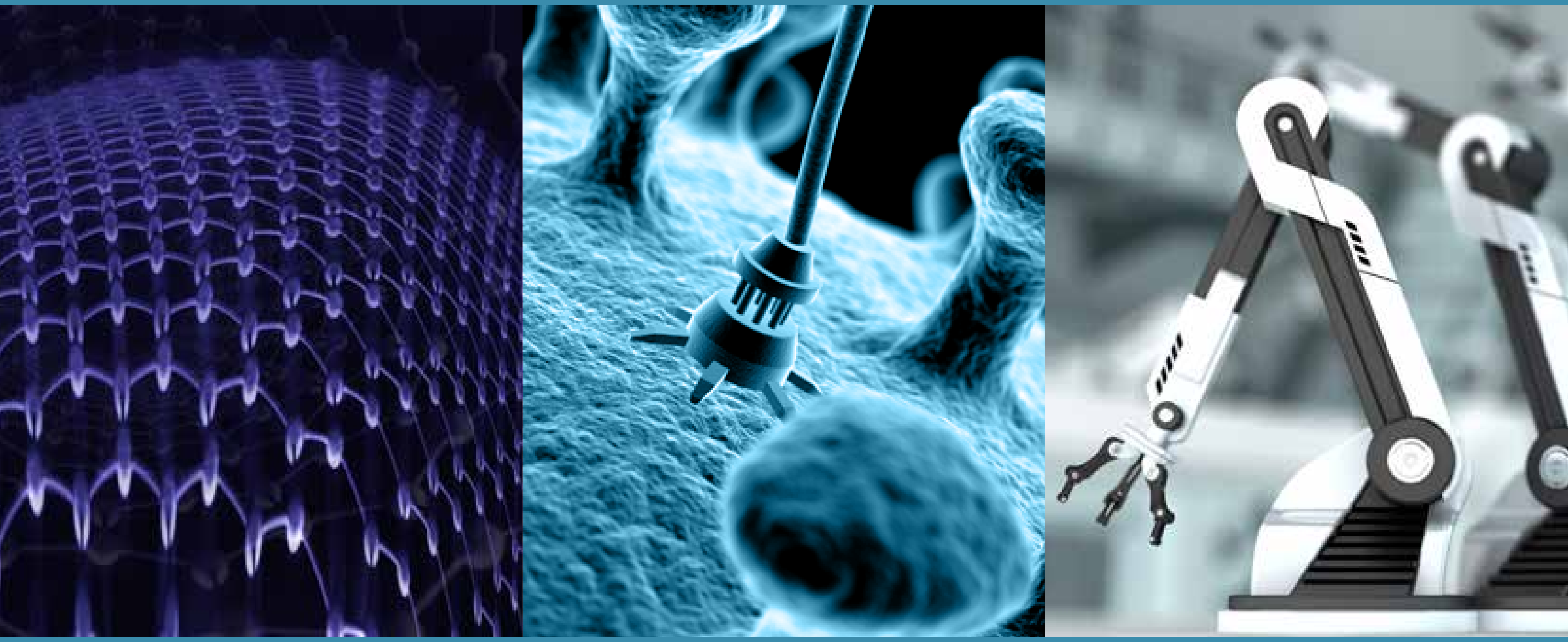
World Intellectual Property Report

Breakthrough Innovation and Economic Growth

Economics & Statistics Series



2015

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Foreword

Policies which spur economic growth are imperative for governments the world over. Sustained growth improves living standards, creates new employment opportunities and helps alleviate poverty. While not a panacea, economic growth – if properly channeled – can contribute to stability, security, health and environmental sustainability.

But can continuous growth be taken for granted? A growing chorus of experts is asking this question, and with good reason. The period following the Second World War has seen the fastest global growth on record. Yet since the global financial crisis of 2008, economic growth has disappointed year after year. Can we safely assume that faster growth will eventually resume, or could low growth be the new normal?

Part of the answer depends on the extent to which innovation continues to drive growth. Historically, major breakthroughs in technological innovation have been at the root of long-lasting expansions in economic output. Those breakthroughs changed the face of production. What were once agrarian societies are today industry- and services-based economies, driven by technologies that were unimaginable three centuries ago. In many ways, innovation in the 21st century is thriving as never before. Yet how far the breakthroughs of today can invigorate growth for tomorrow remains an open question.

Intellectual property (IP) is at the center of the innovation–growth nexus. Much has been written about the importance of IP protection for economic growth. However, the precise channels through which IP shapes growth outcomes are complex, and vary across technologies and different forms of IP. To shed greater light on these channels, we have focused our *World Intellectual Property Report 2015* on the theme of Breakthrough Innovation and Economic Growth.

As with our previous reports, the *World Intellectual Property Report 2015* aims to explain and clarify the role the IP system plays in market economies. The report begins by reviewing patterns of economic growth throughout history and exploring the different ways in which innovation affects growth. In so doing, it examines how different forms of IP shape innovation and technology diffusion outcomes.

A novel element of this year's report is a series of case studies that explore the concrete linkages between innovation, IP, and growth in six areas of breakthrough innovation. Three case studies focus on historical innovations: airplanes, antibiotics and semiconductors. The other three examine innovations that currently appear to hold breakthrough potential: 3D printing, nanotechnology and robotics. All six case studies follow a common approach, looking first at the innovation's origin and its contribution to growth; then at the ecosystem which gave rise to the innovation; and finally at the role the IP system plays within that ecosystem.

The report also considers the prospects for future innovation-driven growth. Without claiming to foresee the future, it reviews the various arguments that suggest either a more optimistic or a more pessimistic outlook. Irrespective of today's growth perspectives, the report emphasizes that it remains critically important for governments and business to continue investing in innovation. Successful innovation, whether at the level of the company or the economy as a whole, requires perseverance – not least in periods of low growth when innovation budgets come under pressure.

Breakthrough innovation and economic growth is a multifaceted theme, and this report cannot address every question related to it. It does not, for example, discuss in detail how innovation-driven growth shifts the demand for jobs and shapes the distribution of income. Moreover, while describing how different innovations have diffused to developing economies, the report only touches on what might explain these diffusion patterns; indeed, understanding why some developing economies have managed to climb the technology ladder and others have not remains an unresolved puzzle in economic research.

We hope that this report provides a timely perspective on one of the most important challenges facing policymakers today, and that it will inform discussions among Member States to determine how the IP system can best contribute to innovation-driven growth for all countries.

Francis GURRY
Director General

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Executive Summary

Economic growth has been a powerful force for reducing poverty, creating jobs and improving general living standards. However, it cannot be taken for granted. Before the 18th century the world economy saw little growth. Poverty was widespread and any substantial improvement in living standards for more than the privileged few was beyond imagining. Since then, the world economy has grown at an unprecedented pace – greatly improving the quality of life and generating widespread material prosperity. Even so, some national economies have seen faster and more sustained growth than others, leaving wide disparities in the prosperity of nations today.

One central insight from scholarly research is that lasting economic growth relies on continuous technological progress. Indeed, the last three centuries have seen a series of innovative breakthroughs in different fields of technology that have profoundly transformed productive activity and spurred the growth of new industries. How did these breakthrough innovations come about and how did they increase economic output? Answers to these questions are important, as policymakers continuously strive to improve the enabling environment for future growth. Indeed, as the world economy still reels some seven years on from the global financial crisis, there is serious debate as to whether innovation can continue to deliver rates of growth matching those before the crisis.

This report endeavors to provide an analytical input into that debate. It explores the channels through which innovation promotes growth, and the ecosystems in which innovation flourishes. In so doing, the report pays special attention to the role of the intellectual property (IP) system, which at its heart seeks to support innovative activity.

In addition to reviewing historical patterns of growth and conceptualizing the linkages between innovation and growth, the report's main analytical contribution consists of six case studies of breakthrough innovations. In particular, it focuses on three historical innovations and three innovations which currently hold breakthrough potential (see table 1). Through case studies, one can take account of the different nature of innovative breakthroughs and the evolving context in which innovation takes place. In addition, even though many conclusions are specific to the six cases and may not be generalizable, the commonalities and differences presented by the cases offer food for thought on which policy approaches work best in alternative circumstances.

Table 1: Breakthrough innovations studied in this report

Historical innovations	Current innovations
Airplanes – from hobbyists gliding in the 19th century to a reliable mode of transportation in the first half of the 20th century	*3D printing* – the creation of 3D objects through successive layering of material, aided by digital technology
Antibiotics – from the discovery of sulfa drugs in the 1930s to the birth of the modern pharmaceutical industry	*Nanotechnology* –technology at the scale of one-billionth of a meter, with applications in electronics, health, materials, and other fields
Semiconductors – from amplifying radio waves for better communication in the early 20th century to ever-more potent computer chips driving the ICT revolution	*Robotics* – from the first robots spurring industrial automation to today's autonomous machines with artificial intelligence

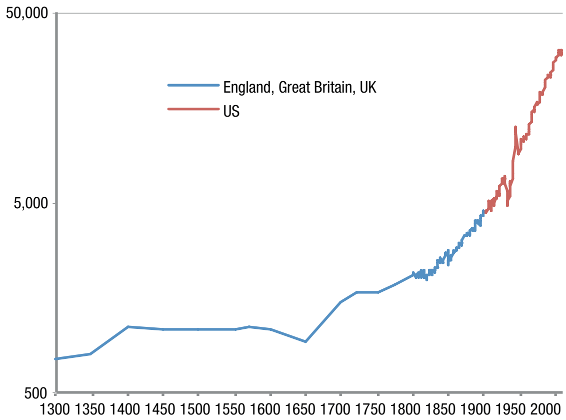
Economic growth throughout history

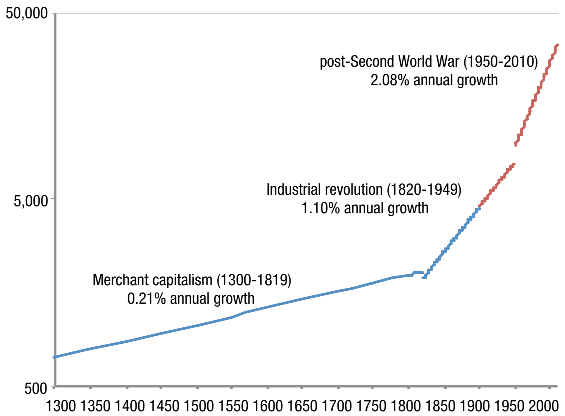
Growth at the frontier took off in the early 19th century and accelerated in the post-Second World War era

Relying on the most comprehensive set of historical estimates available, figure 1 depicts the evolution of GDP per capita at the frontier since 1300. The frontier here means the economy showing the highest economic output per capita at a given point in time. For the purpose of figure 1, these are taken to be England, Great Britain and the United Kingdom (UK) up to 1900, and the United States (US) thereafter.

Figure 1: Growth at the frontier over seven centuries

Real GDP per capita, 1300-2000, logarithmic scale





See figure 1.1

The figure's lower panel divides the seven centuries into three growth periods. The first period, up to the early 19th century, saw only little and sporadic growth, averaging around 0.2 percent per year. The onset of the industrial revolution then led to a sharp increase in the annual rate of growth, to 1.1 percent. Finally, in the post-Second World War era, growth accelerated further to 2.1 percent per year – implying a doubling of income every 34 years. In light of centuries of history, the growth performance since 1950 thus emerges as both spectacular and exceptional.

Diverging growth paths have increased the gap between the poorest and richest countries...

Outside the group of frontier economies, growth performance has been mixed. While selected once-poor economies – notably in East Asia – were able to catch up with the frontier group, no general process of converging per capita incomes has taken place. As a result, the inequality in the prosperity of nations has widened since the 19th century.

...even if fast growth in China and India has been an equalizing force in the world's income distribution and has caused absolute poverty to decline

Widening income inequality across economies does not necessarily imply that the world has become a more unequal place. The distribution of income among citizens worldwide – which takes into account the population size of different countries as well as income inequality within countries – offers a more optimistic picture. Studies focused on the last several decades have shown that the fast growth of populous and initially poor Asian economies, notably China and India, has been an equalizing force in the world's income distribution. In addition, using different poverty thresholds, these studies uniformly document a substantial reduction in absolute poverty levels.

How innovation drives economic growth

Decades of scholarly research in economics have established the central role that innovation plays in driving long term growth. Yet quantifying the innovation contribution – which innovations have accounted for how much growth during which time period – is challenging. The infographic at the end of this report depicts some of the most important innovative breakthroughs over the past 200 years against the background of the frontier growth path shown in figure 1. It is meant as an illustration, and the selection of technologies is subjective.

Despite the quantification challenge, the channels through which innovation spurs growth are well understood conceptually.

Innovation prompts capital deepening...

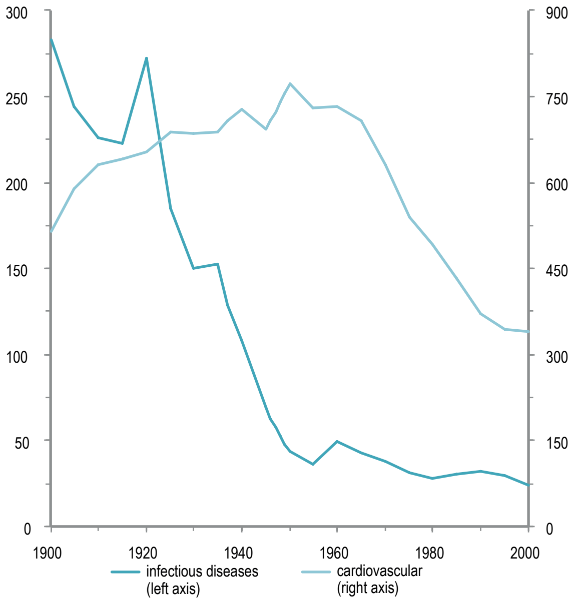
Firms invest in new capital equipment based on the future income they expect those investments to generate. The introduction of new technologies can raise investment returns and lead firms to undertake new investments. Historically, the introduction of major breakthrough technologies has often unleashed investment booms, driving expansions in economic output. The semiconductor case study, for example, discusses evidence that shows that as ICTs took off in the 1990s, firms throughout the US economy rapidly increased their ICT capital stock, especially when compared with other fixed capital assets. In addition, intangible asset investments – the establishment of new business processes, databases and other knowledge-based activities – have become an important component of overall investments and are also linked to the introduction of new technologies.

...supports a growing, healthier and better-educated labor force...

Innovation has been a key force behind the expansion of the workforce. Advances in health technology have prompted a dramatic increase in life expectancy. In 1800, average life expectancy at birth was below 40 years in all developed economies; by 2011 it had risen above 75 years, with Japan seeing the highest average of 83 years. Figure 2 – drawn from the antibiotics case study – illustrates the dramatic reduction in mortality since the arrival of the first antibiotic medicines in the 1930s.

Figure 2: Antibiotics had a profound effect on human health

Mortality due to infectious and cardiovascular diseases, deaths per 100,000 inhabitants, 1900-2000



See figure 2.4

Innovation has also been instrumental in facilitating greater adult participation in the workforce. For example, the arrival of speedy mass transportation has reduced geographical barriers in the labor market. It has similarly promoted access to education. Advances in educational technology, in turn, have widened and deepened educational achievements, leading to a better-educated labor force.

...raises the productivity of firms...

Innovation can affect the productivity of firms through a variety of channels. *Process and organizational innovations* can increase the efficiency with which inputs – especially labor – are converted into output. The resulting productivity enhancements free up resources that can be used to expand output – in the same firm, in the same sector, or elsewhere in the economy.

Product innovation can also have an important effect on firm productivity, especially if it takes the form of powerful new or improved intermediate inputs. The case studies in this report offer numerous examples of radical new products and services that have changed the face of productive activity – including air transport, computers, industrial robots and 3D printers.

...and transforms economic structures

Innovation is often at the root of profound structural transformation. In the medium to long term, such structural transformation affects an economy's productivity through a variety of channels:

- Innovation can change the face of industries, leading to the exit of some firms and the entry of others. In many cases, these changes prompt growth-enhancing efficiency gains and redeployment of production factors.
- Breakthrough innovations typically unleash a reorganization of supply chains, with firms developing unique expertise and specializing in producing goods and services that serve a variety of companies, within and across industries. Technological innovation has also driven the globalization of supply chains – amplifying gains associated with greater specialization.
- As technological innovation gives rise to new economic activity, it prompts the decline of older activity. In the short and medium term, such technological disruption may create hardship for workers whose tasks have become redundant. However, in the long run, the redeployment of workers in growing sectors of the economy represents one of the most important ways through which innovation can generate output growth. In practice, technological progress has prompted a substantial shift away from agriculture and industry toward the service sector. This has largely reflected substantially faster historical rates of productivity growth in agriculture and industry, compared with labor-intensive services.

The diffusion of innovations matters...

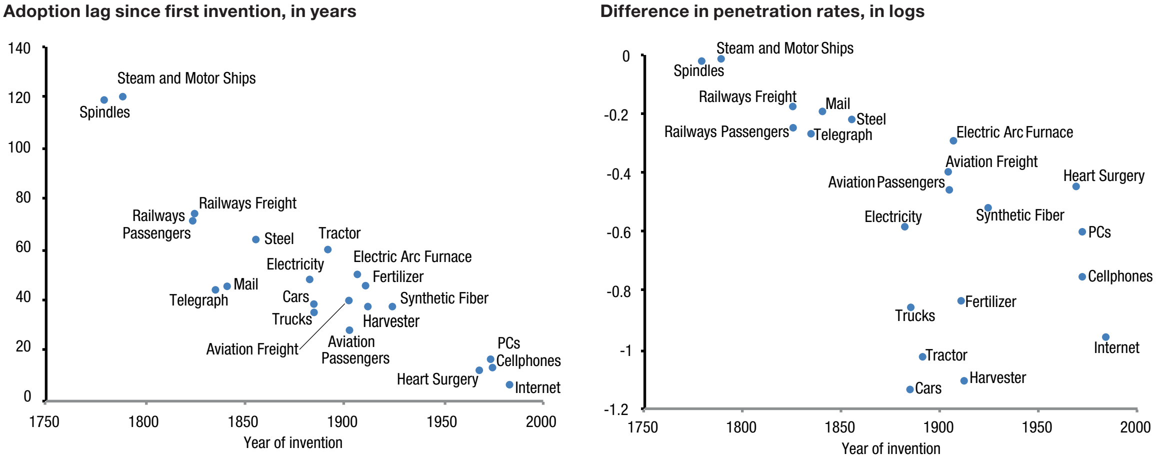
For technological breakthroughs to spur economic growth, they need to diffuse widely throughout the economy. Firms need to learn how to use a new technology, undertake capital investments, reorganize business operations and train workers. Indeed, the arrival of new technologies typically spurs complementary organizational and business model innovations that, in themselves, are responsible for major productivity gains. Competitive dynamics, access to finance, standard-setting and technical regulations, among other determinants, can shape the technology diffusion path in important ways.

...and differs greatly across technologies and recipient countries

How easily does technology diffuse across economies, especially to less developed ones? This question is important. Given the significance of innovation in driving long-run growth, imperfect technology diffusion might be one explanation for diverging levels of economic prosperity.

Recent evidence on technology diffusion patterns points to a mixed picture. On the one hand, it suggests that more recent technological innovations have diffused more rapidly to low- and middle-income countries (see left panel in figure 3). On the other hand, it also suggests that more recent innovations have seen a greater gap in how intensively economies use technology (see right panel in figure 3).

Figure 3: Faster but less pervasive technology diffusion



See figure 1.7

For economies to make productive use of technologies developed abroad, they need to possess sufficient *absorptive capacity* – including the human capital able to understand and apply technology, organizational and managerial know-how, and institutions that coordinate and mobilize resources for technology adoption. In many cases, absorptive capacity also entails the ability to undertake incremental technological and organizational innovation in order to adapt technology to local needs.

Ecosystems giving rise to breakthrough innovation

What kind of ecosystem best supports the flourishing of innovation and the adoption of new technologies? The six case studies included in this report point to a number of well-known elements of success:

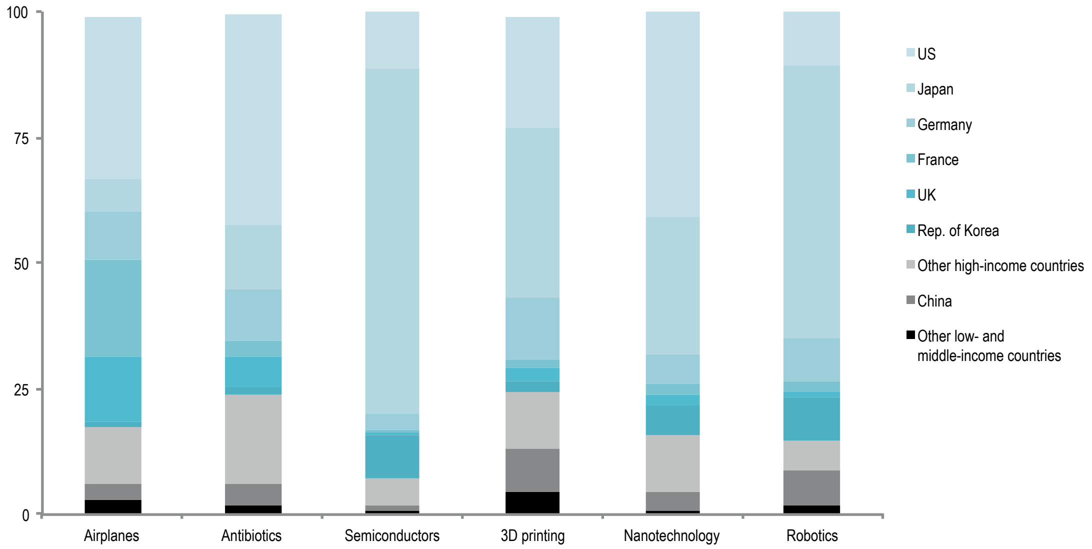
- Governments have been the main source of funding for scientific research that was often instrumental in inventive breakthroughs. In many cases, governments have also played a crucial role in initially moving promising technology from the laboratory to the production stage – often motivated by national defense and industrial policy interests.
- Competitive market forces and efforts on the part of firms were equally crucial, especially in commercializing promising ideas and engaging in follow-on innovation that facilitated scaled-up production, cost reductions and wide-scale adoption of new technologies.
- Linkages between the various innovation actors mattered. They ranged from informal knowledge exchanges, professional networks and worker movements to formal university–industry licensing frameworks and R&D collaborations. They promoted the sharing of knowledge among researchers and connected the upstream and downstream activities that helped transform promising ideas into commercial technologies.

Patenting activity associated with the six breakthrough innovations has been geographically concentrated...

The case studies identify the patents filed around the world that are associated with each of the six breakthrough innovations. While not offering a perfect mirror of the innovation landscape, the resulting patent mappings offer rich information on the geographical and institutional origin of inventions – especially those with commercial potential. They show that across all six case studies, patenting activity has been geographically concentrated (see figures 4 and 5 as well as table 2). High-income countries account for more than 80 percent of filings in all six cases. Even within high income countries, patent filings are concentrated, with the US, Japan, Germany, France, the UK and the Republic of Korea accounting for 75 percent or more of first filings worldwide.

Figure 4: Patenting activity has been geographically concentrated

Share of first patent filings in world total

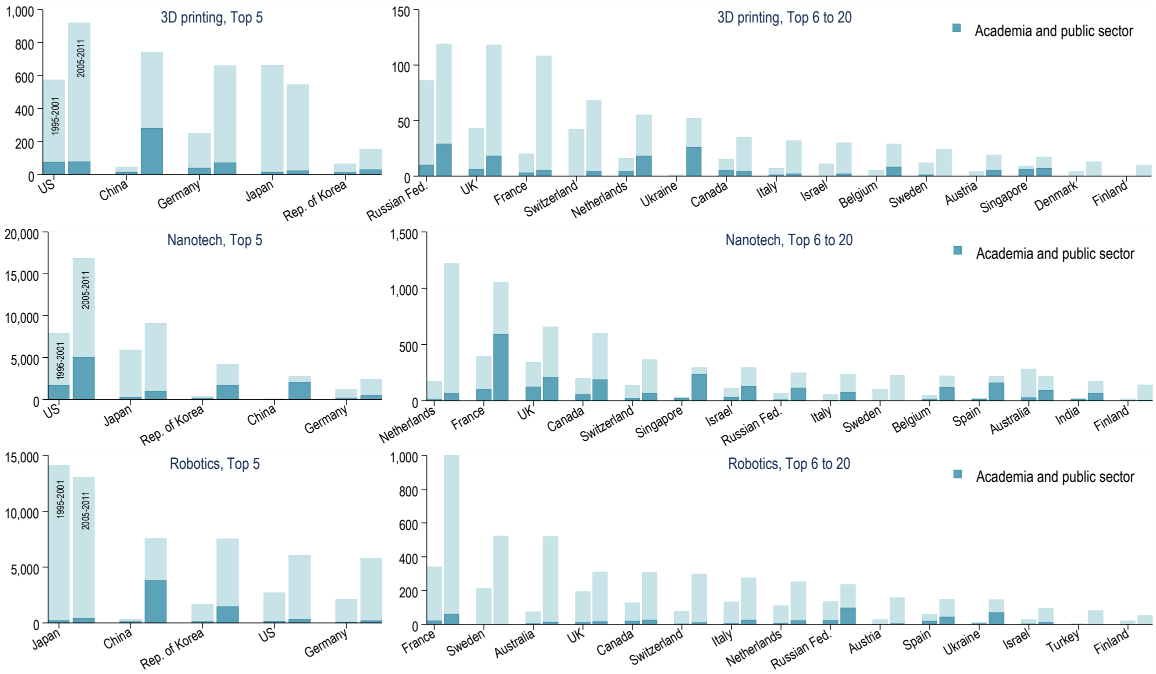


Notes: This figure is a summary of figures 2.3, 2.5, 2.8, 3.2, 3.7 and 3.12, covering the same time periods as the ones shown in those figures. Note that the bars do not exactly sum up to 100 percent, reflecting unknown origins in less than 1 percent of first patent filings.

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

Figure 5: Which countries drive patenting in 3D printing, nanotechnology and robotics?

Top 20 origins in first patent filings, 1995-2001 and 2005-2011



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

Table 2: Five countries between them account for the top 10 patent applicants

Top 10 patent applicants in 3D printing, nanotechnology and robotics since 1995

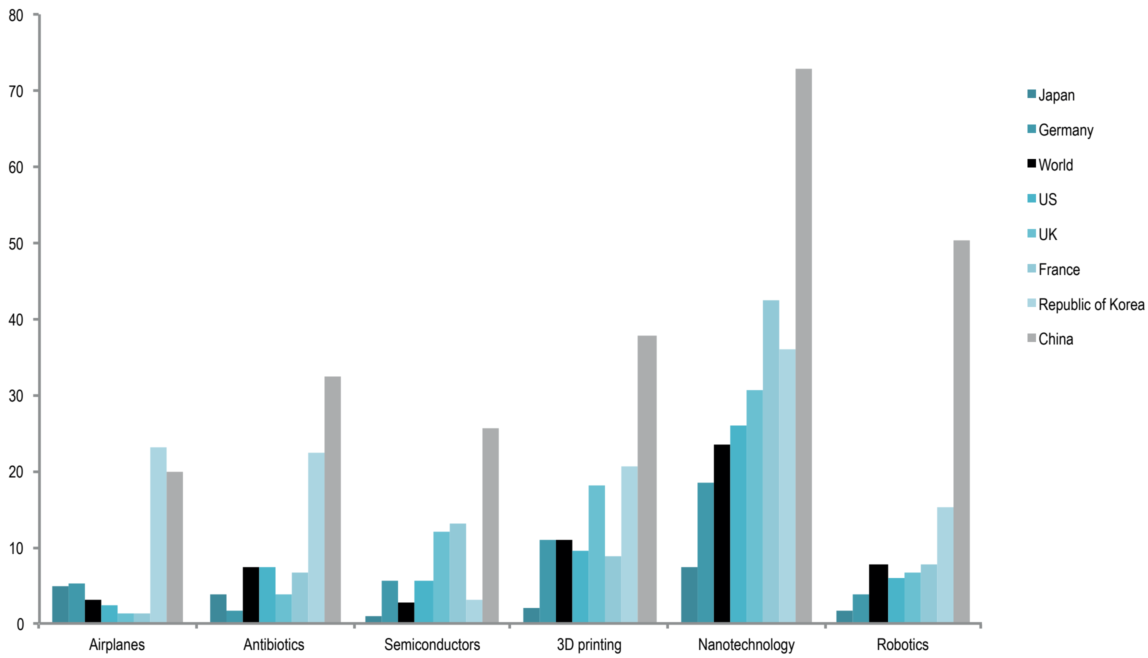
3D printing			Nanotechnology			Robotics		
Applicant	Origin	First filings	Applicant	Origin	First filings	Applicant	Origin	First filings
3D Systems	US	200	Samsung Electr.	KR	2,578	Toyota	JP	4,189
Stratasys	US	164	Nippon Steel	JP	1,490	Samsung	KR	3,085
Siemens	DE	145	IBM	US	1,360	Honda	JP	2,231
General Electric	US	131	Toshiba	JP	1,298	Nissan	JP	1,910
Mitsubishi	JP	127	Canon	JP	1,162	Bosch	DE	1,710
Hitachi	JP	117	Hitachi	JP	1,100	Denso	JP	1,646
MTU Aero Engines	DE	104	Univ. of California	US	1,055	Hitachi	JP	1,546
Toshiba	JP	103	Panasonic	JP	1,047	Panasonic	JP	1,315
EOS	DE	102	Hewlett Packard	US	880	Yaskawa	JP	1,124
United Technologies	US	101	TDK	JP	839	Sony	JP	1,057

Notes: CN = China, DE = Germany, JP = Japan, KR = Republic of Korea, US = United States

See tables 3.3, 3.7 and 3.10

Figure 6: The share of academic patenting is higher for today's innovations

Share of university and PRO applicants in first patent filings, in percent



Note: This figure covers the same time periods as the ones shown in figures 2.3, 2.5, 2.8, 3.2, 3.7 and 3.12.

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

...although China has emerged as an important origin of patenting activity in more recent history

If one looks at more recent history, China emerges as an important origin of patents in 3D printing, nanotechnology and robotics. In particular, looking at first patent applications filed since 2005, Chinese applicants account for more than a quarter of first filings worldwide in the case of 3D printing and robotics – the highest share among all countries. In the case of nanotechnology patent filings since 2005, Chinese applicants make up close to 15 percent of fillings worldwide – the third largest origin of patents.

Innovation today appears to be more closely connected to science than in the past...

Another notable finding from the patent mapping is that the science system and formal linkages between scientific institutions and companies appear to be more important today than in the past. Figure 6 depicts the share of applicants from universities and public research organizations (PROs) for the six innovations studied in the report. It shows higher shares of academic patents for 3D printing, nanotechnology and robotics, compared with the three historical cases. Nanotechnology stands out, with academic applicants accounting for around a quarter of patenting worldwide. Interestingly, the academic patenting share has increased in most countries since nanotechnology took off in the 1980s, suggesting that the scientific base of nanotechnology innovation has become even more important in more recent history.

The greater prominence of universities and PROs in patent landscapes may partly reflect policy efforts to better harness the results of scientific research for commercial development. However, those policy efforts arguably recognize the critical role that upstream research plays in downstream technological progress.

...while the share of academic patents differs markedly across countries

While academic patenting has become more prominent across most of the major patenting origins, there are also notable differences. In the case of Japan, universities and PROs never account for more than 10 percent of total first filings. By contrast, China generally shows the highest shares of academic patenting, exceeding 70 percent for nanotechnology and 50 percent for robotics. On the one hand, this may suggest more limited R&D capacity in Chinese firms in the relevant technology fields, which may imply a lower rate of technology commercialization. On the other hand, as the historical case studies illustrate, a strong scientific base may, in the long term, spawn new firms and industries once technological breakthroughs occur.

The evolving role of IP

IP incentivizes innovation...

As the patent mappings illustrate, innovators in all six cases relied on the patent system to protect the fruits of their innovative activities. In some cases – especially 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.

...and enables technology markets

Equally important, the six case studies document how innovation flourished as a result of implicit or explicit knowledge-sharing arrangements. For example, the first clubs of amateur airplane inventors in the 19th century operated not unlike the open-source communities which today contribute to 3D printing and robotics research. In the case of semiconductors, cross-licensing agreements were important for the commercialization of new technologies and follow-on innovation. Today, many firms engaging in 3D printing, nanotechnology and robotics research have embraced open innovation approaches. They recognize that they may be better innovators by collaborating with others even if that involves some sharing of proprietary knowledge.

In many cases, the IP system has facilitated the sharing of knowledge, by encouraging disclosure and providing a flexible tool for innovators to decide which technologies to share, with whom and on what terms. However, the cases studies also illustrate the importance of social norms in supporting knowledge sharing and the role of government intervention to encourage knowledge sharing when it is in the public interest.

While technology markets were already important for the development of airplanes in the early 20th century, they are bound to be more important today. Pushing the technology frontier requires increasingly complex technological challenges to be overcome. The more prominent role of upstream scientific research is one response to this challenge (see above). In addition, the case studies suggest that firms increasingly specialize, realizing that they may be both more innovative and more efficient by focusing on selected research, development, manufacturing, or marketing tasks. By providing a flexible basis for licensing, IP enables specialization and is at the heart of modern technology markets.

One possible concern about today's innovation ecosystems is the large number of patent filings, which may give rise to patent thickets that could stifle rather than enable technology markets. In addition, there are concerns that widespread patenting might inhibit knowledge sharing. However, the evidence presented in the 3D printing, nanotechnology and robotics case studies suggests that so far, patent thicket concerns have not materialized and the IP system appears to have accommodated different knowledge-sharing mechanisms. It is important to keep in mind, however, that many of the technologies discussed in these case studies are still at a relatively early stage of development and some have yet to see any commercialization. There may well be greater conflicts surrounding IP in the future.

Patent applicants mainly seek protection in high-income markets

The patent mappings carried out for the six case studies uniformly suggest that innovators have overwhelmingly sought patent protection for their inventions in high-income countries plus China (see table 3 for the three current innovation fields). This likely reflects the large size of these countries' markets, as well as the presence of competitors with frontier technological capabilities.

Table 3: Patent applicants mainly seek protection in high-income markets

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

	3D printing	Nanotechnology	Robotics
US	46.6	84.6	36.5
Japan	33.6	52.1	38.7
Germany	37.7	39.8	28.6
France	32.4	36.9	21.9
UK	32.9	37.6	21.3
Republic of Korea	11.8	25.2	19.2
Other high-income countries	16.4	20.5	9.5
China	38.3	31.8	36.6
Other low- and middle-income countries	2.8	2.7	1.4

Notes: This table is a summary of figures 3.5, 3.10 and 3.14, covering patents first filed in 1995 or later and for which at least one patent office issued a grant. Values for "other high-income countries" and "other low- and middle-income countries" are GDP-weighted averages (unweighted averages are similar in magnitude).

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

Only a small share of first patent filings in the relevant technological fields had equivalent patents in low- and middle-income countries other than China. This suggests that patents have been neither helpful for technology dissemination to those countries when it has occurred, nor harmful for dissemination when it has not happened. It rather points to the presence or lack of absorptive capacity as the main factor explaining the extent of technology dissemination. It is important to keep in mind, however, that this conclusion is based on aggregate patent filing patterns; given the highly skewed distribution of patent values, some individual patents may well exert disproportionate influence in certain technology fields. In addition, the conclusion is specific to the six technologies at hand.

Technology itself is shaping the evolution of the IP system

Throughout history, newly emerging technology raised difficult issues for IP policymaking. Patent offices and courts sometimes faced difficult questions about the patentability of founding inventions. In addition, the historical case studies document how court decisions, new laws and targeted government interventions led to a continuous adaptation and calibration of IP policy. This evolution is bound to continue. The case studies of today's breakthrough innovations have brought to light several new considerations that will inevitably shape IP policy in the future:

- Copyright is becoming increasingly relevant for technological innovation. This first happened with the inclusion of software within the domain of copyrightable subject matter. As software has become an integral feature of many new technologies – including 3D printers and robots – so has the role of copyright widened. In addition, copyright can protect any kind of digital expression, including 3D object designs and the design of computer chips. It is yet unclear whether this trend just signifies a shift in the use of different IP forms, or whether it raises fundamentally new policy challenges.
- The emergence of low-cost 3D printing has the potential to enable the easy reproduction of any object that may be protected by industrial design and possibly other IP rights. A natural question is whether this development will render the enforcement of those rights more difficult – similar to the challenge that digital technology has posed in relation to books, music, movies and other creative expressions protected by copyright. Such a

scenario may still be far off and there are important differences between 3D printing and digital content copying. Nonetheless, the experience from the digital content industry may well hold valuable lessons on how to best manage such a scenario.

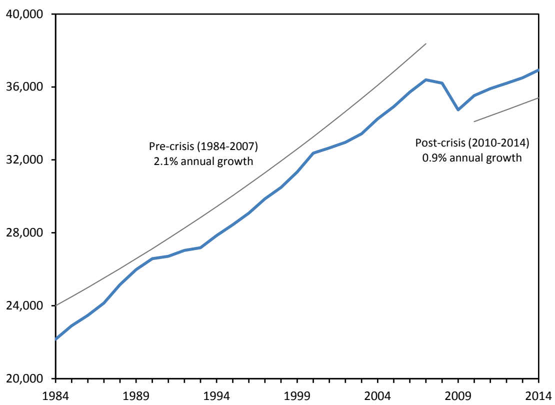
- Trade secrets have always been an important – if not highly visible – form of IP protection. Even though the three case studies offer only suggestive evidence, there are reasons to believe that trade secret policy has become more important. The main reason is that the mobility of knowledge workers has increased. Despite the easy availability of codified knowledge, people remain crucial to put such knowledge to effective use. Trade secret laws regulate how knowledge can flow with people, and thus shape both innovation and technology dissemination outcomes.

Future prospects for innovation-driven growth

As pointed out above, historical data on GDP per capita at the frontier points to spectacular and exceptional growth in the post-Second World war period. Yet growth since the onset of the global financial crisis in 2008 appears anything but spectacular. Figure 7 depicts the evolution of per capita GDP in high-income countries since the mid-1980s. Before the crisis, growth averaged 2.1 percent per year. Not only did the crisis prompt a sharp decline in economic output, average annual growth since 2010 has fallen to 0.9 percent.

Figure 7: The end of spectacular post-Second World War growth?

Real GDP per capita in high-income OECD countries, 1984-2014



See figure 1.8

Optimists reckon that faster growth will resume...

Does the financial crisis mark the beginning of a new era of lower growth? Has the innovation-driven growth engine lost steam? Optimists contend that the world economy is still suffering from a post-financial crisis debt overhang. Eventually, market forces should lead economic growth to return to its long-term path determined by economies' fundamental productive capacities. In addition, looking at the potential for innovation to continuously sustain future growth, there are reasons to be optimistic:

- Never before has the world invested so many resources in pushing the global knowledge frontier. While the financial crisis has left a mark in some countries, R&D spending was far less affected than economic output. Moreover, the emergence of China as an innovator – along with the rapid growth of R&D expenditure in the Republic of Korea – has increased the diversity of the global innovation landscape.
- There still appears to be significant potential for innovation to generate productivity gains and transform economic structures. ICTs have already made important contributions to growth. However, if history is any guide, there is more to come. The growth contributions of major technological breakthroughs have only occurred with decades-long delays. The next generation of ICT innovations – centered on artificial intelligence – holds plenty of promise.
- There are numerous other fields of innovation that hold potential to spur future growth. These include the three fields discussed in this report. For example, the growing use of 3D printers and intelligent robots may well prompt the reorganization of supply chains in many sectors, with possibly sizeable growth effects. Other innovation fields showing significant promise include genetic engineering, new materials and various forms of renewable energy. New technologies have also dramatically improved the research tools that drive the process of scientific discovery. In particular, ICT-driven techniques such as big data analysis and complex simulations have opened new doors for research advances across many areas of technology. For optimists, the interplay between science and technology generates a self-reinforcing dynamic that seems unbounded.

...but doubts persist

Contrasting these optimistic perspectives, some economists have expressed doubt as to whether growth at the frontier in the coming decades will match the post-Second World War record. They put forward several arguments:

- Demographic shifts and other factors have pushed advanced economies into a state of "secular stagnation", whereby economies' realized growth persistently falls short of its potential. While innovation still contributes to future growth, persistently weak growth performance may become self-fulfilling: firms may shun investment opportunities created by new technology, long spells of unemployment may mean that workers lose skills or never acquire them, and fewer firm startups and "scale-ups" may slow the structural transformation of the economy.
- Estimates of economies' productivity growth show a decline that started well before the onset of the crisis. Chiefly, the US economy saw a marked pick-up of productivity growth from 1995 to 2003, mainly attributed to ICTs; however, productivity growth since then has been significantly slower. More generally, research shows that the growth potential of advanced economies started to decline in the early 2000s, mainly accounted for by a drop in productivity growth.
- Pessimists argue that the growth contribution of ICTs has been largely realized and there is no innovation of comparable significance on the horizon. Matching the achievements of earlier innovations in relation to speed of travel, life expectancy and long-distance communication may well be challenging. In addition, there is much less scope for innovation to increase labor force participation; if anything, demographic shifts in developed economies will lead to declining participation. One may also question the productivity of future innovative activity. Pushing the knowledge frontier is becoming progressively more difficult as the "low-hanging fruit" is plucked.

Finally, some economists wonder whether today's GDP measurement framework misses the true impact of new technology. This argument comes in two forms. One is that the tools of statisticians increasingly fall short of capturing quality improvements and new forms of economic output. The other is that the very concept of GDP is ill-suited to capture the societal welfare gains associated with today's innovation. In particular, many new technologies are highly expensive to develop but, once developed, relatively cheap to produce or can even be replicated for free. As such, they contribute little to economic output but may raise welfare disproportionately. However, other economists argue that under-measurement of GDP is not a new phenomenon and there is no convincing evidence that it is worse today than it was in the past.

Conclusion

Only time will reveal how future frontier growth compares with its post-Second World War path. However, continuously investing in innovation will remain imperative for policymakers and business alike. The report's cases studies document the long time it takes to turn promising ideas into workable technologies, for those technologies to be refined, and for companies and consumers to embrace them. Successful innovation, whether at the level of the firm or the economy as a whole, requires perseverance – not least in periods of low growth when innovation budgets come under pressure.

Policymakers will also need to ensure that the IP system contributes to an ecosystem conducive to innovative breakthroughs. Since the onset of the industrial revolution, the IP system has continuously adapted to the demands and challenges of newly emerging technology. This trend is bound to continue, and is best guided by careful consideration of available evidence and openness to the direction of technological change.

Table of Contents

Chapter 1
A Look Inside the Economic Growth Engine

Economic growth has been a powerful force for reducing poverty, creating jobs and improving general living standards. However, it cannot be taken for granted. Before the 18th century the world economy saw little growth. Poverty was widespread and any substantial improvement in living standards for more than the privileged few was beyond imagining. Since then, the world economy has grown at an unprecedented pace – greatly improving the quality of life and generating widespread material prosperity. Even so, some national economies have seen faster and more sustained growth than others, leaving wide disparities in the prosperity of nations today.

What explains the variations in growth observed throughout history? Scholars have long puzzled over this. The onset of gradually faster growth in the second half of the 18th century prompted the first theories of economic growth – as proposed, for example, by Adam Smith, David Ricardo, Thomas Robert Malthus and John Stuart Mill.[1] Important insights have emerged since then. One central insight is that lasting economic growth relies on continuous technological progress. Indeed, the last three centuries have seen a series of innovative breakthroughs in different fields of technology that have profoundly transformed productive activity and spurred the growth of new industries.

Against this background, this report asks what role the intellectual property (IP) system plays in the growth process. It does so in two parts. First, it reviews the nature of economic growth throughout history and explores the channels through which different IP rights affect growth outcomes – a task performed in this opening chapter. Second, it studies the role of IP more concretely in the case of three historical breakthrough innovations – airplanes, antibiotics and semiconductors – as well as three current innovations with seeming breakthrough potential: 3D printing, nanotechnology and robotics. These case studies will form the core of chapters 2 and 3, respectively.

This opening chapter takes a look inside the economic growth engine. It starts by establishing key stylized facts about economic growth throughout history (section 1.1). It then explores the channels through which innovation drives long-term growth (section 1.2). Against this background, the chapter takes a closer look at the innovation process, exploring how frontier innovations come about and how they disseminate within and across economies (section 1.3). With these building blocks laid, the discussion moves on to consider the various ways in which different IP rights affect innovation and knowledge diffusion outcomes (section 1.4). The final section ponders what growth prospects the future may hold in the wake of the recent financial crisis (section 1.5).

1.1 – Economic growth throughout history

For much of human history, economic growth was simply unknown. By today's standards, living conditions were dismal and they stayed largely the same from one generation to the next. This changed gradually some 200 years ago with the onset of the first industrial revolution, powered by steam engines, cotton spinning and railroads.[2] Since then, sustained economic growth has become the new normal, even if it has not been uniformly spread across time and space.

This section seeks to set the scene by reviewing growth performance over the past two centuries. In particular, a careful analysis of available data and historical studies point to four stylized facts:

1. Growth at the frontier took off in the early 19th century and accelerated in the post-Second World War era.
2. Economic growth has led services to displace agriculture as the main economic activity and has prompted increased urbanization.
3. Diverging growth performance has increased the gap between the poorest and richest economies.
4. Over the past decades, economic growth has gone hand in hand with rising inequality within countries, but fast growth in China and India has been an equalizing force in the world's income distribution and has caused absolute poverty to decline.

1. For a review, see Samuelson (1978).

2. See Gordon (2012).

The following discussion elaborates on these four stylized facts in turn.

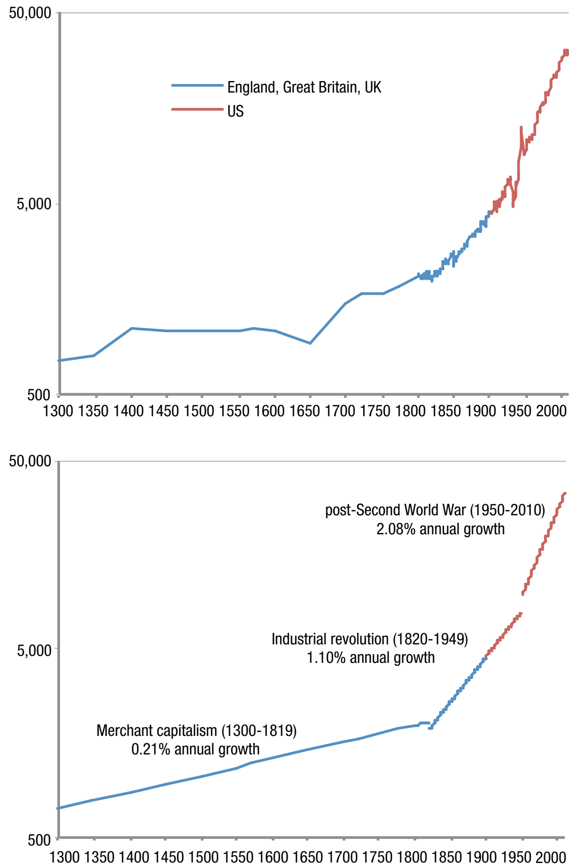
Stylized fact #1
Growth at the frontier took off in the early 19th century and accelerated in the post-Second World War era.

Studying growth performance going back centuries is challenging. Advanced economies only started compiling national accounts – enabling the measurement of gross domestic product (GDP) – in the first half of the 20th century. Most developing economies only did so much later. Economic historians have estimated GDP values for the time before official data became available, making use of historical production, wage, tax and other data records. For selected economies, there are thus estimates of economic output available going back two and more centuries. These estimates are far from perfect. As one moves into the distant past, their margin of error is bound to increase. In addition, as section 1.2 will further explain, comparing GDP values across time raises difficult questions about how to account for changes in the nature and quality of goods and services produced. In all likelihood, comparisons of GDP values over the long run are bound to substantially underestimate improvements in the material standard of living, as they do not fully capture the benefits associated with the arrival of new technology.[3]

Notwithstanding these problems, the work of economic historians is the only source of empirical information on long-run growth performance and it thus bears careful consideration. Relying on the most comprehensive set of historical estimates available – those generated by the Maddison Project – figure 1.1 depicts the evolution of GDP per capita at the frontier since 1300.[4] The frontier is captured by the economy showing the highest economic output per capita at a given point in time. For the purpose of figure 1.1, these are taken to be England, Great Britain and the United Kingdom (UK) up to 1900, and the United States (US) thereafter.[5]

Figure 1.1: Growth at the frontier over seven centuries

Real GDP per capita, 1300-2000, logarithmic scale



Notes: GDP values are in 1990 international dollars, adjusted for differences in purchasing power across countries. For 'England, Great Britain, UK', estimates apply to England up to 1700, to Great Britain from 1700 to 1850, and to the UK from 1851 onwards. Annual growth rates are the slopes of the logarithmic trend lines for the three periods.

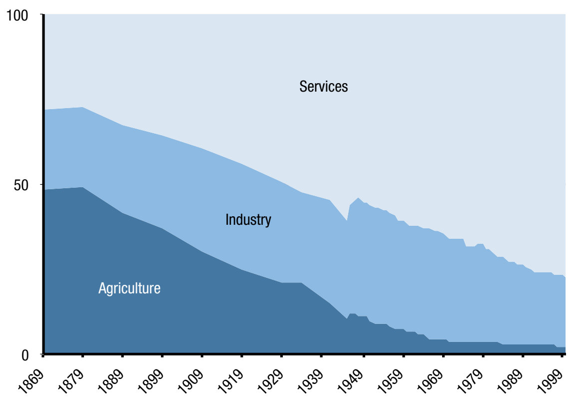
Source: The Maddison Project, *www.ggdc.net/maddison/maddison-project/home.htm*, 2013 version.

3. See DeLong (1998) and Coyle (2014).
4. See Bolt and van Zanden (2014).
5. This approach follows Gordon (2012).

The figure's lower panel divides the seven centuries into three growth periods and shows trend lines depicting average growth of per capita GDP during these periods. The first period – labeled "merchant capitalism" following Kuznets' (1967) original terminology – saw only little and sporadic growth, averaging around 0.21 percent per year.[6] The onset of the industrial revolution then led to a sharp increase in the annual rate of growth, to 1.10 percent.[7] To underline the significance of this growth pickup, 0.21 percent annual growth implies a doubling of income every 331 years, whereas 1.10 percent growth implies the same every 64 years. Finally, in the post-Second World War era, growth accelerated further to 2.08 percent per year – implying a doubling of income every 34 years. In light of centuries of history, the growth performance since 1950 thus emerges as both spectacular and exceptional.

Figure 1.2: The rise of services

Share of US employment in different sectors, 1869-2000, in percent



Notes: "Agriculture" includes agriculture, forestry and fishing; "industry" includes manufacturing, mining and construction; "services" includes transportation and public utilities, wholesale trade, retail trade, finance, insurance, real estate and government as well as the "services" category of the Bureau of Economic Analysis (BEA). Data for 1929 and earlier refer to the Kendrick estimates, as explained in US Bureau of the Census (1975).

Source: BEA, National Income and Product Accounts, table 6.8B, and US Bureau of the Census (1975).

Stylized fact #2

Economic growth has led services to displace agriculture as the main economic activity and has prompted increased urbanization

In medieval societies, agriculture was the center of economic activity. The onset of more rapid economic growth in the early 19th century led to a gradual transformation of economic output, initially away from agriculture and toward industry and services, and – at a later stage – entirely toward services. Figure 1.2 illustrates this transformation for the US, looking at the employment shares of the three main economic sectors since the mid-19th century. In 1869, agriculture accounted for close to half of total employment, with industry and services accounting for around a quarter each.[8] In the 131 years that followed, agriculture lost its dominance and by 2000 it accounted for a mere 2.4 of total employment. The share of industry first expanded to reach a peak of 34.4 percent in 1953, but then fell to 20.4 percent in 2000. The service sector has seen the most dynamic growth. By 1934 it already accounted for more than half of total employment, and by 2000 for more than three-quarters.

A similar picture emerges when looking at the value-added share of each sector in GDP. In 2010, services made up 73.6 percent of economic output in high-income countries, with industry accounting for 25.0 percent and agriculture 1.4 percent.[9] In a nutshell, economic growth has converted the agrarian societies of a few centuries ago into today's services-based economies.

6. Broadberry *et al* (2011) attribute 14th-century growth in GDP per capita to the population decline associated with the Black Death. Similarly, growth in the second half of the 17th century coincided with a declining population.
7. Figure 1.1 follows Maddison (2001) in adopting 1820 as the year marking the transition from the "merchant capitalism" era to the "industrial revolution" era.
8. The choice of 1869 as the starting year in figure 1.1 simply reflects data availability. Historical studies suggest that the structural shift toward industry and services started much earlier. For example, Broadberry *et al* (2011) estimate that the share of agriculture in English GDP fell from 49.1 percent in 1381 to 26.8 percent in 1700, while the services share rose from 23.1 to 34.0 percent over the same period.
9. As reported in the World Bank's World Development Indicators database.

This structural shift had a profound impact on economic geography. Labor freed by the agricultural sector agglomerated in urban areas, which offered not only job opportunities but also access to health, education, retail markets, transportation, entertainment and other amenities. Urbanization accelerated markedly with the onset of the industrial revolution in the 19th century. The United Kingdom – the frontier economy of the 19th century – saw the share of the total population living in cities of 5,000 or more inhabitants rise from one-fifth in 1800 to two-thirds in 1900.[10] London emerged as the world's largest city, reaching one million inhabitants around 1800 and growing to 5.6 million inhabitants by 1891.[11] By comparison, Paris only reached the one million mark in the mid-19th century, New York in 1871, and Berlin in 1880.[12] Indeed, urbanization took longer in other advanced economies. In the US, the urban population share stood at a relatively modest 31.3 percent in 1900, and it surpassed the two-thirds threshold only in the second half of the 20th century.[13] Still, by 2010 close to four-fifths of the population in all high-income countries lived in urban areas.[14]

Stylized fact #3
Diverging growth paths have increased the gap between the poorest and richest countries

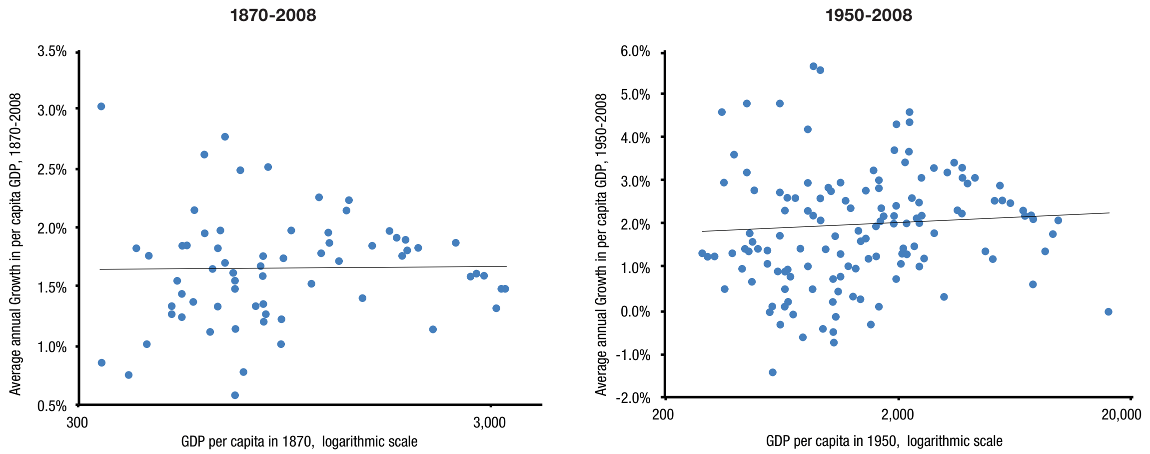
Has economic growth been evenly spread across the world? In particular, how have economies outside the frontier group fared since growth started to accelerate in the 19th century? The short answer is that there has been "divergence, big time" – as famously noted by Pritchett (1997). In 1870 – the earliest year for which data for a wide range of economies are available – GDP per capita of the richest economy was around 10 times that of the poorest economy; by 2008 the gap had widened to a factor of 126.[15] While selected once-poor economies – notably in East Asia – were able to catch up with the frontier group, no such general process of convergence has taken place across the world. Figure 1.3 illustrates this point by plotting initial income against subsequent growth for all economies, as far as available data go. If incomes had converged, one would expect the scatter plots to show a negative correlation, indicating faster growth in initially poorer economies. However, there is no such negative correlation – neither during the full 1870-2008 period nor during the shorter post-Second World War period.[16]

Sustained growth at the frontier and the lack of convergence by non-frontier economies have led to sharp differences in absolute income levels across the world. To illustrate this point, consider the experience of Germany and Ecuador. In 1870, Germany had a per capita income of United States dollar (USD) 1,839 compared with Ecuador's income of USD 411– a difference of USD 1,428. From 1870 to 2008, average annual growth in both economies was largely the same, around 1.8 percent. As a result, Germany's per capita income increased to USD 20,801 in 2008 and Ecuador's to USD 5,005. In turn, the absolute difference in income levels increased elevenfold, to USD 15,796.[17]

10. See Bairoch and Goertz (1986).
11. As derived from London's historical census data, available at *data.london.gov.uk/dataset/historic-census-population*.
12. See Watson (1993).
13. As derived from US Bureau of Census data, available at *www.census.gov/population/www/censusdata/files/table-4.pdf*. Using a threshold of cities with 2,500 or more inhabitants, the urban population share stood at 63.1 percent in 1960.
14. As reported in the World Bank's World Development Indicators database.
15. These estimates rely on the Maddison Project database (see also figure 1.3). In that database, Australia was the richest and the Republic of Korea the poorest country in 1870, and the US was the richest and the Democratic Republic of the Congo the poorest country in 2008.
16. The slopes of the linear regression lines shown in figure 1.3 are not statistically different from zero. Note, however, that there has been long-run income convergence among high-income economies (Pritchett, 1997).
17. All figures in this example are in 1990 international dollars and come from the Maddison Project database.

Figure 1.3: Poorer economies have not grown faster than richer economies

Initial income versus subsequent growth



Notes: GDP values are in 1990 international dollars, adjusting for differences in purchasing power across countries. The left panel includes all 67 economies for which the Maddison Project database provides GDP per capita estimates for 1870. The right panel includes 138 economies for which 1950 GDP per capita figures were available; it excludes three small oil producing economies – Equatorial Guinea, Kuwait and Qatar – as their growth performance was heavily influenced by cyclical factors either at the beginning or at the end of the 1950–2008 period.

Source: The Maddison Project, *www.ggdc.net/maddison/maddison-project/home.htm*, 2013 version.

In addition, initial differences in per capita incomes have largely persisted over time. Eight of the ten richest economies in 1870 are still among the ten richest economies of 2008. Only Hong Kong and Singapore were able to break into the top ten.[18] To be clear, most economies outside the frontier group have also seen sustained economic growth, promoting far better living standards for their citizens than in the 19th century. However, growth patterns across the world have not narrowed inequalities in the prosperity of nations; they have widened them.

Stylized fact #4

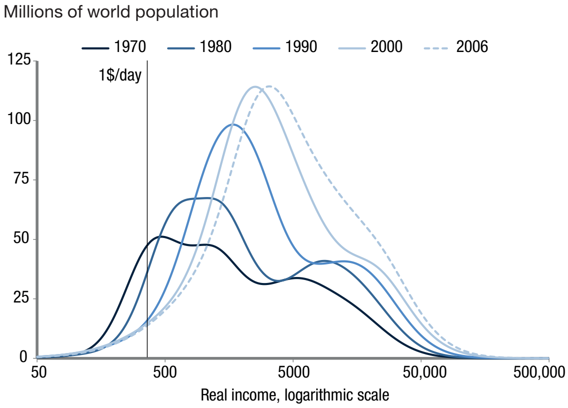
Over the past decades, economic growth has gone hand in hand with rising inequality within countries, but fast growth in China and India has been an equalizing force in the world's income distribution and has caused absolute poverty to decline

If nations' incomes have diverged, does this mean that the world has become a more unequal place? Not necessarily, for two reasons. First, the above analysis treats each country the same, ignoring that some countries are far more populous than others. Second, it does not consider changes in the distribution of income within countries, which affects the prosperity of the average citizen.

18. As previously, these comparisons are based on GDP per capita figures from the Maddison Project database.

To assess whether the world has become a more or less equal place, one needs to analyze how the distribution of income across all citizens in the world – rather than countries – has evolved over time. Sala-i-Martin (2006) performed precisely such an analysis. Using data on GDP per capita and the national income distribution of 138 countries, this study estimated the world distribution of income going back to 1970.[19] It reached three conclusions. First, most countries have seen growing income inequalities among their citizens. Second, despite this and despite the growing divergence of incomes across countries, world income inequality has fallen. This conclusion may at first appear counterintuitive. However, it is explained by the fast growth of populous and initially poor Asian economies, notably China and India, which saw their incomes converge to those of the advanced economies. Subsequent research, relying on different data and alternative estimation approaches, has been more cautious about concluding that overall world inequality has fallen.[20] However, it has confirmed the equalizing force that the growth of large Asian economies has exerted on the global distribution of income.

Figure 1.4: Growth has reduced extreme poverty



Notes: The lines depict the world distribution of income in different years, whereby the area under each line und above the horizontal axis represents world population in any given year. Real income is measured in 2000 international dollars, adjusting for differences in purchasing power across countries.

Source: Pinkovskiy and Sala-i-Martin (2009).

Third, economic growth has substantially reduced levels of extreme poverty – as captured by income of one dollar a day or less. Figure 1.4 – relying on an update to Sala-i-Martin's estimates – depicts the world distribution of income since 1970 as well as the one-dollar-a-day threshold. It shows how economic growth has shifted the world income distribution to the right. Especially fast growth in large and initially poor Asian economies has transformed its shape into a single-peak distribution. In the process, the extreme poverty headcount fell from 403 million 1970 to 152 million in 2006. In addition, in 1970 most poor people lived in Asia, whereas by 2006 they were mostly found in Africa. Other studies, at times using different poverty thresholds, have arrived at different estimates of poverty levels.[21] However, they uniformly document the substantial reduction in extreme poverty and its geographical shift.

1.2 – How innovation drives economic growth

Why has the growth performance of economies varied so much over time and across the world? What fuels the economic growth engine? Few questions in economics have generated so much research. This section reviews the main drivers of economic growth, seeking to identify in particular the main channels through which innovation generates growth. It focuses on the long-term determinants of economic growth, ignoring business-cycle fluctuations that lead an economy to temporarily deviate from its fundamental growth path (see section 1.5 for further discussion).

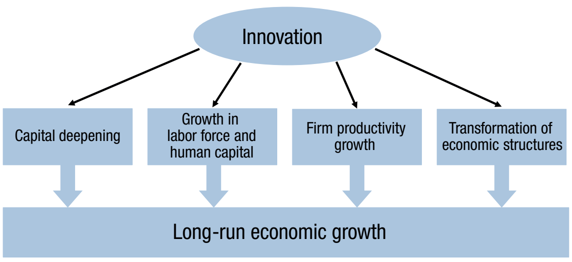
The most common "workhorse" that economists use to isolate the sources of long-term growth is the so-called growth accounting framework, usually attributed to the Nobel prize-winning economist Robert Solow.[22] This framework decomposes output growth into two components: first, a component attributable to the accumulation of production factors – mainly capital and labor, later expanded to include human capital; and second, a component capturing an economy's overall productivity growth, also referred to as total factor productivity (TFP) growth.

19. Sala-i-Martin (2006) imputes missing data points through econometric forecasting and by relying on data from neighboring countries.
20. Lakner and Milanovic (2013), for example, employ survey data to capture countries' average incomes, rather than the national accounts data employed by Sala-i-Martin (2006). They estimate a higher Gini coefficient than Sala-i-Martin which has hardly fallen over time. See also Pinkovskiy (2013).
21. See, for example, Chen and Ravallion (2004).
22. See Solow (1956; 1957).

The growth accounting framework goes some way to explain why some nations have grown faster than others.[23] For example, empirical studies have pointed to high rates of investment and the absorption of surplus rural labor into the formal labor force as key explanations for the rapid growth of several East Asian economies over the past decades.[24] However, in trying to understand how technological innovation has driven growth, the growth accounting framework faces two important limitations. First, even though technological innovation is often thought to be a key determinant of TFP growth, it can also have profound effects on factor accumulation, as further explained below. Second, empirical studies typically capture TFP growth as the residual growth left after accounting for the influence of production factors. As such, they cannot offer any insight into the precise forces that lead economies to become more productive.

Obtaining such causal insights is challenging. Technological innovation has complex effects on the behavior of firms and workers and the structure of economies. Nonetheless, one can broadly distinguish four transmission channels – as illustrated in figure 1.5.[25] This section elaborates on these transmission channels.

Figure 1.5: Innovation spurs growth through different channels



Capital deepening

Firms invest in new capital equipment based on the future income they expect those investments to generate. The introduction of new technologies can raise investment returns and lead firms to undertake new investments. Similarly, new technologies affect the decisions of governments to invest in public goods, especially the provision of an economy's infrastructure. Indeed, neoclassical growth theory predicts that without any technological progress, diminishing returns on capital investment set in and economic growth converges to zero.[26]

Historically, the introduction of major breakthrough technologies has often unleashed investment booms, driving expansions in economic output. For example, the arrival of railway technology in the 19th century prompted massive infrastructure investments that, in themselves, drove sizeable output fluctuations.[27] More recently, as information and communication technologies (ICTs) took off in the 1990s, studies show that US firms throughout the economy rapidly increased their ICT capital stock, especially when compared with other fixed capital assets.[28] In addition, intangible asset investments – the establishment of new business processes, databases and other knowledge-based activities – have become an important component of overall investments and are also linked to the introduction of new technologies.

Growth in labor force and human capital

Historically, technological innovation has been a key force behind the expansion of the workforce. First and foremost, advances in health technology have prompted a dramatic increase in life expectancy. For example, in 1800 average life expectancy at birth was below 40 years in all developed economies; by 2011 it had risen above 75 years, with Japan seeing the highest average of 83 years.[29] By reducing the burden of chronic disease and disability, technology has also contributed to a progressively healthier – and thus economically more productive – workforce.

23. See, for example, Mankiw *et al* (1992) for econometric evidence.
24. See Young (1995; 2003), although Nelson and Pack (1999) argue that high rates of investment were only possible because those successful East Asian economies learned how to use new technologies effectively.
25. Maddison (1997) offers a similar categorization.
26. See Solow (1956).
27. See chapter 5 in O'Brien (1977).
28. See, for example, Stiroh (2002).
29. See Roser (2015).

Innovation has been instrumental in facilitating greater adult participation in the workforce. For example, the introduction of refrigeration, indoor plumbing, the washing machine, supermarkets and other innovations freed family members – especially women – from routine household tasks, enabling them to enter into formal employment. Similarly, the arrival of speedy mass transportation reduced geographical barriers in the labor market. These factors have also promoted access to education, increasing the quality of the labor force. Advances in educational technology, in turn, have widened and deepened educational achievements, further augmenting the economy's human capital base.

Firm productivity growth

Innovation can affect the productivity of firms through a variety of channels. *Process innovations* can increase the efficiency with which inputs – especially labor – are converted into output. Often, such efficiencies result from the deployment of new capital equipment, as described above. The resulting productivity enhancements free up resources that can be used to expand output – in the same firm, in the same sector, or elsewhere in the economy. Similarly, process innovations that lead firms to reap greater economies of scale lead to greater output with the same level of capital and labor input.

Product innovation has more varied effects on productivity. One form of such innovation is the quality upgrading of existing products – for example, the introduction of more powerful computers, longer-lasting batteries and more energy-efficient refrigerators. If firms manage to produce the same output level with the same inputs but the output is of superior quality, product innovation directly leads to improved firm productivity. While conceptually this is straightforward, measuring quality improvements in economy-wide output poses a substantial challenge, as explained in box 1.1.

A second form of product innovation is the introduction of new products that did not previously exist. Such products could either be sufficiently distinct varieties of existing products – for example, a new car model – or more fundamental breakthroughs such as the first tablet computer. Since the firm introducing the new product did not produce it previously, one cannot evaluate how such innovations directly affect the firm's productivity. As in the case of quality improvements, correctly measuring the growth of economic output when new products enter the marketplace can be challenging (see box 1.1).

Ultimately, the productivity effects of new products depend crucially on whether buyers of new products are final consumers or other firms which use the products as a production input. In the case of the former, consumers of new products invariably adjust their consumption basket, leading to changes in the composition of output. How such changes affect productivity is uncertain. However, since consumers voluntarily purchase the newly available products, their welfare is bound to increase.

New products that serve as intermediate inputs for other firms may give rise to important productivity gains.[30] Indeed, the introduction of electricity, affordable long-distance travel, telecommunication, computing and many other goods and services has historically led to substantial productivity gains in firms across a wide range of sectors.

Finally, just as process and product innovations can raise a firm's productivity performance, so can they render the functions of government more efficient. In recent history, for example, the introduction of ICTs in the delivery of government services – often labeled 'e-government' – has markedly improved the quality and cost-effectiveness of these services.[31]

30. Grossman and Helpman (1991) model such productivity gains as an increase in the diversity of intermediate inputs.
31. The Australian Government has published a comprehensive study describing the quality and efficiency gains from e-government, available at *www.finance.gov.au/agimo-archive/__data/assets/file/0012/16032/benefits.pdf*.

Box 1.1: Capturing new goods and services in GDP statistics

Measuring economic growth relies on the efforts of statisticians to quantify overall economic output. Since one cannot meaningfully add quantities of oranges and apples – let alone quantities of tablet computers, taxi rides and doctor visits – statistician rely on the market valuation of these quantities. Multiplying quantity times price for each good and service, and adding the resulting valuations together yields an economy's GDP.

Calculating so-called *nominal GDP* values for any given year is relatively straightforward. However, difficulties arise if one wants to track economic output over time. To begin with, changes in nominal GDP may reflect changes in underlying quantities, changes in prices, or both. For example, a high inflation rate might lead to a sizeable increase in nominal GDP, even if quantities remain unchanged. For this reason, statisticians have devised the concept of *real GDP*, which measures the physical quantity of economic output using the prices of a given base year.

However, an intricate problem arises from product innovation that prompts new goods and services to enter the marketplace. If those new goods and services do not relate to any previous ones, prices from a previous base year are not available. The only way to include them in real GDP calculations is to update the base year. But which year to choose is not obvious. The prices of new goods and services will often decline rapidly, and quantities grow quickly, in the first years after their introduction; choosing an early base year might then overstate real GDP growth. For this and other reasons, statistical offices in many countries have introduced so-called chain-weighted approaches to real GDP measurement, whereby the base year is implicitly updated every year.

If new goods and services reflect quality improvements on previously existing ones, prices from a previous base year do exist.[32] However, comparing the quantities of the new goods and services to those of the old ones would be misleading. For example, if quantities were expressed in boxes of strawberries, one would naturally adjust for a change in the weight of boxes from one year to the next. Similarly, if one were to count boxes of computers, one should adjust for the increase in the computing power of each box from one year to the next.[33] Statisticians have devised methods for making such quality adjustments. Using so-called matched-model and hedonic techniques, one can estimate hypothetical price indices that capture changes in the price of goods and services, holding their quality characteristics constant. These price indices are then used to deflate nominal GDP values, yielding a measure of real GDP that accounts for quality improvements.[34]

Chain-weighting and hedonic techniques are important tools to accommodate product innovation in GDP measurement. However, they are not perfect.[35] Above all, they rely on the ability of statistical offices to quantify and collect data on a large array of quality attributes of goods and services. Even the best-resourced offices only perform hedonic adjustments for a limited set of goods and services. Moreover, certain quality gains do not easily lend themselves to quantification – such as innovations leading to improved safety, security, sustainability and overall quality of life.

Finally, it is important to point out that real GDP growth only partially captures the welfare gains associated with product innovation. This is partly because of imperfect measurement, as just described. More importantly, GDP growth just seeks to measure how output evolves over time, not how consumers – and society at large – value any output expansion. While there are good reasons why one would expect output and welfare to correlate, they are fundamentally different concepts.

Sources: Landefeld and Parker (1997), Landefeld and Grimm (2000) and United Nations (2009).

32. In practice, the distinction between a new good and a good of superior quality can be ambiguous. For example, new functionality in a product may be considered a quality improvement; however, if the new functionality is sufficiently important and leads to new uses of the product, it may be regarded as an entirely new product. This ambiguity further complicates measurement efforts. See OECD (2001).
33. This example is taken from Landefeld and Grimm (2000).
34. Another important measurement challenge is which types of creative and innovative activities of companies should be accounted for as intermediate consumption and which as asset investments. For example, the *System of National Accounts 2008* recognizes R&D spending and software as fixed asset investments (see *unstats.un.org/unsd/nationalaccount/sna2008.asp*). Other intangible asset investments may follow in future.
35. For a review of methodological criticisms, see Hulten (2003).

Transformation of economic structures

Innovation has far-reaching effects on the growth performance of firms. Equally if not more important, new technologies are often at the root of profound structural transformation. In the medium to long term, such structural transformation affects an economy's productivity performance through a variety of channels.

First, new technologies can change the face of industries, leading to the exit of some firms and the entry of others. In addition, the intensity of competition may change. In many cases, these changes prompt growth-enhancing efficiency gains and redeployment of production factors. Vibrant competition can spur technology dissemination and future innovation.[36] However, such an outcome is not certain. Technology may well lead to more concentrated industry structures, sometimes even prompting the concern – and intervention – of competition authorities.[37]

Second, technological innovation often unleashes a reorganization of supply chains. Typically, such reorganization involves greater specialization, with firms developing unique expertise or producing specialized inputs that serve a variety of companies, within and across industries. Increased specialization can generate important efficiencies that translate into economy-wide productivity gains. Technological innovation has also facilitated the globalization of supply chains. The participation of a wider and more diverse range of international suppliers amplifies the productivity gains associated with greater specialization.

Third, as technological innovation gives rise to new economic activity, it prompts the decline of older activity. For example, the arrival of automobiles replaced travel by horses, obviating the need for large numbers of workers to clean the streets of horse manure. Similarly, the introduction of telephone technology enabling direct dialing obviated the need for manual switchboard operators. In the short to medium term, such technological disruption may create hardship for those whose tasks have become redundant. However, in the longer term, the redeployment of workers in growing sectors of the economy represents one of the most important ways through which innovation can generate output growth.

As shown in figure 1.2, in practice technological progress has prompted a substantial shift away from agriculture and industry toward the service sector. This has largely reflected substantially faster historical rates of productivity growth in agriculture and industry, compared with labor-intensive services.[38] Accordingly – if somewhat counterintuitively – agriculture and industry have freed workers who have found employment in a growing service sector.[39] From this perspective, a shrinking share of industry in output has not necessarily been a worrying sign of "deindustrialization" – as is sometimes claimed – but a natural byproduct of technological progress.

1.3 – Frontier innovation and diffusion

The discussion above has shown the central role of innovation in driving long-term growth. But which innovations account precisely for how much growth? The infographic at the end of this report depicts some of the most important technological breakthroughs over the past 200 years, along the frontier growth path shown in figure 1.1. It is meant as an illustration, and the selection of technologies is clearly subjective.

36. Aghion *et al* (2005) formally explore how competition and innovation interact. See also the discussion of endogenous growth in section 1.3
37. Examples of industries shaped by new technologies that have faced the scrutiny of competition authorities include telecommunications (AT&T), computer operating systems (Microsoft) and online search (Google).
38. See Baumol (1967) and Baumol *et al* (1985), though the latter article also points to heterogeneity within the service sector, with some service activities such as communications and broadcasting having seen fast productivity growth.
39. In addition to technology, the rise of the service sector arguably also reflects the rising demand for services – including education, health, travel and entertainment services – as economies grow richer.

Box 1.2: Quantifying the growth impact of past innovations

Studies seeking to quantify the growth impact of specific innovations have mostly relied on the growth accounting framework outlined in section 1.2. In particular, they capture the growth contribution through two components: (i) capital deepening measured by the growth of capital inputs associated with a particular innovation and (ii) TFP growth in the sector that produces the goods underlying the innovation.

Two studies which have adopted this framework are Crafts (2004) for the impact of steam technology on British economic growth during the late 18th and 19th century, and Oliner and Sichel (2003) for the impact of ICTs on US growth in the last quarter of the 20th century. Table 1 presents their estimates, which are expressed as annual percentage contributions to labor productivity growth.

Crafts' study captures capital deepening by the growth in horsepower associated with steam technology. Although James Watt's steam engine was patented in 1769, Craft's estimates suggest that its contribution to labor productivity growth was not higher than 0.02 percent per year until 1830. It then rose to 0.04 percent (1830-50), 0.12 percent (1850-70) and 0.14 (1870-1910). These estimates illustrate both the delayed and long-lasting impact of the steam engine.

Oliner and Sichel's study measures capital deepening by the growth of ICT capital – computer hardware, software and communication equipment. Their estimates suggest a higher overall contribution to growth than from steam technology, especially in the second half of the 1990s. In addition, most of the growth contribution is due to capital deepening – the greater use of ICTs throughout the economy. As in the case of the steam engine, the growth impact of ICTs took time to materialize, though the delay is much shorter in comparison.

The above estimates are bound to underestimate the true growth impetus from the new technologies. Above all, the estimation approach only captures TFP growth in the technology-producing sectors. It ignores possible productivity spillovers in other sectors of the economy. In the case of steam technology, Crafts believes such spillovers may have been significant after 1850. At the same time, cyclical effects may bias the estimates presented in table 1 and may, in particular, cause an overestimate of the ICT contribution in the second half of the 1990s (Gordon, 2000).

Table 1: Growth contributions from steam technology and ICTs

	Steam technology in Britain					ICTs in the US		
	1760-1800	1800-30	1830-50	1850-70	1870-1910	1974-90	1991-95	1996-2001
Capital deepening	0.004	0.02	0.02	0.06	0.09	0.41	0.46	1.02
TFP	0.005	0.001	0.02	0.06	0.05	0.27	0.41	0.77
Total contribution	0.01	0.02	0.04	0.12	0.14	0.68	0.87	1.79

Source: Oliner and Sichel (2003) and Crafts (2004).

Unfortunately, it is difficult to make a precise link between historical growth performance and different innovations, for at least two reasons. First, the multitude and complexity of the transmission channels outlined in section 1.2 and the simultaneous impact of various technologies make it difficult to isolate the contribution of a single innovation. Second, the adoption of technologies takes time and the technologies themselves evolve, rendering any attempt at causal attribution problematic. Notwithstanding these difficulties, some studies have at least partially quantified the growth contributions of selected historical innovations in some countries (see box 1.2).

More generally, economists have gained important insights regarding two questions that are critical for understanding the innovation-growth nexus:

- How does frontier innovation come about?
- How do technologies diffuse across economies?

This section summarizes key insights that have emerged regarding these two questions.

How does frontier innovation come about?

At the beginning of the 19th century, technological innovation was largely performed by individual inventors and small-scale entrepreneurs. By the 20th century, modern innovation systems emerged, whereby a variety of organizations collectively push the knowledge frontier – including scientific institutions, large R&D-intensive firms and entrepreneurial startups.

Technological breakthroughs have largely occurred as a result of three forces. First, scientific discoveries have been instrumental in providing the foundations for commercial innovations. To name but one example, the development of the liquid-crystal display relied on scientific advances in the field of organic chemistry. Second, the needs of government – especially in the area of defense – have been a key impetus for the development of many technologies that found application throughout the economy later on. Finally, the needs of the marketplace and competitive market forces have prompted firms to invest in the development of new technology to gain an edge over their rivals.

Box 1.3: Intangible asset investments

Endogenous growth theory highlights the importance of intangible asset investments in knowledge-intensive industries. However, measuring their amounts and comparing them to tangible asset investments has always been challenging. Company financial statements and national accounts have traditionally treated intangible activities as intermediate inputs rather than investment. Conventional measures of business investment focus on tangible assets such as plant and equipment, buildings and vehicles.

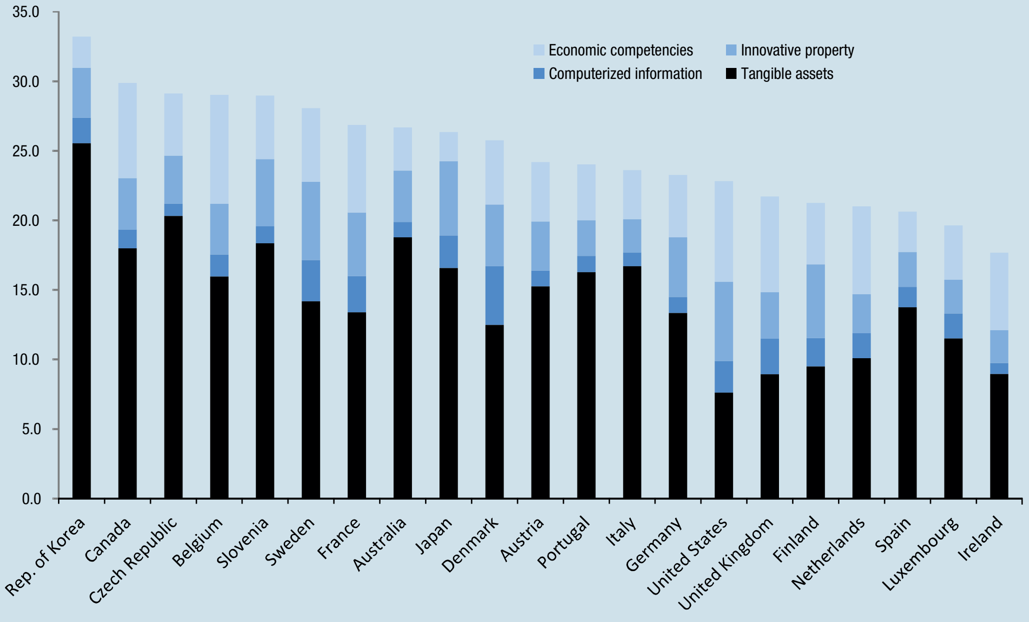
To establish a more complete picture of business investment, researchers have constructed a new measurement framework that breaks intangible assets down into the following components (Corrado *et al*, 2012):

1. Computerized information
   - software
   - databases
2. Innovative property
   - mineral exploration
   - scientific R&D
   - entertainment and artistic originals
   - new products/systems in financial services
   - design and other new products/systems
3. Economic competencies
   - brand equity (advertising; market research)
   - firm-specific resources (employer-provided training; organizational structure).

Estimates of intangible asset investments relying on this framework are now available for a large number of advanced economies (see figure 1.6). They consistently show that intangible assets account for sizeable shares of total business investments – exceeding 50 percent in Denmark, Finland, France, the Netherlands, the UK and the US.

Figure 1.6: Intangible asset investments account for substantial shares of total business investment

Investment as a percent of value added, 2010



Note: For Canada, Japan and the Republic of Korea estimates refer to 2008.

Source: OECD (2013), figure 1.28.

Explaining why economies invest in innovation and what implications those investments have for an economy's growth path has been a fertile field in economics. Interestingly, neoclassical growth theory – which was among the first attempts to formally model the growth process – did not consider how technological progress comes about; it merely demonstrated that growth would come to a standstill without it. This drawback provided the impetus for *endogenous growth theory*, which explicitly incorporated incentives for innovation into models of economic growth. In particular, in formal models of endogenous growth, firms invest in R&D to generate future profits and to avoid being overtaken by competitors, mainly by introducing new and better-quality products. Competition between firms then generates a dynamic innovation race that leads to sustained increases in productivity. These models capture a key characteristic of today's knowledge-intensive industries: firms invest in intangible assets – not only R&D, but also design, software, workers' skills and organizational know-how – and they frequently launch new products that replace older ones. Indeed, available data underscore the importance of investments in intangible assets as a share of total business investments (see box 1.3).

However, some economists have criticized endogenous growth theory as too mechanistic.[40] In particular, while acknowledging that the fruits of innovative activity are uncertain, endogenous growth models assume that they fall within a predetermined probability distribution. However, many innovative breakthroughs of far-reaching importance have been accidental in nature – meaning that they do not fall within a range of outcomes known in advance.

Motivated by such criticism, a second strand of the growth literature – *evolutionary growth theory* – emphasizes the specific historical circumstances of innovative activity and the complexity of interrelationships, with causal mechanisms changing over time.[41] In evolutionary growth theory, firms cannot foresee all technological possibilities and resort to "rules of thumb" when they engage in innovation. The path of technological progress is determined by a selection process in which market forces and other economic institutions play a key role.

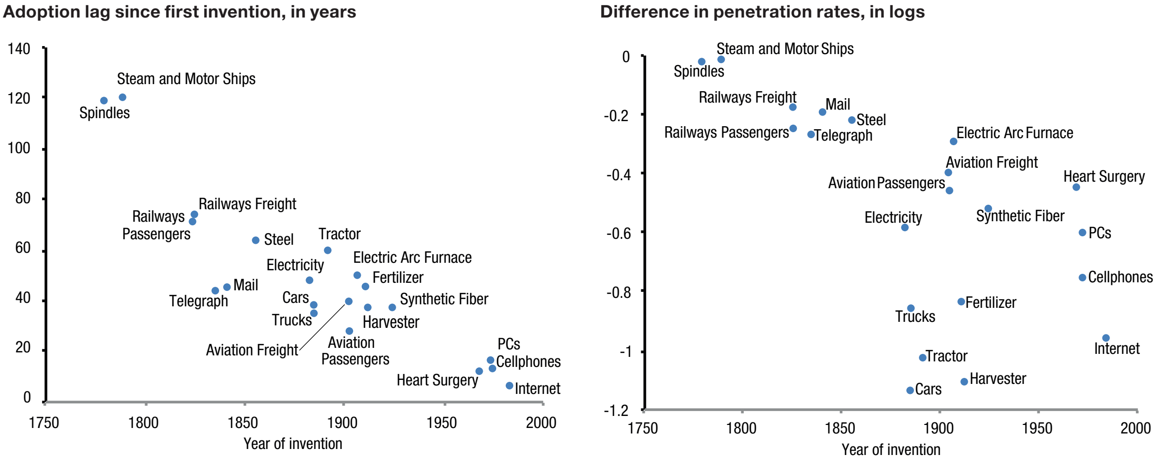
40. See Nelson and Winter (1982) for a key contribution and Verspagen (2004) for a review of the literature.
41. See Verspagen (2004).

In the evolutionary approach, innovation takes place incrementally and the direction of change only becomes clear over time. Despite occasional "eureka" moments and drastic steps forward, even major historical breakthroughs took years and decades to develop, requiring many incremental steps. In addition, their economy-wide impact relied on firms learning how to use a new technology, undertaking capital investments, and reorganizing business operations. Indeed, the arrival of new technologies typically spurs organizational and business model innovations that, in themselves, are responsible for major productivity gains. The infographic at the end of this report lists just-in-time manufacturing and the bar code as examples of major innovations falling into this category.

Incremental innovation is also critical for the flourishing of so-called general purpose technologies (GPTs).[42] While there is no uniform definition, GPTs generally refer to technologies that have a wide variety of uses and find application in a large range of economic sectors, and that exhibit strong complementarities with existing or potential new technologies, providing fertile grounds for follow-on innovation. Most treatments of GPTs include the steam engine, railways, the motor vehicle, electricity and ICTs as key examples.[43] Historical studies of GPTs have demonstrated their importance for stimulating growth, but have also found that their growth stimulus often occurs with a long delay – estimated, for example, at 80 years for the steam engine (see box 1.2) and 40 years for electricity.[44] Recent endogenous growth research has linked the emergence and adoption of GPTs to long-run cycles of economic growth, providing an explanation for the growth spurts and slowdowns observed throughout history. Interestingly, the prediction of growth cycles mirrors the concept of "long waves" – also called Kondratiev waves – which feature in early evolutionary approaches, especially the work of Joseph Schumpeter.[45]

42. Bresnahan and Trajtenberg (1995) coined the term "GPT", though it is similar to the concepts of "basic innovation" and "technology paradigm" employed in the evolutionary growth literature (Verspagen, 2004).
43. However, there is no consensus even on these five technologies. For example, Crafts and Mills (2004) raise doubts as to whether the steam engine should be considered a GPT.
44. See Crafts (2004) for the steam engine and David (1990) for electricity.
45. See Schumpeter (1939). In fact, it was Schumpeter who coined the term Kondratiev wave, after the Soviet economist Nikolai Kondratiev, who first drew attention to long-run fluctuations in economic output.

Figure 1.7: Faster but less pervasive technology diffusion



Notes: The adoption lag since first invention captures the average adoption lag across all countries for a given technology. The difference in penetration rates captures the average difference relative to average penetration in Comin and Mestieri's group of "Western countries". For presentational purposes, the two charts omit several technologies.

Source: Comin and Mestieri (2013).

While the more recent focus on GPTs thus suggests some convergence in endogenous growth and evolutionary theories, these two approaches still disagree on the essential nature of the growth process.[46] The former views it as a deterministic process which, at its core, remains stable over time. The latter views it as a process which is closely tied to the nature of technology and which therefore changes over time. This difference has important implications for designing growth-enhancing policies. While endogenous growth models can formulate policy recommendations on the basis of fundamental principles, evolutionary approaches caution that policies appropriate for one technological paradigm may not be so for another.

How do technologies diffuse across economies?

So far, the discussion has focused on the contributions of frontier innovations, regardless of their origin. However, innovations are rarely fully homegrown. Relying on international patent filing data, Eaton and Kortum (1994) estimate that within developed economies, ideas are highly mobile; even for a large economy like the US, they find that about half of productivity growth derives from foreign technology. But how easily does technology really diffuse across economies, especially to less developed ones?

This question is important. As described in section 1.1, the last 200 years have seen diverging levels of economic prosperity across the world. Given the importance of new technologies in driving long-run growth, could imperfect technology diffusion be one explanation for economic divergence?

Recent evidence on technology diffusion patterns points to a mixed picture. On the one hand, it suggests that more recent technological innovations have diffused more rapidly to low- and middle-income countries. Comin and Mestieri (2013) have assembled data covering 25 technological breakthroughs since the late 18th century and their adoption in up to 132 countries. They find that average adoption lags for those technologies have declined markedly over the past 200 years (see left panel in figure 1.7). Most dramatically, recent technologies such as mobile telephony and the Internet arrived in developing economies within a few years after their introduction in developed economies.

46. See Verspagen (2004).

On the other hand, Comin and Mestieri also look at how intensively different economies have used new technologies once they have been introduced. In particular, they estimate long-run penetration rates for the same set of technologies, and how differences in those penetration rates have evolved over time. On this measure, they find that more recent innovations have seen a greater gap in use between developed and developing economies (see right panel in figure 1.7). At first, this finding seems surprising, considering for example the remarkably wide adoption of mobile telephones and the Internet within most developing economies. However, those technologies have found even more uses in developed economies, and the use gap compared with earlier technologies turns out to be larger.[47]

Notwithstanding these general patterns, the extent of diffusion differs greatly across technologies and recipient countries. To begin with, there are a variety of diffusion channels, notably international trade, foreign direct investment (FDI), direct technology licensing, skilled worker migration and cross-border information flows. Some of these channels are more "fluid" than others. Where technology is directly embedded in goods and services, the import of those goods and services can go a long way toward reaping the benefit of new technology. For example, important health technologies – such as vaccines, antibiotics and mosquito nets – have seen wide adoption in low- and middle-income countries; they are credited with substantial improvements in the quality of life, even in poor countries that have seen little economic growth.[48]

However, a crucial element of successful technology diffusion in these cases is that technology recipients do not need to fully understand the technology in order to apply it. For many other technologies, such an understanding may be necessary and their successful application may require substantial organizational know-how as well as investments in complementary equipment and infrastructure. Economists have thus emphasized the critical role of *absorptive capacity* for successful technology diffusion. Effective absorptive capacity relies on human capital able to understand and apply technology, organizational and managerial know-how, and institutions that coordinate and mobilize resources for technology adoption. In many cases, absorptive capacity also entails the ability to undertake incremental technological and organizational innovation in order to adapt technology to local needs. Indeed, at the limit, the difference between absorptive capacity and innovative capacity blurs.

Some countries have been more successful at creating absorptive capacity than others. In particular, economists have argued that at least part of the success of the fast-growing East Asian countries lay in their ability to ignite a process of technological learning and absorption that provided the basis for economic catch-up.[49] However, what precise mix of policies is most conducive for developing absorptive capacity remains the subject of considerable debate. In particular, many policies that were seemingly successful in East Asia – for example, trade protection, state-directed lending and technology transfer requirements in FDI contracts – did not produce the same success when applied in other developing economies, notably many African and Latin American economies. This suggests that a successful policy mix may depend critically on the economic and institutional context of the developing economy in question and the contemporary technology paradigm, mirroring the policy caution expressed by evolutionary growth theory (see above).[50]

47. Comin and Mestieri (2013) go on to show that their estimates of technology diffusion patterns can explain 80 percent of the income divergence between poor and rich countries since 1820.
48. See Kenny (2011) and section 2.2 on the public health impact of antibiotics.
49. See Nelson and Pack (1999).
50. For a review of the debate on successful catch-up growth policies, see Fagerberg and Godinho (2004).

1.4 – Innovation and IP rights

As described in the previous section, individual inventors and small-scale entrepreneurs were the driving force behind innovation at the outset of the industrial revolution. Early economic writings thus had little scope to investigate the circumstances of innovative activity. For example, in his famous treatise on *The Wealth of Nations*, Adam Smith observed that "[a] great part of the machines […] were originally the inventions of common workmen, who, being each of them employed in some very simple operation, naturally turned their thoughts towards finding out easier and readier methods of performing it."[51]

The arrival of more formal innovation systems in the 20th century stimulated scholarly thought on the nature of the innovation process and the role of governments in supporting innovative activities in market-based economies. Two important insights – attributed to Nobel prize-winning economist Kenneth Arrow – on the process of inventive activity galvanized economic thinking:[52]

- Inventive activity is risky. When embarking on a problem-solving exercise, it is uncertain whether a solution can really be found.
- Information on how to solve a problem possesses characteristics of what economists call a public good: many people can simultaneously use it, and the problem solver often cannot prevent reproduction of the information. This characteristic is also known as the *appropriability dilemma* of inventive activity.

Faced with these two fundamental difficulties, Arrow concluded that, left alone, markets would underinvest in inventive activity relative to what would be socially desirable. To avoid wasting resources should a problem-solving effort fail, firms operating in competitive markets may forgo inventive opportunities; and if competitors can immediately free ride on a successful solution, the inventing firm may reap little financial reward.

This market failure has given rise to various forms of government intervention that shape the face of modern innovation systems. These interventions broadly fall into three categories.[53] First, the government supports publicly-funded research taking place in universities and public research organizations (PROs). These institutions typically engage in basic research that pushes the scientific knowledge frontier, and for which commercial applications are not always within immediate sight. Second, the government funds R&D activities of private firms, by means of public procurement contracts, R&D subsidies, tax credits, prizes, soft loans and related mechanisms. Some forms of support target specific areas of technology, notably in the area of national defense, whereas others are technology-neutral and the direction of R&D reflects the decision of firms.

Finally, the government grants IP rights as a way of mobilizing private financing for privately undertaken R&D. This section will take a closer look at how different IP rights shape innovative activity. It draws on earlier World IP Reports that provide a more in-depth discussion of many of the considerations outlined below.[54]

IP rights and innovation incentives

IP laws enable individuals and organizations to obtain exclusive rights to inventive and creative output. Ownership of intellectual assets limits the extent to which competitors can free ride on these assets, enabling firms to profit from innovative efforts and addressing the appropriability dilemma at its heart. The most relevant IP forms that address appropriability problems are patents and utility models, industrial designs, plant variety rights, copyright and trade secrets.[55]

51. See Smith (1776).
52. See Arrow (1962).

53. See table 2.2 in WIPO (2011).
54. See WIPO (2011) and WIPO (2013).
55. Goodridge *et al* (2014) associate different forms of IP to the intangible asset investment framework outlined in Box 1.3. They find that half of UK knowledge investments in 2011 were protected by IP rights, notably copyright, trademarks and unregistered design rights.

Survey evidence confirms that many firms regard IP as important in securing returns on R&D investment. However, its importance differs markedly across industries. In some industries – notably, pharmaceuticals and chemicals – IP rights are central to firms' business models. In other industries, firms rely on alternative mechanisms of profiting from R&D, notably by introducing products faster than competitors and generating consumer goodwill through branding. In fact, the importance of branding highlights the indirect role that another IP form, namely trademarks, plays in fostering innovation. Through trademark protection, consumers have confidence that they are purchasing what they intend to purchase – a prerequisite for effective branding campaigns.

IP rights incentivize market forces to guide innovative activity. They allow decisions about which innovative opportunities to pursue to be taken in a decentralized way. To the extent that individuals and firms at the forefront of technology are best informed about the likely success of innovative projects, the IP system promotes an efficient allocation of resources for innovative activity.

While this has traditionally been the key economic rationale for protecting IP rights, there are several other ways in which IP rights can shape innovation outcomes. To begin with, while IP rights do not directly solve the problem of risk associated with inventive activity, they can improve the functioning of financial markets in mobilizing resources for risky innovation. In particular, evidence suggests that the grant of a patent at an early stage in the innovation process can serve to reassure investors that a start-up firm is in a position to generate profits if the innovation is successfully commercialized.[56]

In addition, although inventing sometimes means finding solutions to stand-alone problems, more often it is a cumulative process whereby researchers build on existing knowledge to develop new technologies or products. IP rights, especially patents, play an important role in the process of cumulative innovation. Patent applicants must disclose the problem-solving information underlying an invention. This promotes timely disclosure of new technological knowledge, and allows follow-on inventors to build on that knowledge.[57]

At the same time, patents may in certain circumstances create a barrier for follow-on innovation. Sometimes, the commercialization of an innovation requires use of third-party proprietary technology. Other right holders may refuse to license their technologies or may demand royalties that render the innovation unprofitable – leading to so-called hold-up problems. Even where they are willing to license, coordinating the participation of a large number of right holders may be too costly.

Finally, the grant of exclusive IP rights affords firms market power, viewed by economists as the ability to set prices above marginal production costs. In many cases, market power is limited by competition from substitute technologies or products. However, for radical innovations, market power may be substantial. The ability of companies to generate profits above competitive levels is part of the economic logic of the IP system. However, it also implies a distortion in the allocation of resources, as markets move away from the economic ideal of perfect competition. Above-marginal cost pricing can also slow the diffusion of technologies (see below). In policy design, this distortion is mitigated by the fact that most IP protection is time-bound; once expired, IP rights no longer restrict competition.[58]

IP rights, technology markets and diffusion

IP rights enable the licensing or transfer of intellectual assets – an increasingly important facet of modern innovation systems. Markets for technology facilitate specialization in the innovation process. Firms may be both more innovative and efficient by focusing on selected research, development, manufacturing, or marketing tasks. For example, a given firm may find it is particularly good at figuring out how to extend the life of batteries, but other companies might be better at turning the underlying inventions into components for different electronics products. Similarly, a firm may know how best to market an innovative product in its home market, but prefer to partner with another firm in an unfamiliar foreign market.[59]

56. See Graham *et al* (2009).
57. Evidence for the UK and the US suggests that technology in-licensing represents between 40 and 44 percent of total business enterprise spending on R&D. See Arora *et al* (2013).
58. Reflecting the different rationale for protection, trademark protection is not time-bound as long as owners renew their trademark registrations.
59. This argument mirrors the one on economy-wide specialization made in section 1.2.

IP facilitates the functioning of technology markets in several ways. In the absence of IP rights, firms would be reluctant to disclose secret but easy-to-copy technologies to other firms when negotiating licensing contracts. In addition, while intellectual assets can, in principle, be transferred through private contracts independent of any IP right, IP titles offer a delineation of these assets combined with an assurance of market exclusivity. IP rights thus convey important information than can assist the drawing up of contracts.[60]

Technology markets are also at the heart of so-called open innovation strategies. In many industries, firms face a trade-off between guarding and sharing knowledge. On the one hand, they need to earn a return on their R&D investment, which calls for preventing knowledge from leaking to competitors. On the other hand, absolute protection of all ideas may not always be in firms' best interest. They may be better innovators by collaborating with others, even if that involves some sharing of proprietary knowledge. In addition, technology sharing may also help in developing nascent markets for new products. IP rights are at the heart of the trade-off between guarding and sharing knowledge. They allow firms to flexibly control which technologies to share, with whom and on what terms.

Yet another important function of technology markets is to facilitate the commercialization of inventions coming out of scientific laboratories. The commercial potential of these inventions is often highly uncertain and they require substantial further investment to turn them into marketable technologies. Universities and PROs have neither the resources nor the expertise to undertake such investment. However, they can file patents on their inventions and license or transfer them to firms that do.

Finally, IP rights affect how technologies diffuse within and across countries. On the one hand, exclusive rights, by their nature, may hinder the diffusion of new technologies – at least in countries where those rights have effect. On the other hand, IP rights may enable technology diffusion, just as IP rights enable technology markets more generally. The ultimate role of IP rights, then, depends on the nature of the technology in question – in particular the degree to which it can be reverse-engineered – and the absorptive capacity of the recipient (see section 1.3).

60. For empirical evidence, see Gans *et al* (2008).

Trade secrets and worker mobility

An often-overlooked link between the IP system and innovation performance is through the mobility of knowledge workers. The diffusion of highly specialized and non-codified knowledge often relies on workers moving from one firm to another. However, to what extent are such workers allowed to use the knowledge they acquired as past employees, if such knowledge is secret? The legal answer to this question lies in so-called non-compete clauses included in employment contracts. These clauses restrict an employee from using information learned during employment in subsequent business efforts, at least for a certain period. However, the inclusion and content of non-compete clauses is subject to regulation, with different jurisdictions adopting different approaches.[61]

Policymakers face a trade-off in setting the ground rules for non-compete clauses. Allowing workers substantial leeway to take knowledge from one firm to another promotes the diffusion of knowledge, fueling the innovation system and promoting technology adoption.[62] At the same time, it may lead firms to forgo innovative activities for fear that the fruits of these activities might in the future leak to a competitor. Empirical evidence suggests that non-compete rules matter for the degree of worker mobility, especially for inventors with firm-specific skills and for those who specialize in narrow technical fields.[63] However, the economy-wide importance of such rules is still not well understood. They cover not only technological knowledge, but also organizational know-how and business practices. Their relevance is thus not limited to technology-intensive firms and includes, for example, firms in the service sector, which account for the predominant share of economic output in high-income economies (see section 1.1).

61. See Caenegem (2013).
62. Gilson (1999) argues that the non-enforcement of post-employment non-compete clauses in California has been a significant factor driving innovation in Silicon Valley firms.
63. See Marx *et al* (2009).

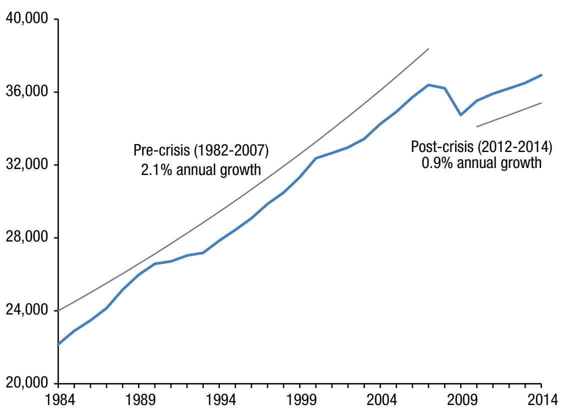
1.5 – Future prospects for innovation-driven growth

The first stylized fact in section 1.1 characterized the growth performance at the frontier after the Second World War as both spectacular and exceptional. Yet growth since the onset of the global financial crisis in 2008 appears anything but spectacular. Figure 1.8 depicts the evolution of per capita GDP in high-income countries since the mid-1980s. Before the crisis, growth averaged 2.1 percent per year, matching the post-war rate of frontier growth shown in figure 1.1. Not only did the crisis prompt a sharp decline in economic output, average growth since 2010 has fallen to 0.9 percent.

Does the financial crisis mark the beginning of a new era of lower growth? Has the innovation-driven growth engine lost steam? While only time will provide the definitive answer, the last few years have seen lively scholarly debate on what growth prospects the future may hold. This final section synthesizes some of the key arguments put forward. It first presents the optimists' case that the recent growth decline is temporary and faster growth will return, then moves on to the pessimists' case why growth might be sustainably lower in the years and decades to come.

Figure 1.8: The end of spectacular post-Second World War growth?

Real GDP per capita in high-income OECD countries, 1984-2014



Notes: GDP values are in constant 2005 dollars. Annual growth rates are the slopes of the logarithmic trend lines for the two periods.

Source: World Bank World Development Indicators.

The optimists' case

The main reason why the growth decline may be temporary lies in the root cause of the crisis. In particular, the crisis was unleashed by the bursting of a debt-financed asset bubble that left the balance sheets of firms and households in distress.[64] The desire to repair balance sheets through greater savings has prompted a persistent shortfall of aggregate demand, leading to wide gaps between actual output and potential output. With interest rates having hit the zero lower bound, central banks have had difficulty closing this output gap through traditional monetary policy instruments. The post-financial crisis debt overhang has thus imposed a persistent drag on economic growth in developed economies.[65]

An optimist would submit that market forces will eventually eliminate persistent output gaps and economic growth will return to its long-term path determined by economies' fundamental productive capacities. Economic history has indeed seen prolonged downturns before, which caused scholars to predict the end of growth. For example, John Maynard Keynes observed in 1931: "We are suffering just now from a bad attack of economic pessimism. […] The prevailing world depression, the enormous anomaly of unemployment in a world full of wants […], blind us to what is going on under the surface to the true interpretation of the trend of things."[66]

In today's context, focusing on the long-run growth trend shown in figure 1.1 – rather than the "aberration" associated with the financial crisis – still paints an overwhelmingly positive outlook for future growth. In addition, looking at the potential for innovation to continuously sustain future growth, there are reasons to be optimistic.

64. See Koo (2014).
65. See Lo and Rogoff (2015).
66. See Keynes (1931).

To begin with, never before has the world invested so many resources in pushing the global knowledge frontier. Figure 1.9 depicts trends in R&D expenditure for the world and for the six largest R&D-spending countries. It shows a consistent upward trend since the mid-1990s. While the financial crisis has left a mark in some countries, R&D spending was far less affected than economic output. Moreover, from relatively little R&D spending in the early 1990s, China overtook Japan in 2009 to become the second-largest R&D spender after the US. The emergence of China as an innovator – along with the rapid growth of R&D expenditure in the Republic of Korea – has increased the diversity of the global innovation landscape.

There also still appears to be significant potential for innovation to generate productivity gains and transform economic structures. ICTs have already made important contributions to growth (see box 1.2 and section 2.3). However, if history is any guide, there is more to come. The growth contributions of past GPTs have only occurred with decades-long delays (see section 1.3).[67] Indeed, the next generation of ICT innovations – centered on artificial intelligence – holds plenty of promise. Brynjolfsson and McAfee (2014), for example, characterize the impact of digital innovation as exponential, drawing on the parable of sequential doubling of rewards on a chessboard, with most of the second half of the chessboard yet to come. Among other considerations, ICTs have potential to raise productivity in the service sector, which has traditionally been considered a drag on growth.[68] Evidence for the US economy, for example, points to especially fast productivity growth in distribution services – an industry that has made intensive use of ICTs.[69]

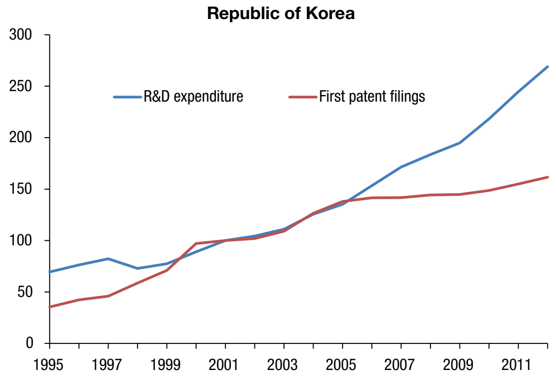
In addition, there are numerous other fields of innovation that hold promising potential for spurring future growth. These include the three fields discussed in chapter 3 – 3D printing, nanotechnology and robotics – as well as genetic engineering, new materials and various forms of renewable energy. New technologies have also dramatically improved the research tools that drive the process of scientific discovery. In particular, ICT-driven techniques such as big data analysis and complex simulations have opened new doors for research advances across many areas of technology. For optimists, the interplay between science and technology generates a self-reinforcing dynamic that seems unbounded.[70]

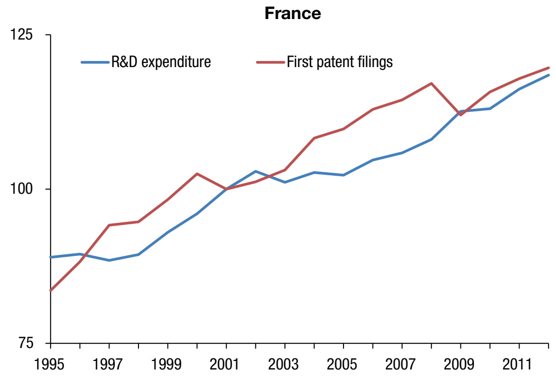
A somewhat different argument of the optimists' camp – partly in response to weak productivity performance in recent history, as explained below – is that today's GDP measurement framework misses the true impact of new technology. This argument comes in two forms. One is that the tools of statisticians increasingly fall short in capturing quality improvements and new forms of economic output (see box 1.1).[71] The other is that the very concept of GDP is ill-suited in capturing the societal welfare gains associated with today's innovation. In particular, many new technologies are highly expensive to develop but, once developed, relatively cheap to produce or can even be replicated for free. As such, they contribute little to economic output but may raise welfare disproportionately.[72]

67. See David (1990).
68. Owing to historically slower productivity growth in services than in manufacturing, Maddison (1997) characterized the growing share of services in economic output as a "significant structural drag".
69. See Jorgenson and Timmer (2011). More generally, Triplett and Bosworth (2003) find that since 1995 productivity growth in the US service sector has matched economy-wide productivity growth.
70. See Mokyr (2014).
71. McGuckin and Stiroh (2001) find that measurement problems in certain service industries that rely extensively on ICTs – such as finance, business services and wholesale trade – have implied a sizeable downward bias in estimates of US productivity growth.
72. See Mokyr (2014) and Glaeser (2014).

Figure 1.9: Innovation performance shows mixed trends

R&D expenditure and first patent filings, index (2001=100), 1995-2012





Notes: R&D expenditures are in constant 2005 dollars. In the case of R&D expenditure, the world aggregate refers to a group of 33 countries for which data for most years are available. The group includes all large OECD countries as well as China and Russia. Selected data points were extrapolated.

Source: OECD and WIPO Statistics Database.

The pessimists' case

The pessimists' case starts with doubts about whether market forces will be sufficient to eliminate the output gaps left by the financial crisis. The length of the economic downturn and the failure to restore full employment in many developed economies suggests that something fundamental has changed. These doubts have given rise to theories about so-called "secular stagnation" – a term introduced by economist Lawrence Summers in 2013.[73] A technical definition of secular stagnation is that only negative real interest rates would equate savings and investments with full employment. In the presence of low inflation and a zero lower bound on policy interest rates, output gaps persist, generating subdued growth – also referred to as "the new mediocre".[74]

There is considerable debate among macroeconomists regarding what may be behind secular stagnation. Demographic shifts and changes in the structure of financial markets have been cited as possible causes. Interestingly, some economists have also mentioned technology as an explanatory factor, arguing that the latest wave of ICT innovation has required relatively little investment.[75]

Concerns about secular stagnation do not *per se* question the potential of innovation to contribute to future growth. Nevertheless, persistent output gaps may negatively affect the transmission channels through which innovation generates growth. In particular, weak overall demand may lead firms to shun investment opportunities created by new technology, long spells of unemployment may lead workers to lose or not acquire skills, and fewer firm startups and "scale-ups" may slow the structural transformation of the economy.

Independent of secular stagnation concerns, the pessimists' camp also casts fundamental doubt on the potential for innovation to drive future growth. One ground for such doubt is an observed decline in TFP growth that started well before the onset of the crisis. Chiefly, the US economy saw a marked pick-up of TFP growth from 1995 to 2003, mainly attributed to ICTs (see box 1.2); however, since then TFP growth has been significantly slower.[76] More generally, analysis by the International Monetary Fund (IMF) confirms that potential output started to decline in the early 2000s across all advanced economies, mainly accounted for by a drop in TFP growth.[77]

73. See Summers (2014).
74. The term "new mediocre" is attributed to IMF Managing Director Christine Lagarde; see *www.imf.org/external/np/speeches/2014/100214.htm*.
75. For a summary, see the collection of essays edited by Teulings and Baldwin (2014).
76. See Fernald (2014).
77. See IMF (2015).

Could it be that the growth contribution of ICTs has been largely realized and, without any innovation of comparable significance on the horizon, future growth will disappoint? In a provocative article, economist Robert Gordon makes precisely this case.[78] He argues that ICTs have seen faster adoption and follow-on innovation compared with previous GPTs, with key productivity benefits such as the replacement of tedious and repetitive clerical labor by computer already occurring in the 1970s and 1980s. More recent ICT innovations have consisted of entertainment and communication devices that are smaller and smarter, but which do not radically spur economic productivity.

More generally, Gordon argues that it will be hard to match the achievements of earlier innovations. For example, the dramatic improvements in the speed of travel, life expectancy and long-distance communication could only happen once, with future improvements bound to be minor in comparison. Similarly, there is much less scope for innovation to increase labor force participation; if anything, demographic shifts in developed economies will lead to declining participation.

In addition, one may question the productivity of future innovative activity. Pushing the knowledge frontier is becoming progressively more difficult as the "low-hanging fruit" is plucked. In addition to real R&D expenditure, figure 1.9 shows trends in first patent filings – the patent metric that comes closest to the concept of a unique invention. Aside from China, since the mid-2000s most countries have seen faster growth in R&D expenditure than first patent filings, leading to a falling R&D yield. One should not read too much into these trends, as patent-filing trends may reflect shifts in patenting strategies. However, contrary to the 1980s and the second half of the 1990s, patenting trends do not suggest an upturn in R&D productivity in more recent history.[79]

Finally, the claim that GDP statistics fail to capture the true impact of innovation is hard to evaluate. The use of hedonic and other techniques has improved GDP measurement in those countries in which statistical offices are equipped to use them (see box 1.1). From this view, the quality of today's statistics should be better than decades ago. It is undoubtedly the case that GDP statistics do not capture the full welfare benefits new innovations offer, but the key question is whether the under-measurement problem is worse today than it was in the past. There is no convincing evidence that would suggest it is and establishing such evidence may well be impossible.[80]

78. See Gordon (2012).
79. See Fink *et al* (2015) for a more in-depth discussion of long-term patent filing trends. They identify greater internationalization as one important shift in patenting strategies.
80. See DeLong (1998).

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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		

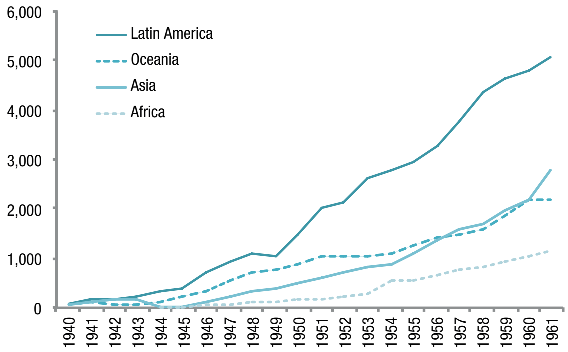
* Refers to early models only.

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

Passenger-miles, in millions



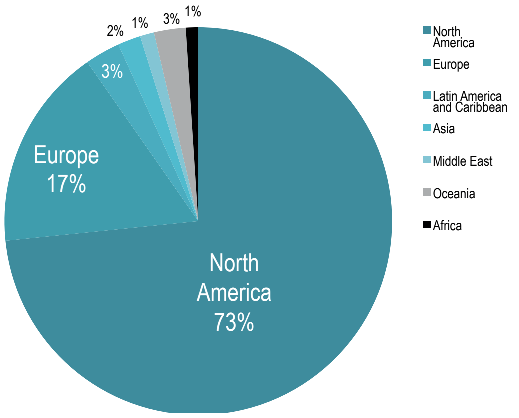
Source: Davies (1964).

15. Brooks (1967).

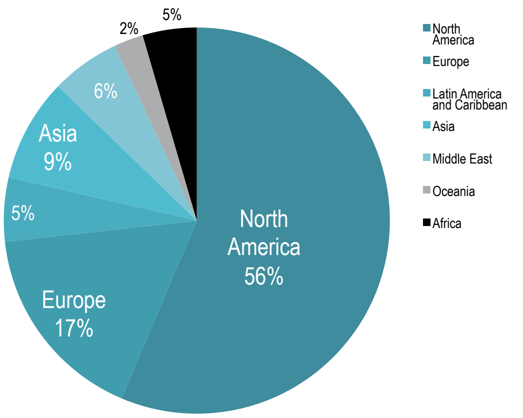
By the mid-1970s, countries outside Europe and the US were also purchasing airplanes for their own national flag carriers (see figure 2.2 below).

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.

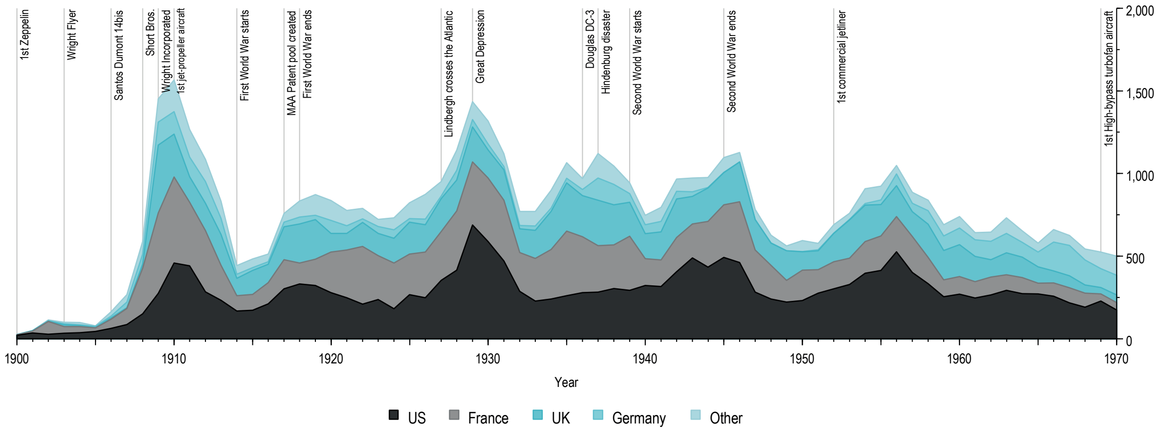
Throughout these changing dynamics in the airplane innovation ecosystem, one element seems to have held constant from 1900 to 1970: the main innovative activities in aviation were geographically concentrated in the US and Europe, in particular France, Germany and the UK, albeit with differing levels 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.

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.

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.

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]

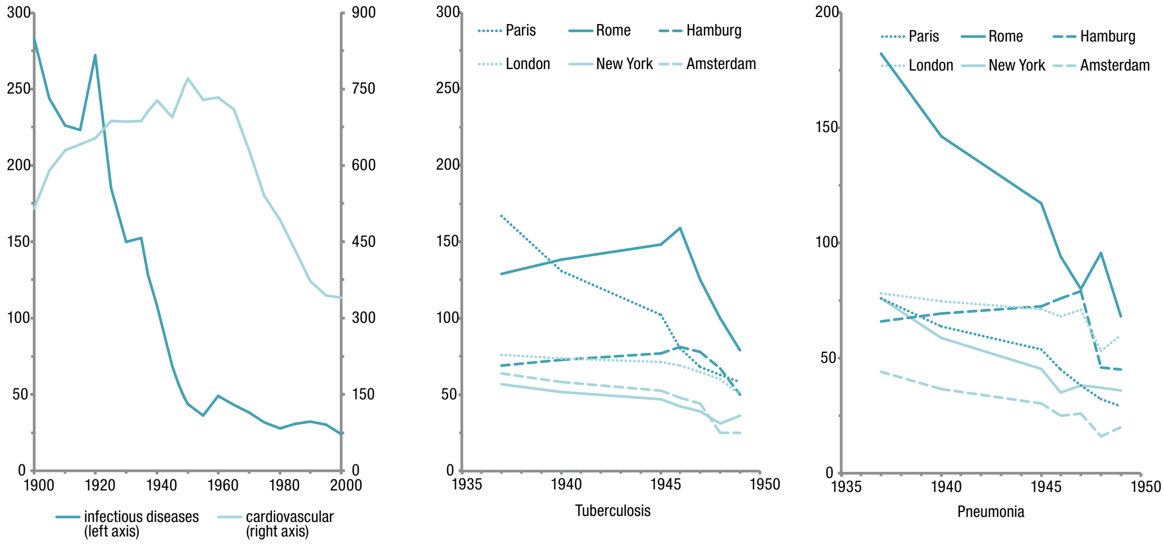
Following streptomycin, other firms also began searching soil samples for antimicrobial activity. Some of the early successes were chlortetracycline (1948), chloramphenicol (1948), oxytetracylcine (1950), and tetracycline (1955).[59] Another important early class of drugs was the cephalosporins (1964), 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

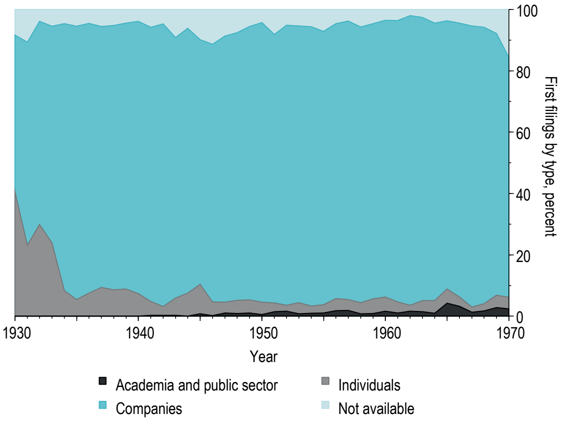
In the case of all three antibiotics, downstream innovations built on pre-existing science, demonstrating the strong links between science and industry. The channels through which academics contributed to industrial innovation varied, from "simply" doing the fundamental research to developing embryonic 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.

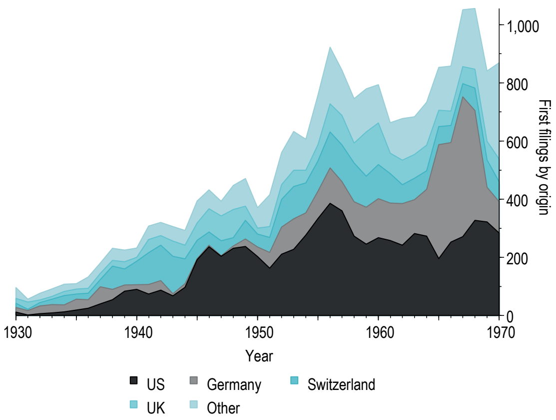
As with many other breakthrough innovations in history, wartime disruption was an important inducement to change, and military procurement and defense R&D played a particular role in the development of GPTs.[69] In different ways, war was crucial in the development of both sulfa- and penicillin-related 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

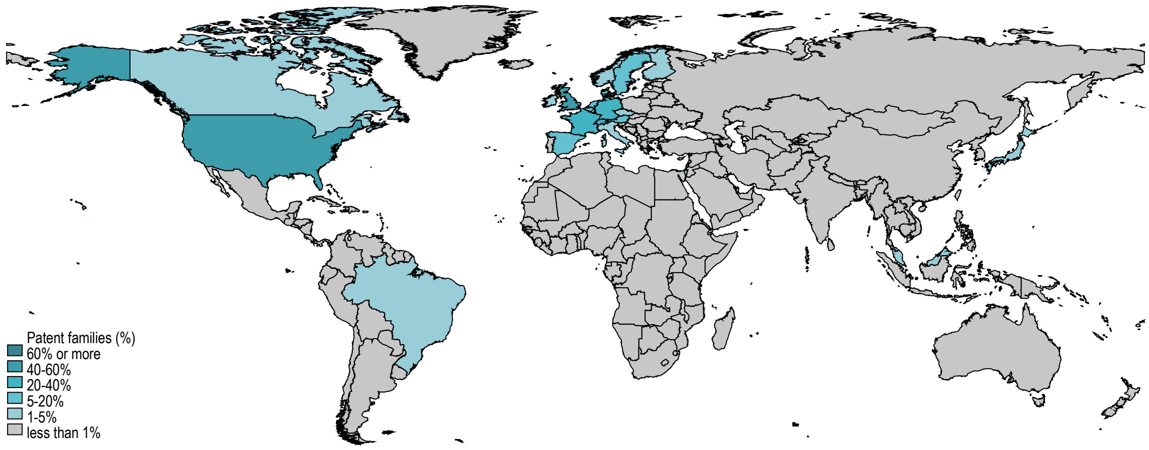
Another of the goals of a patent system is to promote disclosure. Some accounts of the development of sulfa indicate that Bayer had concerns about the effects of publicizing the invention which led it to delay applying for patent protection until other variants of sulfa had been found. There was no way 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

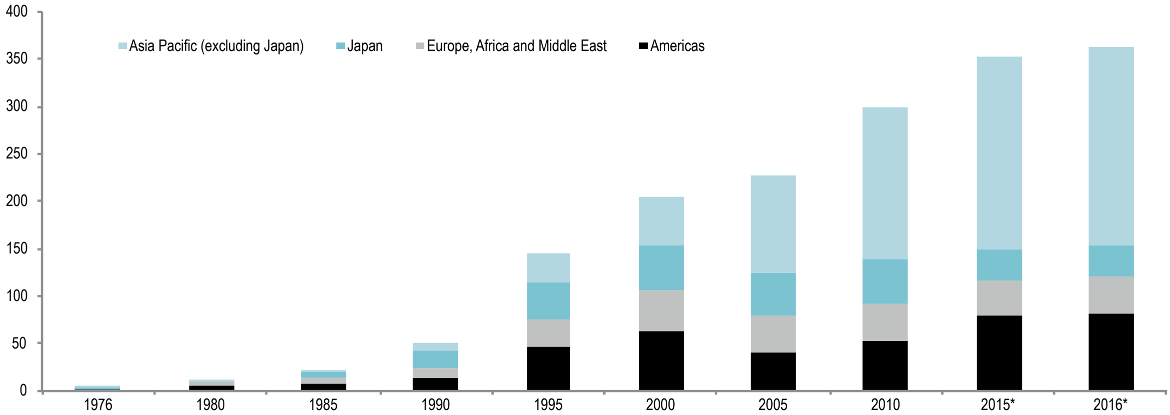
Semiconductors have had significant economic impact which continues to the present. Until the 1970s, semiconductor devices were used to generate and control electrical current and to detect radio signals. Various industries, such as transport, chemicals and aluminum adopted semiconductor devices with 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

USD billion, current prices, 1976-2016



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.

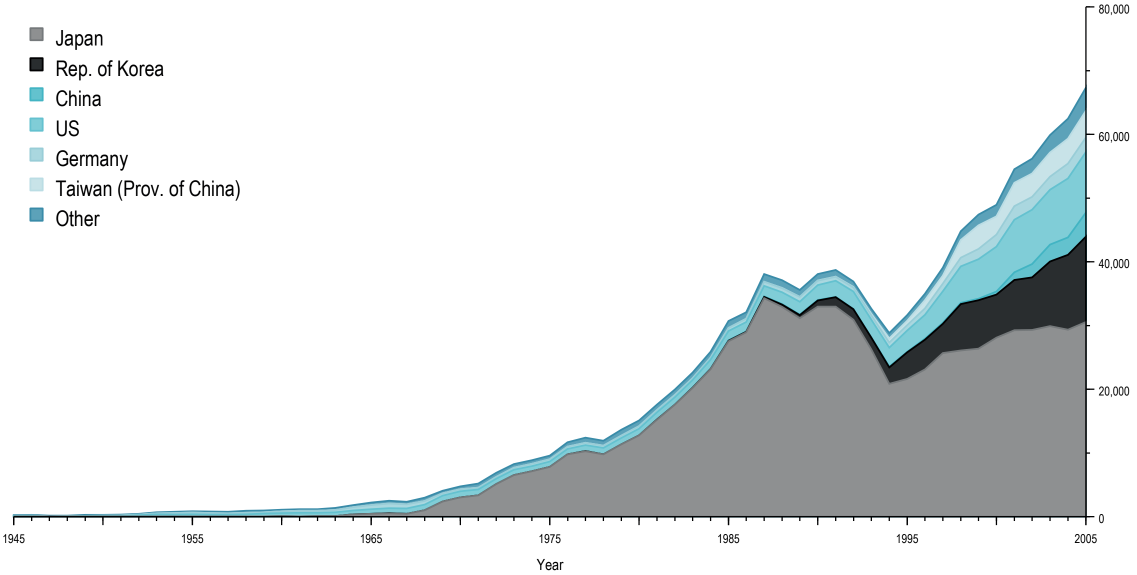
Early concentration in the US and Europe and diffusion to Asia

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).

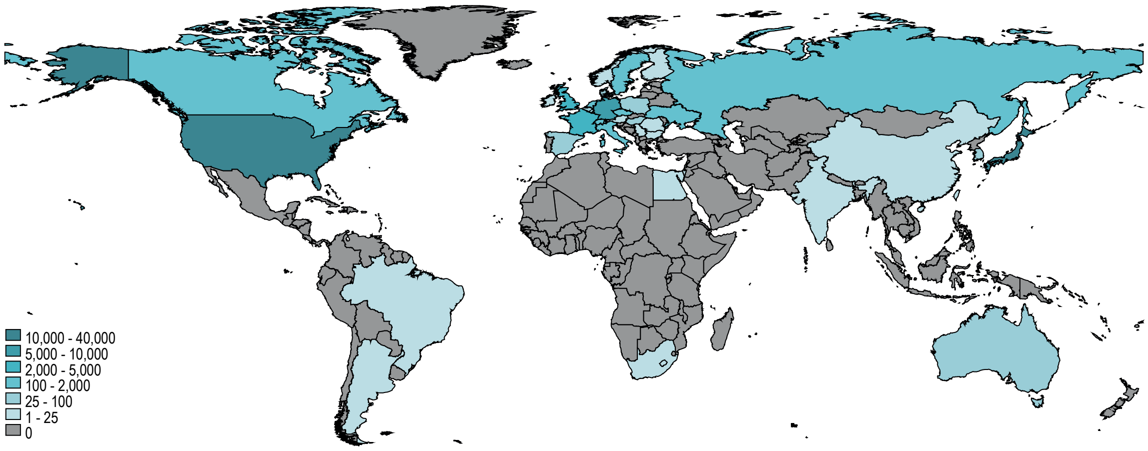
Figure 2.8 depicts the number of first patent filings worldwide in semiconductors from 1945 to 2005. This period captures the time of invention – from the transistor in 1947 to the microprocessor in 1971 – and the subsequent period of diffusion. In the first period, the US and Japan led semiconductor 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.

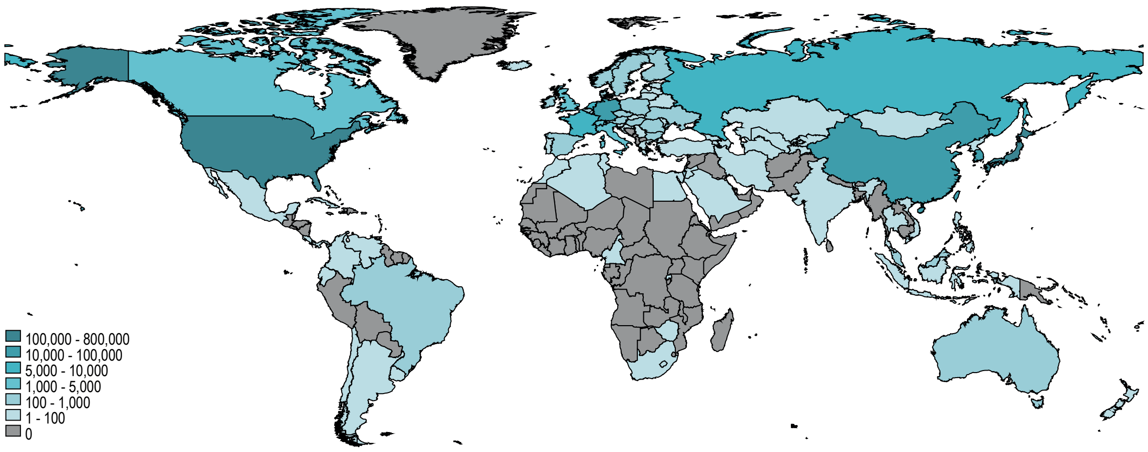
126. See, for example, Wolfson (1993).

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.

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).

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.

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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Chapter 3
Innovations with Future Breakthrough Potential

Today's innovation landscape has evolved greatly since the early days of innovation-driven growth. As described in chapter 1, never before has the world economy devoted so many public and private resources to pushing the global knowledge frontier. Innovation is geographically more diversified than a century ago, with Asian economies – especially China – emerging as new sources of innovation.

And innovation has never been as multifaceted as it is today. Products introduced long ago such as the car and the textile fiber still see rapid technological progress. In addition, new fields of innovation have emerged that open up new possibilities to meet the needs and challenges of humanity. Information and communication technologies (ICT) have had a pronounced impact on the innovation process, notably by facilitating scientific discovery and commercial research and development (R&D) through fast data processing and by spurring the fertilization of ideas across different technology fields.

Yet it has not necessarily become easier to achieve innovation breakthroughs and ensure their diffusion across the economy with long-lasting dividends in terms of economic growth. Technological problems are becoming ever more complex and there may be natural limits on the scope to further improve on past achievements, such as fast travel, high life expectancy and long-distance communications. It is not clear to what extent today's much-enhanced innovation systems will surmount these challenges.

This chapter explores three innovations that currently appear to have breakthrough potential: 3D printing, nanotechnology and robotics. As with the selection of the case studies in chapter 2, the choice of these three innovation fields is somewhat arbitrary. Nonetheless, they all feature in contemporary discussions about possible growth-spurring technologies of the future.[1] In addition, they all possess at least some characteristics of a general purpose technology (GPT), especially in that they have a wide variety of uses and may find application in a large range of sectors.[2]

The three case studies are presented in sections 3.1 (3D printing), 3.2 (nanotechnology) and 3.3 (robotics). The discussion follows the structure of the case studies in chapter 2, first looking at the origin of each innovation and its contribution to growth, then at its ecosystem, and finally at the role of IP. Section 3.4 will seek to distill some of the main lessons learned from the three cases.

As a critical caveat, 3D printing, nanotechnology and robotics – while not entirely new – are still at relatively early stages of development. In contrast to chapter 2, the case studies in this chapter thus cannot draw on the benefit of hindsight, rendering some of the discussion somewhat speculative. Indeed, there is great uncertainty as to how the three innovations will shape future growth and this chapter does not pretend otherwise. It is important to keep this uncertainty in mind when reading the three cases.

1. See, for example, Mokyr (2014) and the patent landscape reports on promising new technologies produced by the UKIPO at *www.gov.uk/government/collections/intellectual-property-research-patents*.
2. As pointed out in the introduction to chapter 2, there is no consensus definition of GPTs.

3.1 – 3D Printing

"The next episode of 3D printing will involve printing entirely new kinds of materials. Eventually we will print complete products – circuits, motors, and batteries already included. At that point, all bets are off."

Hod Lipson,
Director of Cornell University's Creative Machines Lab

3D printing – known in the industry as *additive manufacturing* – refers to a set of manufacturing technologies where 3D objects are created by adding successive layers of material on top of one another, aided by specialized computer programs for both process control and object design.

This section traces the development of 3D printing and its economic contribution. It then describes the ecosystem that has given rise to this innovation, paying particular attention to factors that have been crucial in advancing it. Finally it focuses on the role of the IP system in the development of 3D printing and notes some potential challenges that this innovation may pose to that system.[3]

3.1.1 – The development of 3D printing and its economic importance

In a general sense, the technological roots of 3D printing date all the way back to the 19th century, to photosculpture and topography works.

But it was not until the late 1960s that attempts began to create three-dimensional objects using specialized computer programs. One took place at the Battelle Memorial Institute in Columbus, Ohio, and the other was by Wyn Kelly Swainson in Berkeley, California. A decade later, the first functional 3D printing technique was reported by a Japanese scientist, Hideo Kodama, at the Nagoya Municipal Industrial Research Institute.

Soon thereafter, different 3D printing processes appeared (see table 3.1). Each of these was based on a different printing technique and there were also some variations in the type of raw materials used for printing.

As a complement to the 3D printing process, a new file format describing the surface geometry of 3D objects was required. 3D Systems – the company that introduced the first commercial 3D printer based on *stereolithography* – also developed the first file format, known as STL.[4] This format evolved to become an industry standard used until recently.

As this innovation gained wider acceptance in commercial manufacturing, a different market segment emerged – personal 3D printing, also known as personal fabrication.

In the mid-2000s, researchers at universities such as the University of Bath, the Massachusetts Institute of Technology (MIT), Cornell University and Stanford launched this market segment by looking into ways that 3D printing could be made widely available. Their goal was to develop 3D printers that were compact and had general application.[5]

One of these projects, *RepRap*, was conceived to create an open-source 3D printer that would reproduce itself. Its development, along with supporting products and services, has significantly cut the cost of personal 3D printers, making them more accessible to interested consumers.

RepRap has also created a flourishing ecosystem of hardware manufacturers, software programmers and service providers, all of them supporting the 3D printer consumer market. Several of the personal 3D printers available today are based on *RepRap*'s open-source software and hardware, and the technologies they contain.

But not everyone can own a 3D printer or has the capability to build one; enter Fab Lab. Fab Lab is a project started at MIT in 2001, led by Neil Gershenfeld, which focuses on building low-cost, open-source fabrication labs. The basic principle is to encourage users to create what they need without having to negotiate licenses for access to 3D printing systems. Fab Labs are essentially laboratories equipped with industrial-grade fabrication and electronics tools which operate with open-source software and related programs developed at MIT. Users may use these labs to create and print objects that they want or need without having to purchase 3D printing systems.

3. This section draws on Bechtold (2015).

4. STL comes from *STereoLithography*, but it is also known as the Standard Tessellation Language.

5. Lipson (2005).

Table 3.1: A select few 3D printing processes

Year*	Technology	Type	Original Inventors	Company
1984	Stereolithography	Vat photopolymerization technique – a liquid photopolymer is solidified by a control light source, i.e. an ultraviolet laser. This laser hardens the exposed regions of the polymer. The process is repeated layer by layer until the object is finished.	Charles Hull (while at UPV, Inc.)	3D Systems
1986	Selective laser sintering	Powder bed fusion technique – a laser beam is applied to a layer of powder deposited on a build platform. The laser sinters the material into the right shape. Then the build platform moves down and the laser draws the next layer.	Carl Deckard (PhD project at University of Texas, Austin)	University of Texas, Austin, licensed to Nova Automation, later renamed DTM Corporation – acquired by 3D Systems in 2001
1989	Fused deposition modeling; generally known as thermoplastic extrusion methods (see box 3.2)	Material extrusion process – material is selectively dispensed through a nozzle or orifice.	Scott Crump	Stratasys
1989	3DP (three-dimensional printing)	Binder jetting process – an inkjet print head disperses glue to locally bind powder material, similar to the workings of a normal inkjet printer.	Emanuel Sachs and team	MIT licensed to several companies for commercialization, notably Z Corporation, which was later acquired by 3D Systems in 2012

*Refers to the first patent filing year.

Source: Bechtold (2015).

Growing commercial relevance

Since it first became commercially available, 3D printing has had an impact on production processes in various industries and sectors. It first found application as a rapid prototyping process. Engineers and industrial designers used it to accelerate their design and prototyping operations, saving both time and money.

Gradually, as newer 3D printing methods were introduced using new raw materials, it found application in the production of components or even finished products in several industrial sectors, including aerospace and aviation, automobiles, construction, industrial design, medical products and defense. It has even been applied to create consumer products such as fashion, footwear, jewelry, glasses and food.

For firms in these industries, 3D printing allows the production of a small number of goods at low cost. This makes it attractive to those with small-series production.[6]

In many of these cases, 3D printing reduces both the time and cost of production for companies. One consulting report estimates that the cost savings from using 3D printing to produce spare parts for maintenance, repair and operation in the global aerospace market could amount to USD 3.4 billion.[7]

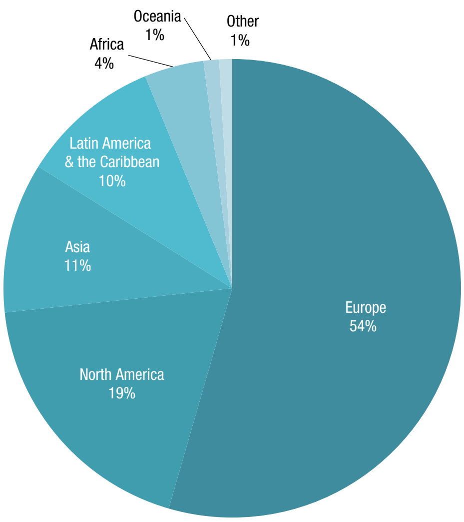
As for the personal 3D printing market segment, the development of open-source 3D printing initiatives and the expiry of related patents have lowered the cost of printers, making them more accessible (see subsection 3.1.3 on the role of patents).[8] Low-cost printers and fabrication labs for personal use have facilitated the diffusion of the technology across many communities and helped meet their diverse needs.

For example, early Fab Labs in India, Ghana, northern Norway and the inner city of Boston in the US have allowed local innovators to make tools for measuring milk safety and testing agricultural machines, blocks to aid in local embroidery business, data tags to allow cellular-based monitoring of herds, solar cells and jewelry from scrap metal, respectively. Currently, there are almost 550 Fab Labs around the world. They are mainly localized in the US and Europe, but still there are 23 Fab Labs in Africa, 58 in Asia and 54 in Latin America and the Caribbean (see figure 3.1).

6. Bechthold *et al* (2015).
7. Assuming that 50 percent of parts are printed by 3D printing (PwC & M Institute, 2014).
8. See Lipson and Kurman (2013), West and Kuk (2014), Bechtold *et al* (2015) and Campbell *et al* (2012).

Figure 3.1: Fab Labs are present in almost all corners of the world

Share of Fab Labs by region, 2015



Source: The Fab Foundation (2015).

Promising effect

The potential impact of 3D printing is significant. First, it may play an increasingly important role not only in rapid prototyping, but also in the production of product components and finished products.[9] For example, it has been used in the medical sector to produce custom-made sockets for hip replacements and hearing-aid shells.[10] By bypassing traditional means of manufacturing, it could enable mass-scale customization of products, reduce inventory costs and optimize product design.

Second, it may lead to a world of decentralized manufacturing. As the creation of information about an object is separated from its production through 3D printing, traditional production channels – both supply and distribution channels – could be disrupted.[11] Essentially, objects could be created elsewhere but produced close to the customer or even by the customer himself. This could then lead to innovation in business models, where efficient targeting of niche markets and integration of customers into the value chain could be achieved.[12]

Third, 3D printing may have a profound impact in geographical areas which are far from manufacturing plants or even distribution channels. For these off-grid communities, 3D printing enables the possibility of manufacturing and fabricating replacement parts or products that might otherwise have been difficult to acquire. One potential application is in less developed economies that may be cut off from normal distribution channels. 3D printing may allow them to acquire products at lower cost by bypassing the traditional manufacturing and distribution chains.[13] And as has been shown with the Fab Labs, it could enable locally designed solutions for local problems, potentially bringing large benefits to these economies. Another, very different off-grid community that might benefit from 3D printing is the International Space Station, where replacement parts are very difficult to come by.

And lastly, as personal 3D printers become more reliable and their design and marketing improve considerably, they have the potential to be attractive to consumers by lowering both costs and environmental impacts of printed products.[14]

Given the changes that 3D printing looks set to bring about in manufacturing processes and distribution channels, its increasing use is likely to affect local job markets.[15] For example, it may displace employment in traditional manufacturing sectors by shifting job openings to places where there is demand for 3D printing. But so far, no scholar has studied this effect.

Estimates of the growth and impact of 3D printing vary widely. Industry observers forecast that the 3D printing market will generate revenues of USD 20 billion by 2020.[16] The financial impact of the technology is estimated at between USD 230 and 550 billion per year by 2025, with the largest impacts being on consumer (USD 100 to 300 billion), direct manufacturing (USD 100 to 200 billion) and the creation of tools and molds (USD 30 to 50 billion).[17] But some projections of market growth are considerably more cautious than others (see table 3.2).

9. See Bechthold *et al* (2015).
10. See Lipson and Kurman (2013) and Bechthold *et al* (2015).
11. See Desai and Magliocca (2014) and Lemley (2014).
12. Ghilassene (2014) and Rayna and Striukova (2014).
13. King *et al* (2014).
14. See Wittbrodt *et al* (2013) with regards to lifecycle costs; and Kreiger and Pearce (2013), Bechthold *et al* (2015) and Lipson and Kurman (2013) on environmental impact.
15. Lipson and Kurman (2013).
16. Wohlers Associates (2014).
17. McKinsey Global Institute (2013).

Table 3.2: Market estimates for 3D printing vary considerably

Market	Estimated potential size/growth rate	Source
Global 3D printing industry (associated technologies, products and services)	USD 10.8 billion by 2021	Wohlers Associates, 2013
Global 3D printing industry (associated technologies, products and services)	USD 4 billion by 2025	Research and Markets, 2013
3D printing materials market (including plastics, metals, ceramics, others)	CARG 19.9% until 2018[18]	RnR Market Research, 2014
3D printing for medical application	USD 965.5 million by 2019, CARG 15.4%	Transparency Market Research

Source: Bechtold *et al* (2015).

Whether forecasts of the future impact of 3D printing prove correct will depend on whether it can overcome some technical challenges. For one thing, the cost of industrial 3D printers is still high, ranging from USD 75,000 to 90,370; some industrial systems can cost over USD 1 million.[19] And while the price of personal 3D printers has dropped significantly from over USD 30,000 a few years ago to USD 1,000 today, they are still unaffordable to many.[20] In addition, suitable raw material is considerably more expensive than many raw materials used in traditional manufacturing processes. One specialized consulting firm estimates that USD 528.8 million was spent on raw materials for 3D printers in 2013.[21]

Furthermore, 3D printing remains a slow process, often requiring many hours or days of printing to finish an object.

Lastly, the extent to which this market grows will depend on future ease of use, the adoption of the innovation beyond enthusiasts and hacker circles, and many other business factors.

Box 3.1: Realizing the potential of 3D printing depends on the development of complementary products

A major factor influencing the wider application of 3D printing is the development of complementary products, namely raw materials and design software.

Early versions of 3D printers could only print plastic materials, making it easy for traditional manufacturers to dismiss the technology since its application was limited.[22] But now, 3D printers can also print using ceramic materials, metal alloys, glass, paper, photopolymers and, to a certain extent, living cells and food.

Until recently, the design software used to create digital images for printing sufficed only for the application of rapid prototyping in the engineering and industrial design fields and the rapid manufacturing needs of certain industrial manufacturers. Despite some improvement, it is still far from being able to fully digitalize representation of images as intricate as the human body and how it moves. Moreover, printing advanced products such as a fully functioning robot would require the development of more sophisticated design software that could take into consideration factors such as functionality in addition to object design.[23]

Further investment in these complementary products is therefore required to facilitate the diffusion of this innovation across industrial sectors and across countries with different income levels.

3.1.2 – The 3D printing innovation ecosystem

Many factors and players have contributed to the advance of 3D printing. Actors from the private and public sectors, advances in complementary products that feed into 3D printing systems and growing demand from both industry and private consumers are some of the factors that have helped push this innovation forward.

18. CARG refers to compounded annual rate of growth.
19. See McKinsey Global Institute (2013), Wohlers Associates (2014).
20. McKinsey Global Institute (2013).
21. Wohlers Associates (2014).
22. Lipson and Kurman (2013).
23. Lipson and Kurman (2013).

Describing the 3D printing innovation landscape

Most of the patented 3D printing inventions are concentrated in the US, Germany, Japan and, more recently, China.

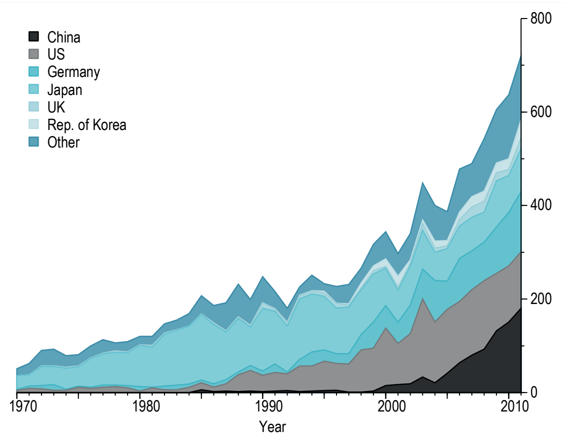
Figure 3.2 shows the evolution of patent filings over the years by applicants' residence in the top six countries. In the early 1980s, Japanese applicants were prolific in filing for patents on their 3D printing inventions, but by the 2000s they had been overtaken by US applications. By 2010, Chinese applicants were filing for more 3D printing applications – almost as many as the Japanese and US applicants combined.

In addition, most 3D printing patent applicants are firms (see figure 3.3). This is not surprising given that many of the early inventors in the field tend to establish their own companies. Except for a handful of large players, these firms tend to be small and medium-sized enterprises.[24]

Universities are increasingly participating in this field – albeit at a much lower share than firms. In fact, a couple of the more important 3D printing processes originated from MIT and the University of Texas System, particularly the University of Texas, Austin. To this day, these two universities own considerable patent portfolios in the field. However, these university patents are usually licensed out to private firms for commercialization. For example, the inkjet 3D printing technology developed by MIT was licensed to several firms for their own application and commercialization.[25]

Figure 3.2: China, Germany, Japan and the US account for roughly 80 percent of all 3D printing patent filings

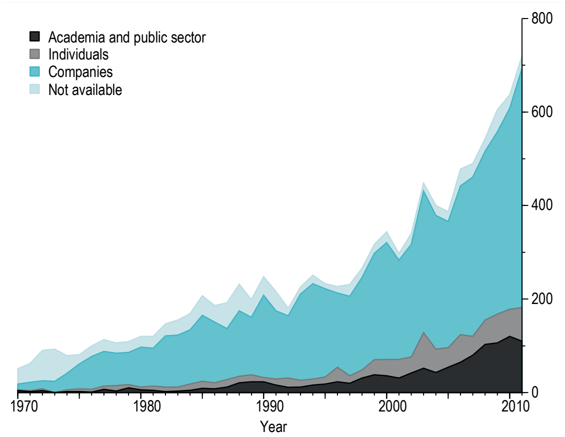
First patent filings by origin, 1970-2011



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

Figure 3.3: Firms file most 3D printing patents but there is increasing participation from academia and the public sector

First patent filings by applicant type, 1970-2011



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

24. Expertenkommission Forschung und Innovation (2015).
25. Wohlers Associates (2014).

Industrial 3D printing

The industrial 3D printing market is mainly comprised of small and medium enterprises, but two large system manufacturers dominate the industry: Stratasys and 3D Systems, both based in the US. These two firms were among the few early movers in the market – introducing their own 3D printing processes, *stereolithography* and *fused deposition modeling*, respectively – and they are currently the top patent applicants in this industry, as evidenced by the number of patents filed in table 3.3. Other important global players include Beijing Tiertime of China, and EOS and Envisiontec, both based in Germany.[26]

Table 3.3: Top ten firms filing for patents, since 1995

Company name	Country	Number of first patent filings
3D Systems	US	200
Stratasys	US	200
Siemens	Germany	145
General Electric	US	131
Mitsubishi Heavy Industries Ltd	Japan	120
Hitachi	Japan	117
MTU Aero Engines	Germany	104
Toshiba	Japan	103
EOS	Germany	102
United Technologies	US	101

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

3D printing is a research-intensive industry. Several rounds of improvements on early 3D printing processes were required to develop a proper functioning process.[27] This reliance on intensive R&D activities continues today. Recently, a specialized 3D printing consulting firm revealed that firms spent on average 19.1 percent of their revenues in 2013 on R&D investments.[28]

Supporting development through public and private initiatives

Various government initiatives have facilitated the development of 3D printing. In many instances these have helped offset the risky R&D endeavor of investing in this innovation. In the late 1980s, the Osaka Prefectural Industrial Research Institute, a Japanese public research organization, licensed out its 3D printing invention to several Japanese companies to develop and manufacture. These companies, including Mitsubishi Heavy Industries and NTT Data Communication, continue to be significant participants in the industry to this day.

More recently, large-scale government initiatives have been established in the US, European Union and China, to name a few. As well as general research funding through various national science foundations in several countries, there are also targeted 3D printing projects. For example, both the US Department of Defense and the US National Laboratories have been active supporters of 3D printing research.[29] Some of these projects relate to energy, military and even outer space applications.[30] The EU set aside a total budget of EUR 225 million to fund 3D printing research for 2007-2013.

In China the government has made large strategic investments in 3D printing technologies; these are more important in advancing innovation than company-driven R&D.[31] The heavy investment in 3D printing by the Chinese government is reflected in the number of patent applications filed by Chinese universities; in some cases these filings exceed those of US and European universities (see table 3.4 and figure 3.4).

26. However, Beijing Tiertime and Envisiontec do not appear in the list of top 10 patent filers in table 3.3. This reflects our search and selection criteria based on the latest information available (see also technical notes).
27. Prinz *et al* (1997).
28. Wohlers Associates (2014).
29. Wohlers Associates (2014).
30. The US Department of Energy's ARPA-E has recently funded a project to produce a 30 kW induction motor using only 3D printing technologies (Langnau, 2014, Oct. 6). NASA is investigating the use of 3D printing technologies for the production of replacement parts in outer space missions, and the NASA Langley Research Center has been leading a US government interagency 3D printing working group since 2010 (Wohlers Associates, 2014).
31. Expertenkommission Forschung und Innovation (2015).

Table 3.4: Top ten university and PRO patent applicants, since 1995

University name	Country	Number of first patent filings
Fraunhofer Society	Germany	89
Chinese Academy of Sciences	China	79
Huazhong University of Science & Technology	China	46
MIT	US	37
Xi'an Jiaotong University	China	34
University of Southern California	US	31
South China University of Technology	China	27
Harbin Institute of Technology	China	24
TNO	Netherlands	24
Beijing University of Technology	China	17

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

Government initiatives also serve a second role – to provide linkages between the different actors in the ecosystem. Many of these initiatives bring together researchers in academia and the private sector along with manufacturers with the intention of diffusing the innovation throughout the economy. The US, for example, has poured USD 50 million into a public-private partnership to bring 3D printing technologies into mainstream manufacturing.[32] This partnership brings together 50 companies, 28 universities and research labs and 16 other organizations. A similar initiative was recently announced by the Australian government that would bring together 14 manufacturing firms, 16 local universities, 4 industry agencies, the Australian federal agency for scientific research and the Fraunhofer Institute for Laser Technology. One of the manufacturing firms involved in the initiative is SLM Solutions GmbH, a German 3D printing manufacturer.[33]

Moreover, there is also a push from the 3D printing industry to facilitate the adoption of this innovation into other industries. Efforts to standardize terms, processes, interfaces and manufacturing technologies are currently underway in the US and Europe. One such effort is the ASTM International Committee F42 on Additive Manufacturing Technologies in the US, another is the EU project Support Action for Standardization in Additive Manufacturing (SASAM).

ASTM International – an international standards organization for materials, products, systems and services – has also adopted a new standard file format for transferring information between design programs and 3D printing systems. The new XML-based file format can represent information about color, texture, material, substructure and other properties of an object. In contrast, the de facto industry standard, STL, only enables the representation of information about a surface mesh.

Personal 3D printing

Unlike the industrial 3D printing market, the personal 3D printing market was created based on an infrastructure that aims to keep the design and makeup of the innovation open to all by building on a collaborative and sharing dynamic between innovators and users. This has led to a distinct innovation ecosystem consisting of open-source enthusiasts, hardware manufacturers, software programmers, service providers, novel funding methods and user innovators.

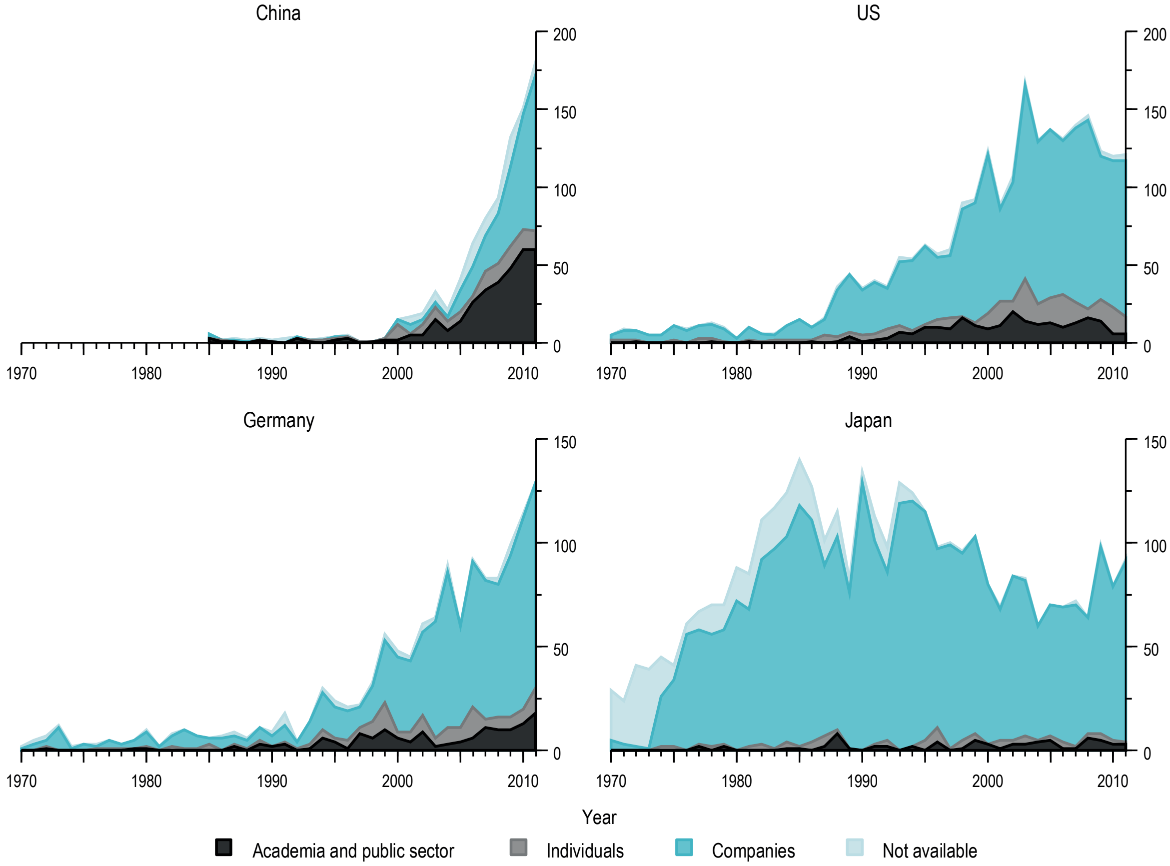
Within this ecosystem, innovative advances can come from consumers as well as the firms producing 3D printers.[34] Users can explore new applications for 3D printers and the few that are sophisticated enough may even be able to alter and improve upon existing hardware and software. This user role in innovation is an unusual feature of the ecosystem. *RepRap*, for example, relies on roughly 25 core contributors and a large support community to help advance the technology. Its contributors and community members include enthusiasts, early adopters of emerging technologies, hackers and academic researchers.[35] And most of them tend to be driven by personal needs, intrinsic motivation and reputational goals rather than monetary gains.[36]

Moreover, the blurred distinction between producers and users of personal 3D printing in originating innovation reinforces the importance of the community and its linkages to the manufacturers. One important link is through online platforms. In fact, the collaborative nature of the personal 3D printing community might not have been possible without advances in digital innovation.

32. The "America Makes" initiative under the umbrella of the "National Network for Manufacturing Innovation" proposed in 2012. See *http://americamakes.us*.
33. Innovative Manufacturing CRC (2015).
34. Lipson and Kurman (2013), Bechthold *et al* (2015).
35. Jones *et al* (2011), Malone and Lipson (2006)
36. Jong and Bruijn (2013).

Figure 3.4: Universities and public sector organizations file a higher proportion of 3D printing patent applications in China than similar resident applicants in other leading countries

First patent filings by applicant type, since 1970



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

Digital communication infrastructure – such as communication platforms, open-source control systems and software repositories as well as online market places – has facilitated the collaborative innovation ecosystem on which the open-source 3D printing community builds.[37]

Furthermore, this community grows as more and more people are plugged into the digital world.

The importance of complementary products and services to the market

In support of the open-source nature of 3D printers, many 3D printing software programs have been created. All of them are licensed, either under open-source licenses or under proprietary copyright licenses – but most are provided for free. In many cases, these specialized programs are included in 3D printing clients such as Repetier-Host. Others, such as Autodesk, offer various free 3D printing design software programs.

37. Bechthold *et al* (2015), West and Kuk (2014).

In addition, specialized service providers that provide support to the personal 3D printing community have appeared. Some of these providers allow users to share 3D design files through platforms like Thingiverse. Others use centralized 3D printing services to print 3D objects and have them shipped to the user, as in the case of Shapeways. In 2012, Shapeways shipped one million 3D-printed parts.[38] And in 2014, the company featured nearly 500,000 3D objects and 23,000 shop owners and product designers from 133 different countries.[39]

The proven success of this market is attracting established companies from related industries. Companies such as Office Depot, Staples and UPS are currently offering 3D printing services on a trial basis in a select number of their stores.

And lastly, since innovators have refrained from using patent protection to appropriate returns from most of the technical advances in the personal 3D printing market, new funding mechanisms were needed to support the development in this area. Various personal 3D printing projects have benefited from crowdfunding platforms such as Kickstarter. M3D raised USD 3.4 million, Formlabs USD 2.9 million and WobbleWorks USD 2.3 million on Kickstarter for 3D printing-related projects.[40] Some of the crowdfunded projects may have proven popular on Kickstarter because of the media hype surrounding personal 3D printing technologies, but they also demonstrate the ability of this community to raise funds in novel ways.

3.1.3 – 3D printing and the IP system

A full 3D printing system will often touch upon various IP rights: patent rights in 3D printing components, processes and raw printing material, trade secret protection of 3D printing manufacturing processes, copyright protection of controlling software programs, design protection of 3D object designs, copyright protection of 3D object designs and trademark protection of the 3D printer product.

The combination of each of these IP rights has affected the advancement of 3D printing innovation for both the industrial and personal market segments, and is likely to impact future innovation. It affects how early innovators are able to appropriate returns on their R&D investment as well as the diffusion of the innovation.

Enabling early developments

Early inventors of 3D printing technology seem to have relied on the patent system to establish the novelty of their invention, and to give them a foothold in the market. Many of them started companies based on their patented inventions, and later commercialized them. Patents thus seem to have helped the inventors secure their place in the market, and may have played an important role in the development of the industry. And while the industry has seen several mergers and acquisitions, a few of the pioneering companies still exist today.

Licensing also played an important role in diffusing the 3D printing technologies from research institutes to industries, among firms, even across continents. Some licenses sought to promote commercialization of the inventions, others to facilitate their use across wider fields of industrial application.

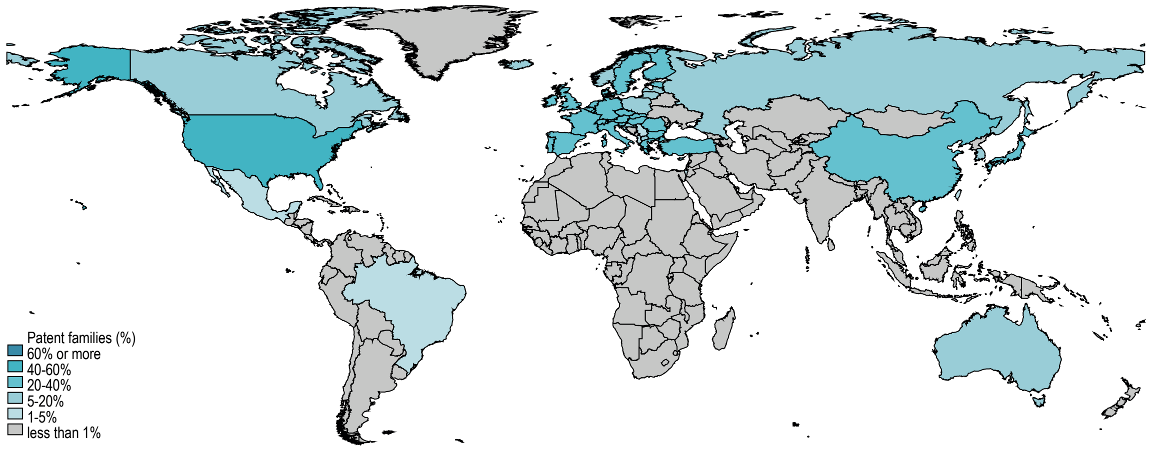
How important patents may have been to prevent rivals from imitating the technology is difficult to ascertain. For one thing, 3D printing systems – both in the industrial and personal market segments – are relatively difficult to reverse engineer.[41] Even the raw materials, which tend to be proprietary, are often produced by a few specialized firms that control their supply, which in turn may add to the cost of imitating any of these printers.

Moreover, there have been many different 3D printing technologies that use varying materials and processes introduced since the first patent on 3D printing was granted. Demand for each type of 3D printing technology varies according to the needs and types of application. Therefore, they do not directly compete with one another, and may not infringe on each other's proprietary technologies.

38. McKinsey Global Institute (2013).
39. Muzumdar (2014).
40. See *www.kickstarter.com*.
41. Wohlers Associates (2014).

Figure 3.5: 3D printing patent applicants are most likely to file for protection in the US

Share of patent families worldwide for which applicants have sought protection in a given country, since 1995



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

Nevertheless, there has been anecdotal evidence suggesting that 3D printing companies are enforcing their proprietary inventions in the industrial market segment. These companies include some of the major players in the market such as 3D Systems, DuPont, EOS, Envisiontec and Stratasys.[42]

Figure 3.5 depicts the different jurisdictions in which patent protection for a specific invention has been sought. The US receives a significant portion of 3D printing patent filings; over 60 percent of patents are filed there. China and the rest of Europe also receive a large share of patent filings, about 40-60 percent, while middle-income countries such as Argentina, Brazil, Malaysia and South Africa get less than 20 percent. These figures suggest that patented 3D printing inventions are diffusing to middle-income countries, although to a far lesser degree than the top four countries where 3D printing patents originate (China, Japan, Germany and the US).

How does IP relate to the personal 3D printing market, where the inventors tend to be driven by personal needs, intrinsic motivation and reputational goals rather than monetary gains? The short answer is that IP is still relevant.

First, advances in personal 3D printing would not have been possible without early developments in the industrial market segment. Many of the technologies used in personal 3D printing markets are proprietary technologies owned by companies operating in the industrial segment. For example, *RepRap* and other open-source 3D printing platforms are based on Scott Crump's fused deposition modeling technique; the original patent expired in 2009. Another open-source 3D printer by the Fab@Home project is based on both fused deposition modeling and Hull's *stereolithography* processes, for which both patents expired in 2004.

Expiry of these patents may be one of the reasons why the personal 3D printing market took off. Second, while the rise of open-source implementation of these processes coincides with the expiry of related key patents, future improvements on these inventions are still protectable under various IP rights such as patents and/or trade secrets. For example, MakerBot – founded as an open-source personal 3D printing manufacturer in 2009 – kept almost all of the design and make of its *Replicator 2* secret.[43]

Third, the open-source codes that users share rely on copyright and its viral effect to facilitate this sharing by keeping the software public.[44]

And finally, the design files created and uploaded by individuals may be protected by copyright, and the 3D printout's aesthetic under industrial design, which the individual may choose to protect and enforce.

42. See Yen-Tzu and Hsin-Ning (2014).

43. West and Kuk (2014).

44. See for example Nadan (2002).

Box 3.2: Restricting the use of the term "FDM" in the US

Fused deposition modelling, or FDM, is a technique invented by Scott Crump in the late 1980s. In 1989 Crump was granted a patent on this process by the USPTO (US Patent 5,121,329), and proceeded to commercialize the process through Stratasys, a company he co-founded with his wife, Lisa Crump.

About 15 years later, Adrian Bowyer started the open-source *RepRap* project which would develop a self-replicating 3D printer. This printer was built based on Crump's proprietary 3D printing technique. Some argue that Bowyer chose this process because it is relatively easy to build and satisfied his ideals for an open-source, self-replicating 3D printer. Others argued that it was timed to coincide with expiry of the patent in 2009.[45]

Fast forward to today. Most open-source 3D printing platforms are based on the RepRap source code and still use Crump's technique.

While the patent on this technique has expired, enabling the manufacturers of these printers to enter the market without having to negotiate a license with Stratasys or face infringement risks, they may not refer to the printing technique as "fused deposition modeling." This is because on January 28, 1991, Stratasys took out a trademark on the term "FDM" (US trademark Serial Number 74133656), thereby limiting its use by other manufacturers.[46] Instead, other manufacturers use the terms "fused filament fabrication," "plastic jet printing," or in general "thermoplastic extrusion" to describe this particular 3D printing process.[47]

Rising tensions between the two market segments

The distinction between the two market segments of industrial versus personal 3D printing is gradually fading as the personal segment of the market becomes more commercially viable. For example, the industrial 3D printing players are starting to pay more attention to the personal market space. At the Consumer Electronics Show held in January 2012, 3D Systems introduced its version of the personal 3D printer, called the Cube. Then, in June 2013, Stratasys released a press release announcing a merger with MakerBot, one of the main personal 3D printing companies.

Moreover, there are potential spillover benefits in the industrial market when the personal segment thrives, and vice versa.

This tension is pronounced when business strategies for the two market segments intersect, particularly when the industrial players enter the personal market space and the issue arises of open versus closed appropriability regimes.

The personal 3D printing ecosystem was built around the open sharing philosophy, while its industrial counterparts relied – and continue to rely – on proprietary knowledge and technologies to advance innovation. Any further innovation in this area may involve open-source codes which may then be incorporated into proprietary, closed, hardware.

There has been some negative feedback from the open 3D printing communities with regard to this tension. And one way that the community has responded to any effort to patent an invention that may have been open-sourced is to participate in the debates concerning patent applications, for example through the USPTO's Peer to Patent initiative.[48] But for now, it is not clear how this will affect sharing within the personal 3D printing ecosystem.

Challenges to the IP system in the personal 3D printing market

The personal 3D printing market segment raises new challenges to the IP system, especially with regard to how to enforce existing IP rights. Any person with access to a 3D printer can print any object as long as they have digital representations of that object. Thus, exact replicas of designs that may be protected under industrial design right or copyright may be easily reproduced and sold without the right holder's permission. This problem of infringement of an existing IP right is compounded when multiple individuals participate in producing and selling illegal copies for profit. Thus, personal 3D printing potentially raises issues of large-scale infringement of existing IP rights by 3D printing users.

Underlying this challenge is the tension between what is legal and what is enforceable in practice.

45. See Freeman (2013).
46. The term "fused deposition modeling" is not trademarked but Stratasys can rely on the US common law trademark right whereby the term is associated with the company, thus precluding its use by others.
47. Banwatt (2013).
48. Clinic Staff (2013), Samuels (2013). On the USPTO initiative, see Shapiro (2003).

In principle, when a user prints a proprietary object in three dimensions using his or her own 3D printer, or sends it to a 3D printing service, he or she may infringe several IP rights. He or she may infringe the design right or copyright that protects the original appearance of the object. If the design is distinctive enough to identify the source of the object and to qualify for trademark protection, then the unauthorized 3D print could also infringe that trademark right. However, whether or not an unauthorized 3D copy of a protected object constitutes IP infringement will depend on the scale of the print and the rules governing exceptions and limitations to IP rights in different jurisdictions.

Potential mass-scale infringement could have significant detrimental effect on the ability of IP right holders to appropriate returns on their investment. These infringements may undercut sales in the IP holders' markets and, to a certain extent, may even lead to the dilution of their brand.

However, many practical issues make it hard to enforce IP rights in the personal market. First, there are many potential infringers and identifying actual infringers is likely to be difficult. Second, infringers will most likely be customers of the IP right holders. These factors lead to the final problem: enforcement would be costly and could tarnish the firms' image.

One way that IP right holders can enforce their rights is to target intermediaries that provide related personal 3D printing services. However, such intermediaries serve an important function as a platform that facilitates the use of 3D printing, and so targeting them would have adverse consequences for the growth of the industry. Moreover, it would risk undermining the growth of the innovation. Intermediaries perform many beneficial functions for the 3D printing market. They enable the new marketplace for sharing and distributing content, and facilitate distributed manufacturing. Placing liability for potential consumers' infringing behavior on the intermediaries could stifle innovation in the distribution and manufacturing of 3D printers.

The situation brings to mind a similar scenario with regard to the rise of the digital industry and copyright infringement. Lessons from other digital innovations may shed some light on possible avenues to redress IP infringement. First, 3D printing market players may consider changing their business strategies. For example, they could decide to shift their profit focus from the 3D printer market to the secondary market for supply materials, potentially limiting the scale of infringement by pricing their materials high enough to discourage potential IP infringers.

Second, they could consider embracing infringing users' behavior rather than fighting it. Some user-led innovation might add significant value to the original invention. Linking to these user communities would create feedback loops between the industry and consumers, helping create better products and strengthening brand loyalty.[49]

Lastly, IP right holders could rely on technological measures to protect their existing business models. For example, they could employ an approach similar to digital rights management in the music industry by controlling how their consumers can access and use the proprietary product.

However, there is a significant difference between the personal 3D printing market and the digital industry. The scale of infringement in 3D printing is small in comparison to the digital industry, reflecting the nascent stage of this market.[50] In particular, there are many constraints facing the uptake of personal 3D printing. 3D printing requires access to a 3D printer and raw materials, and computer programming skills to use and manipulate the CAD files, factors that demand significant investments in time and money from the user (see subsection 3.1.1 and box 3.1). By contrast, the tools and investment needed to download copyright materials from the internet and then reproduce them are smaller. Most households have the necessary hardware, software and skills to download and reproduce copyrighted content.

49. See Jong and Bruijn (2013).
50. See Mendis *et al* (2015).

3.2 – Nanotechnology

"Nanotechnology is manufacturing with atoms."

William Powell,
lead nanotechnologist at NASA's Goddard Space Flight Center

Nanotechnology is technology at the nanometer scale – the scale of atoms and molecules. A nanometer is one-billionth of a meter, or the length of about 3-20 atoms. Nanoscale particles are not new, but only in recent decades have scientists been able to truly visualize and control nanoscale phenomena. Researchers have produced extraordinary breakthroughs in nanoscale science and engineering with widespread commercial applications.

At the outset, it is important to point out that the term "nanotechnology" encompasses a wide range of innovations. While some explicit definitions of nanotechnology exist, figuring out whether a specific technology falls within a given definition can be challenging.[51] The discussion that follows seeks to synthesize a broad literature on nanotechnology and one should keep in mind the definitional ambiguity as a necessary caveat.[52]

3.2.1 – The development of nanotechnology and its economic importance

Like most fields of innovation, nanotechnology has depended on prior scientific progress. The technological developments of the late 20th century would have been impossible without theoretical breakthroughs in the early 20th century involving the basic understanding of molecular structure and the laws of quantum mechanics that govern nanoscale interactions. Foundational developments in physics, chemistry, biology and engineering paved the way for a vast range of applications today.

51. For example, the US Office of Science and Technology Policy broadly defines nanotechnology as any technology involving "the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications."
52. This section draws on Ouellette (2015).

The first consumer nanotechnology products involved passive nanoscale additives to improve the properties of materials such as tennis rackets, eyeglasses and sunscreen. The nanotechnology umbrella also covers many developments in biotechnology and medicine. The biomolecular world operates on the nanoscale: DNA has a diameter of about two nanometers, and many proteins are around 10 nanometers in size. Scientists have engineered these biomolecules and other nanomaterials for biological diagnostics and therapeutics, such as for targeted drug delivery for cancer treatment.

To get a sense of the technology's scope and potential, it is useful to take a closer look at three strands of nanotechnology innovation: electron and scanning probe microscopy, which are essential research tools for understanding and creating nanoscale devices; fullerenes, carbon nanotubes and graphene, which are some of the most promising nanoscale materials; and commercial nanoelectronics, ranging from transistors to magnetic memory.

Research tools: electron and scanning probe microscopy

The ability to visualize nanoscale structure has been critical to the development of nanotechnology. Nanoscale features cannot be seen even with the most powerful optical microscopes, since they are smaller than the wavelength of light. However, electrons have a much smaller wavelength than visible light – a discovery for which French physicist Louis de Broglie won the 1929 Nobel Prize – and can thus be used to image much smaller features. Max Knoll and his PhD student Ernst Ruska at the Technical University of Berlin published images from the first functional transmission electron microscope (TEM) in 1932. The first commercial TEMs followed a few years later, partly facilitated by Ruska's move to Siemens in 1936. Other electron microscopy technologies emerged in the 1930s, namely the scanning electron microscope (SEM) and the scanning transmission electron microscope (STEM). However, they only saw commercial production decades later, with the Cambridge Instrument Company selling its first SEM in 1965 and the British firm VG Microscopes introducing its first STEM in 1974. Today, most electron microscopes are capable of a spatial resolution approaching 0.13 nanometers for thin samples.

A different technique for imaging nanoscale surfaces is scanning probe microscopy, which involves measuring the interaction between a surface and an extremely fine probe that is scanned over it, resulting in three-dimensional images of the surface. Gerd Binnig and Heinrich Rohrer, working at IBM Zurich, developed the first so-called scanning tunneling microscope (STM) in 1981. For their invention, they shared the 1986 Nobel Prize in Physics – along with Ernest Ruska for his creation of the first electron microscope. In 1985, Binnig invented a different type of scanning probe microscope – the atomic force microscope (AFM) – which he developed with researchers from Stanford University and IBM. With the AFM it became possible to image materials that were not electrically conductive. IBM holds the basic patents on both the STM and the AFM. Both instruments are now routine tools for investigating nanoscale materials with atomic resolution.

Promising nanomaterials: fullerenes, carbon nanotubes and graphene

Some of the most promising nanomaterials are structures in which carbon atoms are arranged primarily in hexagons, including soccer ball-like structures known as fullerenes, cylinders known as carbon nanotubes and sheets known as graphene.

Fullerenes were discovered in 1985 at Rice University by Robert Curl, Harold Kroto and Richard Smalley, for which they received the 1996 Nobel Prize in Chemistry. In 1990, physicists at the Max Planck Institute for Nuclear Physics and at the University of Arizona discovered a method of producing fullerenes in larger quantities. This advance led to considerable fullerene-related patenting activity by entities that now saw commercially viable opportunities, including academic researchers and companies. Fullerenes have been used commercially to enhance products such as badminton rackets and cosmetics, but their most promising applications are in organic electronics and bioscience.

The formation of single-walled carbon nanotubes – cylinders with walls made from a single atomic layer of carbon – was simultaneously reported in 1993 by researchers of NEC Corporation in Japan and by researchers at IBM in California.[53] Since then, research into carbon nanotubes has taken off; for example, at the US National Science Foundation, nanotubes were the second most heavily funded nanotechnology topic between 2001 and 2010. As with fullerenes, a range of commercial products already make use of carbon nanotubes, including thin-film electronics. However, the most promising applications – those that take advantage of the electrical properties of individual nanotubes – still seem many steps away from the commercial stage.[54]

Graphene, the newest carbon-based nanomaterial of interest, was already described theoretically in 1947, but its physical isolation did not occur until 2004, when Andre Geim, Konstantin Novoselov and colleagues at the University of Manchester showed that they could use Scotch tape to extract individual graphene sheets from graphite crystals. In 2010, Geim and Novoselov won the Nobel Prize for their graphene work. Their scientific breakthrough prompted considerable graphene-related patenting, though with few commercial products so far. Graphene has potential applications ranging from electronics to biosensing, but significant hurdles to implementation remain. For example, integrating graphene into solar cells and batteries holds promise for improved energy conversion and storage, but such progress necessitates improvements in high-volume manufacturing and transfer processes.[55]

53. While the discovery of carbon nanotubes is often attributed to the Japanese academic physicist Sumio Iijima in 1991, the Soviet scientists L.V. Radushkevich and V.M. Lukyanovich published a TEM image of a 50-nanometer-diameter carbon nanotube in 1952, and nanotubes were rediscovered a number of times since then. See Monthioux and Kuznetsov (2006).
54. See De Volder *et al* (2013).
55. See Bonaccorso *et al* (2015).

Commercial nanoelectronics

Although many of the potential applications of carbon-based nanomaterial remain speculative, other nanotechnology developments have already had a significant market impact. Nanotechnology has led to significant improvements in commercial electronics, including improved transistors and magnetic memory. For example, as of 2010 about 60 percent of the US semiconductor market involved nanoscale features, for a market value of about USD 90 billion.

The steady shrinking of device size reflects the persistence of "Moore's Law," which describes the doubling of the number of transistors on a chip every 18-24 months (see section 2.3). To shrink devices below 100 nanometers, researchers had to overcome significant challenges. For example, they developed new materials to provide necessary insulation of transistor gates from leakage currents, and improved optical lithography techniques to allow patterning of 30 nanometer features. These advances depended on basic advances in nanofabrication and characterization, and continued scaling is thought to require further fundamental advances, perhaps involving carbon nanotubes or graphene.[56]

Nanotechnology's economic contribution and its growth potential

Nanotechnology has already had an impact on a vast range of technological fields. Some observers believe that nanomanufacturing has the potential to transform economies as profoundly as innovations such as electricity, computers and the Internet. There are potential applications across a wide range of sectors, from improved battery-powered vehicles to more targeted medical therapies to nanotube-enhanced road paving with remote sensing capabilities. In principle, given its broad nature, nanotechnology has the potential to spur growth through all the channels identified in section 1.2.

Nanotechnology also has the potential to enhance social welfare by addressing global sustainability challenges. For example, there has been significant progress in developing nanotechnology-based solutions for water treatment, desalination and reuse. Nanotechnology researchers have improved food safety and biosecurity, produced lightweight but strong nanocomposites for building more fuel-efficient vehicles, created methods for separating carbon dioxide from other gases, and dramatically improved the efficiency of plastic solar cells.

Quantifying the current economic contribution – let alone the future economic growth potential – of all developments in nanotechnology is challenging, if not impossible. Aside from data availability constraints, it is not clear how to assess the value of a nanotechnology invention that is a small but fundamental component of a product of process. For example, the size of features in modern semiconductors is typically in the nanoscale range, and the markets for semiconductors and electronics as a whole are worth over USD 200 billion and USD 1 trillion, respectively.[57] However, it is unclear how much of these values should be attributed to nanotechnology.

Another challenge is to decide which products and services fall within the bounds of nanotechnology – as pointed out at start of this section. Table 3.5 presents different estimates of current nanotechnology-related market size, illustrating how different definitions lead to vastly different estimates. Nonetheless, one can glean from these figures that nanotechnology has already left some mark on economic activity.

56. See Roco *et al* (2010).

57. See Bonaccorso *et al* (2015).

Table 3.5: Different estimates of nanotechnology's economic contribution

Estimate	Geographic scope	Definition of nanotechnology	Source
Revenues of USD 731 billion in 2012	Worldwide	Nano-enabled products	Lux Research
Market size of USD 26 billion in 2014	Worldwide	Narrow definition of nanotechnology applications	BCC Research
Market size of USD 100 billion in 2011	Worldwide	Nanomedicines	BCC Research
Market value of final products of USD 300 billion in 2010	Worldwide	(unclear)	Roco (2001)

3.2.2 – The nanotechnology innovation ecosystem

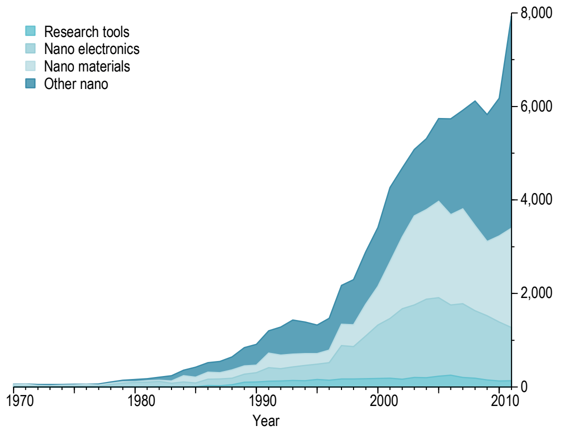
In which ecosystem does nanotechnology flourish? As a first step, it is useful to look at the patent landscape for nanotechnology. While not offering a perfect mirror of the innovation landscape, patent data provide rich information about some of the key innovation actors – especially those involved in the development of technology with commercial potential. To complement this picture, the discussion will then describe some of the main public support programs for nanotechnology R&D, present information about the main R&D actors and explore how knowledge flows through the nanotechnology innovation ecosystem.

The patent landscape

Based on the patent mapping developed for this report, figure 3.6 depicts the number of first patent filings worldwide in the nanotechnology space from 1970 to 2011.[58] First patent filings are the statistical measure closest to the concept of unique inventions. The figure illustrates the fast growth in nanotechnology patenting; since 1995, patenting has grown by an average of 11.8 percent per year. The three areas of nanotechnology innovation discussed in the previous subsection accounted for most of the patenting activity throughout this period. Interestingly, though, patenting in those areas reached a peak in 2004 and other nanotechnology applications have since seen rapid patenting growth.

Figure 3.6: Fast growth in nanotechnology patenting, especially since the mid-1990s

First patent filings by nanotechnology area, 1970-2011



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

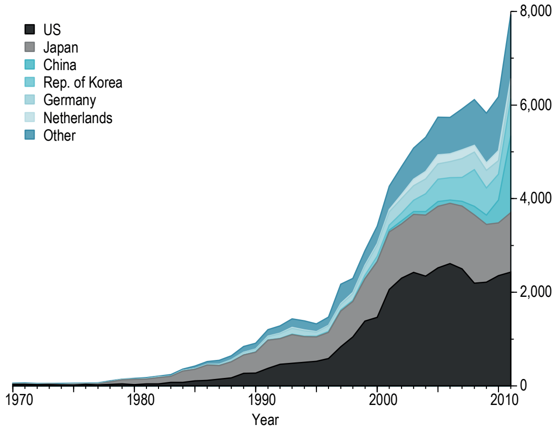
Figure 3.7 shows the same patent filings as figure 3.6, but offers a breakdown by origin of the patent applicant. It shows increasing geographical diversity. Up to the late 1990s, US and Japanese residents accounted for most nanotechnology patent filings, but since then other origins have gained in importance. Particularly noteworthy is the rise of patenting from the Republic of Korea in the early 2000s and, even more recently, from China. Interestingly, while innovators from the Republic of Korea have filed patents for nanomaterials and nanoelectronics, those from China have focused almost entirely on nanotechnology applications outside the three areas discussed in the previous subsection.[59] Since the mid-2000s, US and Japanese patenting activity in nanotechnology has not only declined relative to other origins, but also fallen in absolute terms.

58. The latest available data are for 2011, as patent applications are only published with a delay. See the technical notes to this report for a description of the methodology used to map nanotechnology patents.

59. In particular, 69 percent of nanotechnology patents of Chinese origin filed between 1995 and 2011 fall into the "other" category, compared with 37 percent for Japan, 44 percent for the Republic of Korea and 38 percent for the US.

Figure 3.7: Increasing geographical diversity in nanotechnology innovation

First patent filings by origin, 1970-2011



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

Figure 3.8 offers a full global overview of nanotechnology patenting activity. In addition to the countries mentioned above, several other middle-income countries – notably Brazil, India, Mexico and South Africa – show some level of patenting, even if overall numbers are substantially below those of the main patenting origins.

Finally, it is interesting to ask how important academic patenting is in the nanotechnology field. Figure 3.9 depicts the contribution of different applicant types to overall patenting since 1970. Reflecting nanotechnology's scientific origins, one might have expected the share of company patents to increase over time. However, the opposite is the case. The share of academic patenting rose from 8.6 percent in 1980 to 16.1 percent in 2000, and reached 40.5 percent in 2011 – the highest academic patenting share among the breakthrough innovations discussed in this report. However, there are marked differences across origins. While rising in most countries, the share of academic patenting has averaged 8.2 percent for Japanese applicants, 19.3 percent for German applicants, 26.9 percent for US applicants, 35.6 percent for Korean applicants and 73.0 percent for Chinese applicants.[60] Indeed, the dominance of academic applicants in Chinese patent filings largely explains the marked increase in the global academic patenting share since the mid-2000s (see figure 3.9). It may also explain the different technological focus of Chinese filings discussed above.

60. These shares refer to all first patent filings between 1990 and 2011.

Public support programs

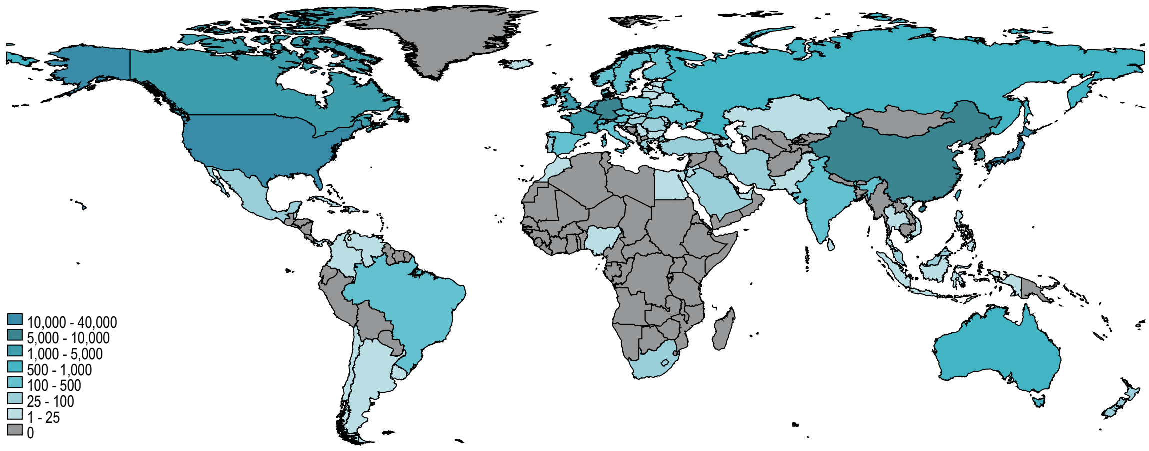
Governments support innovation in nanotechnology through a variety of mechanisms, including direct R&D spending using grants and procurement contracts, innovation prizes and R&D tax incentives. Quantifying the importance of these mechanisms is not straightforward. Available data sources often do not report the nanotechnology-specific portion of public support programs, especially for technology-neutral programs such as R&D tax credits. Varying definitions of nanotechnology and the fact that some programs operate at the state level further complicate the quantification task. Bearing these limitations in mind, available data point to the following:

- Most nanotechnology-specific public support has come in the form of direct grants, both for basic research and for early-stage commercialization. Over 60 countries created national nanotechnology R&D programs between 2001 and 2004. The first and largest such program is the US National Nanotechnology Initiative, which has provided nearly USD 20 billion in support since 2000 through different federal agencies.[61]
- Estimates suggest that global government spending on nanotechnology R&D reached USD 7.9 billion in 2012, led by the US and the EU with about USD 2.1 billion in spending each.[62] Next were Japan with USD 1.3 billion, Russia with USD 974 million and China and the Republic of Korea with just under USD 500 million each. Other middle-income countries seeing substantial government spending on nanotechnology include Brazil and India.
- R&D tax incentives are more difficult to estimate but no less important, as tens of billions of USD are spent each year on such incentives worldwide – from which nanotechnology R&D is bound to benefit.[63]
- Innovation prizes are not a major policy tool in the nanotechnology space. However, there are private non-profit prizes and proposals for a federal nanotechnology prize in the US.[64]

61. See Ouellette (2015).
62. In the case of the EU, this includes spending by both national governments and the European Commission. See Lux Research Inc. (2014).
63. See OECD (2011).
64. See Hemel and Ouellette (2013).

Figure 3.8: The full geography of nanotechnology innovation

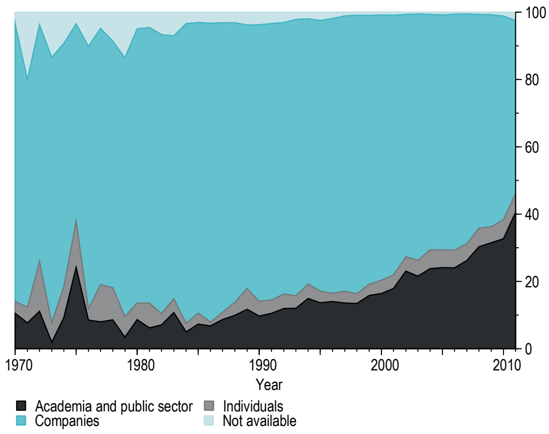
First patent filings by origin, since 1970



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

Figure 3.9: Academic patenting is gaining importance

Share of first patent filings by applicant type, 1970-2011



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

Nanotechnology R&D actors

The nanotechnology innovation ecosystem comprises diverse actors, including government laboratories, universities and other nonprofit research institutions, large businesses and small start-ups. There are also venture capitalists and other intermediaries that have emerged to help facilitate capital and knowledge flows among these actors.

As described above, governments themselves are critical actors in the nanotechnology ecosystem. They perform a significant amount of R&D through national laboratories and state-supported universities. Private universities and other nonprofit research institutes are also major players, typically operating through government grants. Because much university research is published, one way to identify the leading nanotechnology research organizations is to look at total publications. Table 3.6 does so, relying on publication counts in Web of Science – one of the most comprehensive databases indexing scientific publications.[65] For comparison purposes, it also presents the number of patents first filed by those organizations. The institutions with the largest number of nanotechnology publications are the Chinese and Russian Academies of Sciences, the *Centre National de la Recherche Scientifique* of France, and three Japanese universities. All top-20 scientific institutions also file patents for nanotechnology inventions. However, publication and patenting outputs do not show a clear correlation – likely reflecting differences in institutional strategies and patenting policies.

65. The methodologies for mapping nanotechnology publications and patents differ (see Chen *et al* (2013), and technical notes). However, the two metrics should still be broadly comparable.

Table 3.6: Top 20 nanotechnology research organizations, since 1970

Research organization	Country	Number of scientific publications	Number of first patent filings
Chinese Academy of Sciences	China	29,591	705*
Russian Academy of Sciences	Russia	12,543	38*
Centre national de la recherche scientifique	France	8,105	238
University of Tokyo	Japan	6,932	72
Osaka University	Japan	6,613	44
Tohoku University	Japan	6,266	63
University of California, Berkeley	US	5,936	1,055†
Consejo Superior de Investigaciones Científicas	Spain	5,585	77
University of Illinois	US	5,580	187
MIT	US	5,567	612
National University of Singapore	Singapore	5,535	75
University of Science and Technology of China	China	5,527	na
Peking University	China	5,294	247
Indian Institute of Technology	India	5,123	14
University of Cambridge	UK	5,040	43
Nanjing University	China	5,035	95
Zhejiang University	China	4,836	191
Seoul National University	Rep. of Korea	4,831	163
Consiglio Nazionale delle Ricerche	Italy	4,679	17
Kyoto University	Japan	4,540	95

*Reflecting the publication and patent output of all organizations belonging to the respective academy.

†First patent filings relate to the University of California system as a whole.

Source: Chen *et al* (2013) and WIPO based on PATSTAT (see technical notes).

Corporations of all sizes engage in nanotechnology R&D. One estimate suggests that global corporate spending on nanotechnology R&D stood at USD 10 billion in 2012. This figure exceeds the estimate of global government spending on nanotechnology R&D (see above), attesting to the commercial viability of nanotechnology. The countries with the largest corporate R&D spenders were the US, Japan and Germany, whose companies spent a combined USD 7 billion in 2012.[66]

Table 3.7: Top 20 patent applicants, since 1970

Applicant name	Country of origin	Number of first patent filings
Samsung Electronics	Rep. of Korea	2,578
Nippon Steel & Sumitomo Metal	Japan	1,490
IBM	US	1,360
Toshiba	Japan	1,298
Canon	Japan	1,162
Hitachi	Japan	1,100
University of California	US	1,055
Panasonic	Japan	1,047
Hewlett-Packard	US	880
TDK	Japan	839
Du Pont	US	833
Sony	Japan	833
Fujifilm	Japan	815
Toyota	Japan	783
Honeywell	US	773
Chinese Academy of Sciences	China	705
Tsinghua University	China	681
Fujitsu	Japan	673
MIT	US	612
Western Digital	US	568

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

Table 3.7 lists the top 20 nanotechnology patent applicants, which mostly consist of companies. These applicants account for 22.8 percent of all first patent filings identified in this report's patent mapping. East Asian applicants dominate this list – with 10 Japanese companies, Samsung Electronics, Tsinghua University and the Chinese Academy of Sciences; the remaining top-20 applicants are all from the US. While all company applicants among the top 20 are long-established multinational corporations, evidence for the US suggests that the share of patents by small firms has increased over time.[67] In addition, companies focused on nanoelectronics dominate the list of patent applicants in table 3.7. For other nanotechnology applications, new market entrants may well be more important.

66. All R&D estimates are from Lux Research Inc. (2014).

67. See Fernández-Ribas (2010).

Linkages and knowledge flows

What mechanisms link the various nanotechnology innovation actors, and how does knowledge flow among them? Formal license agreements are important, but a substantial amount of transfer occurs through more informal channels. One study on the US nanotechnology industry concluded that "[t]he most widespread mechanism for technology transfer is publications and presentations of technical findings at conferences, workshops, tutorials, webinars, and the like."[68] Professional and academic societies play an important role in facilitating these interactions.

Nanotechnology innovation sometimes follows an orderly progression from academic research to corporate development to a marketed product, but "nonlinear" paths are also common. VC can be a bridge between academia and industry, but global VC investment in nanotechnology was only USD 580 million in 2012, which is just three percent of the overall funding of USD 7.9 billion from governments plus USD 10 billion from corporations.[69] In other words, governments and cash-rich firms play a more critical role in facilitating nanotechnology development.

One important way in which governments facilitate technology transfer is by supplying essential nanotechnology infrastructure that a variety of actors can use. Nanotechnology R&D tends to be highly capital intensive, with research often requiring clean rooms that house expensive fabrication and measurement tools such as the specialized microscopes described in subsection 3.2.1. For example, the US National Science Foundation has funded 14 facilities at US universities, making up the National Nanotechnology Infrastructure Network.[70] Members of the network have provided support for nanoscale fabrication and characterization for all qualified users, including corporations.

Governments also use direct grants to help transfer technologies from academia to industry, funding business startups that seek to commercialize nanotechnology. Relevant programs exist, for example, in the US, Germany, France and China.[71] This direct funding helps mitigate the market entry risk of new business ventures and improves their commercial viability.

Large companies, in turn, have been active in helping commercialize nanotechnology products, including by funding academic research and by collaborating with smaller firms. One study of global nanotechnology innovation concluded that in general, "[l]arge firms play a fundamental role in co-producing and transferring knowledge in nanotechnology by acting as a node of high centrality directly linking the industry's co-patenting network with public research."[72]

Different sets of channels exist for knowledge flows between countries, including for the diffusion of nanotechnology to low- and middle-income countries. Nanotechnology applications of particular interest to poorer economies include energy storage, agricultural productivity enhancements, water treatment and health technologies. Some 60 countries are active in nanotechnology R&D and a diverse set of countries have hosted and participated in nanotechnology conferences. International diffusion occurs through formal collaboration agreements, such as the International Center for Nanotechnology and Advanced Materials consortium involving US and Mexican universities. Nanotechnology also diffuses through skilled migration. For example, nanoscientists in the US are overwhelmingly foreign born, and countries such as China and India have pursued "reverse brain drain" policies to spur the return migration of their nationals. The role of FDI in facilitating nanotechnology diffusion is less clear. For example, one study found that while China has been a popular destination for FDI in general, provinces with greater FDI do not appear to generate more nanotechnology patents; rather, nanotechnology development in China seems to be driven by public-sector investment.[73]

68. See National Research Council (2013).
69. See Lux Research Inc. (2014).
70. See *www.nnin.org/about-us*, which will be replaced by the National Nanotechnology Coordinated Infrastructure.
71. See Ouellette (2015).
72. See Genet *et al* (2012).
73. See Huang and Wu (2012).

3.2.3 – Nanotechnology and the IP system

The foregoing discussion described how different nanotechnology actors have relied on the patent system to protect the fruits of their innovative activity. This subsection takes a closer look at the role of the IP system in the nanotechnology space. It first explores how important patents are in appropriating R&D investments and how innovators protect their patents internationally. It then evaluates the importance of the disclosure function of patents, asks whether patent ownership may slow cumulative innovation, and discusses possible limits to the scope of patentability. Finally, it offers a brief perspective on the role of trade secrets in nanotechnology innovation.[74]

Patenting strategies

As described in Chapter 1, the importance of patents in appropriating returns on R&D investment varies across sectors. In some sectors – notably pharmaceuticals and chemicals – patents play a central role in giving companies a competitive edge. In others – notably many ICT industries – lead time, branding and other mechanisms are crucial. While patents may still play an important appropriation role in such sectors – at least for certain key technologies – companies file patents partly to ensure their freedom to operate and to license their technologies to others.

No evidence is available to shed light on the role of patents in appropriating R&D investment specifically related to nanotechnology. However, given the cross-cutting nature of nanotechnology innovation, it is likely that no general pattern exists, with the role of patents depending on the sector of application. For example, nanotechnology patents relating to biotechnology and chemistry may well play a more important appropriation role than nanoelectronics patents.

The strategic use of patents also has an important bearing on the extent to which nanotechnology innovators seek patent protection beyond their home markets. Figure 3.10 illustrates where patent applicants have sought patent protection for their inventions. It depicts the share of nanotechnology patent families worldwide for which applicants have sought protection. As can be seen, the US is the most frequent destination of patents, with applicants seeking protection there for 85 percent of global first filings. Japan, Germany, the UK and France follow next, with shares of between 37 and 52 percent. On average, a first patent filing for a nanotechnology invention leads to around three subsequent patent filings relating to the same invention.[75] Except for China, Turkey and several Eastern European countries, the destination share of low- and middle-income countries lies below 5 percent.[76]

Several suggestive conclusions emerge from the global patent landscape. First, even though many nanotechnology applications have global reach, innovators mainly seek patent protection in a limited number of high-income countries. On the one hand, this indicates that companies have other means of appropriating R&D investment, as described above. On the other hand, it suggests that innovators do not see a big risk of their technology being imitated in countries with more limited technological capacity. Second, from the viewpoint of most low- and middle-income countries, patent ownership is unlikely to pose a major barrier to technology dissemination.[77] At the same time, the limited interest in patenting indicates that there may be other obstacles to greater adoption of nanotechnologies in those countries.

74. Trademarks are important for protecting an innovator's first-mover advantage and there are questions about whether the use of "nano" as a prefix should be regulated under trademark deceptiveness doctrines. In addition, creative nanoscale art may raise questions of copyright law. However, these IP forms are not further discussed here.

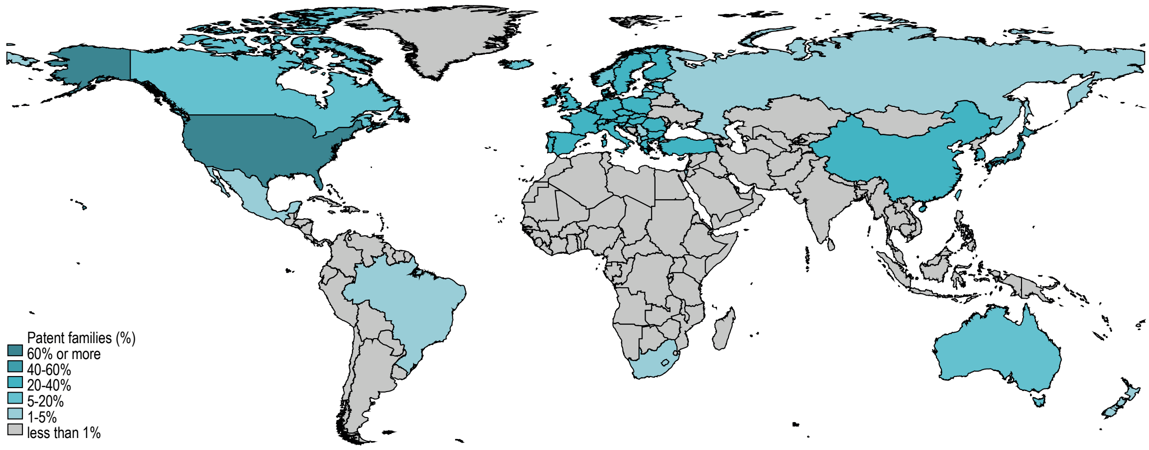
75. This figure refers to nanotechnology patents filed since 1995.

76. The relatively high destination shares of Turkey and Eastern European countries – which are all members of the European Patent Convention (EPC) – likely reflects patent applications at the EPO, many of which are unlikely to result in a national validation in the countries in question.

77. Two caveats are in order here. First, while overall destination shares are low, it could be that applicants seek protection for the most commercially important patents in low- and middle-income countries. Second, the PATSTAT database underlying figure 3.10 does not cover all low- and middle-income countries, thus underestimating the destination share of those countries.

Figure 3.10: Nanotechnology patent applicants mainly seek protection in high-income countries

Share of patent families worldwide for which applicants have sought protection in a given country, since 1995



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

Disclosure through patents

Although disclosure has been a central feature of the patent system since its inception, evidence on how it contributes to knowledge dissemination and follow-on innovation is limited. In fact, some scholars doubt that scientists read patents, which are often seen as legalistic documents written by lawyers. However, a study surveying nanotechnology researchers found that a substantial number of them do find useful technical information in patents.[78] Out of 211 researchers – primarily located in the US – 64 percent reported that they have read patents, and 60 percent of those reading patents for scientific rather than legal reasons said they found useful technical information in them. Respondents reported that patents can show "how a particular device works"; they can "put the ideas and research in context and offer […] some plausible views as to" the respondents' own research; and they can keep researchers "from going down a road that has already been traveled."

While this survey points to the value of patent disclosures, it also shows that the disclosure function of patents could be improved. In particular, 36 percent of respondents have never read patents, and 40 percent of those reading for technical information did not find anything useful. The four main complaints were that patents are confusingly written; that they are unreliable since, unlike scientific journal articles, they do not face critical review; that they duplicate journal articles; and that they are out of date. In addition, 62 percent of patent readers thought the patent they read did not provide sufficient disclosure for a nanotechnology researcher to recreate the invention without additional information.

Accordingly, the study makes several recommendations to improve the disclosure function of nanotechnology patents: existing disclosure requirements should be more strictly enforced; patents should be published earlier – especially for patentees that have little need for secrecy; access to the patent literature should be improved through search and annotation tools; and incentives to cite patents in scientific publications should be created.

78. See Ouellette (2015).

Cumulative innovation and patent thickets

Like most innovative activity, nanotechnology innovation is cumulative in nature, with new inventions typically building on past ones. This raises the question whether patent rights may slow or even forestall cumulative innovation – a concern raised for a number of other technologies.[79]

One legal study of nanotechnology patenting argues that nanotechnology differs from many other important fields of invention over the past century in that many of the foundational inventions have been patented at the outset.[80] Other commentators have raised concerns about the potential existence of nanotechnology patent thickets.[81] To the extent that patent landscapes are overly fragmented and overlapping, they may impede innovation as the transaction costs of bargaining rise and the risk of holdup effects increases. One study attributes overlapping patent rights to patent offices struggling to deal with this new interdisciplinary technology, which does not fit neatly into existing patent classification systems.[82] However, despite these concerns and the fast growth of patenting since the 1990s (see figure 3.6), there is little evidence of actual patent thicket problems so far. This may be because the nanotechnology products market remains too young for such problems to surface, or it may be a sign that nanotechnology licensing markets have been more efficient than predicted.[83]

In addition, while there has been some nanotechnology patent litigation in key jurisdictions such as the US, nothing stands out about nanotechnology patent litigation as compared with patent litigation more generally. Similarly, evidence suggests that nanotechnology patenting may have problems such as slow time to grant and large numbers of difficult-to-search applications, but these are problems affecting the patent system as a whole, not problems specific to nanotechnology patenting.[84]

79. See WIPO (2011) for a more in-depth discussion of how patents affect cumulative innovation processes.
80. See Lemley (2005). He argues that airplanes (between 1903 and 1917) and the radio (between 1912 and 1929) were the last emerging technologies for which the basic ideas were patented.
81. See, for example, Sabety (2004), Bawa (2007) and Sylvester and Bowman (2011).
82. See Bawa (2004).
83. See Ouellette (2015).
84. See Ganguli and Jabade (2012).

Scope of patentability

New technologies often raise questions about what type of inventive claims should qualify for patent protection. International law generally requires patents to be available on "any inventions […] in all fields of technology".[85] However, it allows exceptions that might cover some nanotechnology inventions, including for medical diagnostic methods and for inventions that could endanger health or the environment. Additionally, some countries have introduced certain limits that may exclude certain nanotechnology developments from patentability.

Importantly, the US Supreme Court has recently decided that any "product of nature" such as genomic DNA as well as any "law of nature" such as a method for calibrating the proper dosage of a drug may be excluded from patentability.[86] These decisions raise questions about the validity of many nanotechnology patents in the US.[87] Many nanomaterials exist in nature; for example, carbon-based nanoparticles are produced by common candle flames, and graphene is produced simply by writing with a pencil. There do not appear to have been any challenges yet to nanotechnology patents in light of the Supreme Court's decision, but this could become a concern for patentees.

Other scholars have raised questions about the lack of novelty of certain nanotechnology inventions in relation to the prior art and about a lack of inventive step if inventions merely change the size of existing technologies.[88] However, there is no evidence that these concerns have become a significant barrier to patentability in practice.

85. See the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS).
86. See Ouellette (2015).
87. See Smalley (2014).
88. See Ganguli and Jabade (2012) on the former and Bleeker *et al* (2004) on the latter.

Trade secrets

Because many nanotechnology inventions are difficult to reverse engineer, innovators may prefer to keep them secret rather than apply for a patent. Indeed, evidence suggests that nanotechnology process innovations are particularly likely to be protected by trade secrets.[89] In addition, among nanomaterials producers, those focused on ceramic nanomaterials, nanostructured metals and catalysts are more likely to rely on trade secrets. Accordingly, just looking at nanotechnology patents gives an incomplete and possibly biased picture of the nanotechnology landscape.

As shown in figure 3.9, much nanotechnology research takes place at universities, which have little incentive to keep their inventions secret. However, for many companies, trade secrets are an important strategy to appropriate R&D investment. Significant trade secret litigation in the US suggests that this form of IP protection is important. For example, in 2000 Nanogen sued a former employee for trade secret misappropriation, arguing that the patent applications he had filed on nanotechnology biochips disclosed trade secrets owned by Nanogen. The settlement payment amounted to an estimated USD 11 million. In another case, Agilent Technologies was awarded damages of USD 4.5 million after suing former employees for misappropriation of trade secrets related to liquid chromatography using nanoscale particles.[90]

As in other areas of innovation, trade secret policy must balance providing incentives to companies to invest in R&D with not overly restricting the dissemination of technological knowledge. One key question in this context is to what degree employees of innovating companies can carry their knowledge to competitors. As argued in subsection 3.2.2, labor mobility may be one important vehicle through which specialized knowledge associated with nanotechnology innovation disseminates throughout the economy. However, this is again not a nanotechnology-specific concern. As this section has explained, the nanotechnology innovation ecosystem is in many ways a microcosm of the full innovation ecosystem, and the role of the IP system with regard to nanotechnology appears similar to its role in general.

89. See Lux Research Inc. (2007).
90. See Ouellette (2015) for further details.

3.3 – Robotics

"At bottom, robotics is about us. It is the discipline of emulating our lives, of wondering how we work."

Rod Grupen,
Director of the Laboratory for Perceptual Robotics, University of Massachusetts Amherst

Robotics is the field of technology which drives the development of robots for application in areas as diverse as car factories, construction sites, schools, hospitals and private homes. Industrial robot arms have been in use for industrial automation in automotive and other manufacturing businesses for more than three or four decades. But various strands of existing and newer research fields, such as AI and sensing, have been combined in more recent years to produce autonomous "advanced" robots with more widespread potential use across the economy and society. [91]

3.3.1 – The development of robotics and its economic importance

Encyclopedia Britannica defines a robot as "any automatically operated machine that replaces human effort." According to the International Federation of Robotics (IFR), "[a] robot is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks".[92]

The term autonomy is often used to underline the difference between robots and other machines; a robot has the ability to interpret its environment and adjust its actions to achieve a goal. In terms of technological trajectory, robots are evolving from programmed automation, over semi-autonomous to more autonomous complex systems. Fully-autonomous systems are able to operate and make "decisions" to complete tasks without human interaction.

The history of robotics: robotic arms for industrial automation

Robots, in their most basic form, are not new. The history of robotics started in ancient Greek with *automatons*, essentially non-electronic moving machines which displayed moving objects. The invention of simple automatons continually evolved henceforth, but robots in their current form took off with the process of industrialization, to perform repetitive tasks.

In the more recent history of industrial robots, a few key inventions in two areas stand out as having led to the first incarnation of robots for industrial automation.[93] First, *control systems* allowing humans or computers to control and steer robots from a distance, and second, *mechanical manipulation systems* such as robotic arms or legs to move or grab objects.

With regard to remote control systems, the 1898 invention of a remote-controlled boat which was patented and demonstrated to the public in a park in New York proved central.[94]

As for mechanical manipulation systems, the first industrial robot was developed in 1937 in the form of a small crane. The development of robotic legs and arms was furthered by W.G. Walter, who built the first autonomous robot in the late 1940s.[95] The breakthrough enabling the development of the robotics industry, however, was when George Devol invented and patented the first automatically operated programmable robotic arm in the mid-1950s.[96] Devol then partnered with Joseph Engelberger, considered by many scholars to be the "Father of Robotics", to create a company called Unimation, which produced a robot in 1956 based on Devol's patents. This started the commercialization of industrial robots.[97]

Robotic arms have since been fine-tuned and improved. The first computer-controlled revolute electric arm, for instance, was developed at the Case Institute of Technology, Case Western Reserve University, US. In 1969, researchers at Stanford University invented the so-called Programmable Universal Manipulation Arm,

91. This section draws on Keisner *et al* (2015) and Siegwart (2015).
92. See IFR.

93. See IFR (2012).
94. US Patent 613,809.
95. US Patent 2,679,940. Willard L.V. Pollard and Harold A. Roselund, working for DeVilbiss Co., filed a patent for the first programmable mechanized paint-sprayer in 1942.
96. US Patent 2,988,237. See also Nof (1999).
97. See Rosheim (1994).

allowing for more sophisticated control for assembly and automation.[98] One of these researchers, Victor Scheinman, started Vicarm Inc. to manufacture the arm, which proved fundamental to the development of the robotics industry; he ultimately sold the company to Unimation in 1977.

Largely based on the work of the aforementioned inventors and firms, the first commercial robots were deployed on General Motors' assembly lines in the USA in 1961.[99] The first industrial robot in Europe, a Unimate, was installed in Sweden in 1967. In 1969, the company Trallfa of Norway offered the first commercial painting robot. In 1973, ABB Robotics and KUKA Robotics brought their first robots to market. Since then, the functionality and control of robotic mechanical parts have been continually improved by the robotics industry.

Approximately a decade after Devol filed his patent, Japanese companies began to develop and produce their own robots pursuant to a license agreement with Unimation. By 1970, robotic manufacturing had proliferated throughout the automotive industry in the US and Japan. By the late 1980s, Japan – led by the robotics divisions of Fanuc, Matsushita Electric Industrial Company, Mitsubishi Group and Honda Motor Company – was the world leader in the manufacture and use of industrial robots.

Parallel key inventions in the area of packaging robots – for instance, the Delta packaging robot developed at the Federal Institute of Technology of Lausanne, yielding 28 patents – modernized the packaging industry.

A full-scale humanoid robot developed at Waseda University in Japan laid the foundation for follow-on innovation in the field, facilitating enhanced human–robot interaction relevant to today's consumer-oriented robot markets.

Toward autonomous systems built on artificial intelligence and connectivity

In the journey toward more capable robots, researchers have since worked on increasing autonomy and improving interaction between humans and robots. New materials and innovations in various fields outside the robotics area such as artificial intelligence (AI), mechatronics, navigation, sensing, object recognition and information processing are the core technological developments furthering robotics today.[100] The research has become more interdisciplinary.

In particular, innovation in software and AI will be key technologies for next-generation robots. This matters to help robots maneuver and circumvent obstacles. The seminal breakthrough in developing algorithms instrumental for robotic path planning took place in the mid-1980s.[101] Algorithms are increasingly central to how robots take more complex decisions, for instance, how home or service robots simulate emotions. Researchers are currently working on software that will mimic the human brain, honing language and decision-making skills.

Based on improved connectivity, sensors and processing power, robots are becoming increasingly data-driven, and linked over more intelligent networks. As such, innovation is increasingly about software and hardware integration and thus the delivery of so-called integrated robotic and intelligent operational systems. On the application level, the development of autonomous vehicles and drones is seen as an extension of robotics.

The economic contribution of robotics

Robots already have a demonstrable and significant impact on how manufacturing takes place. Since the start of industrial automation in the 1970s, the uptake of robots in manufacturing has increased significantly. The industrial robot market was estimated to be worth USD 29 billion in 2014, including the cost of software, peripherals and systems engineering (see table 3.8).

98. Scheinman (2015).
99. IFR (2012).
100. Kumaresan and Miyazaki (1999).
101. Smith and Cheeseman (1986).

Table 3.8: Different estimates of the robotics industry revenues

Estimate	Definition	Source
USD 29 billion (2014) USD 33 billion (2017)	Global market for industrial robotics	IFR (2014a)
EUR 50-62 billion (2020)	Global market for industrial robotics	euRobotics (2014)
USD 3.6 billion	Global market for service robots (of which USD 1.7 billion for domestic use)	IFR (2014b)

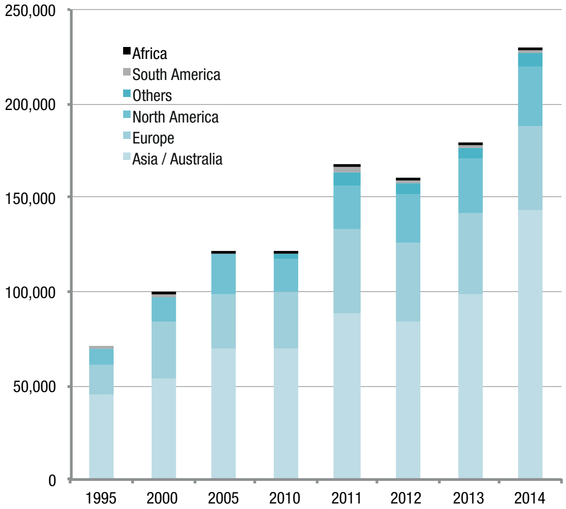
As illustrated by figure 3.11 (top), the number of robots sold is increasing, reaching about 230,000 units sold in 2014, up from about 70,000 in 1995, and projected to increase rapidly in the next few years. Japan, US and Europe were the initial leaders in terms of market size.

Interestingly, the respective shares of various world regions in global robotics sales has changed little, with Asia leading followed by Europe and North America, and rather small volumes in South America and Africa. Yet within Asia, China has gone from no robots in 1995 to overtaking Japan to become the largest robot market. The Republic of Korea is now the second biggest user of industrial robots in Asia.[102]

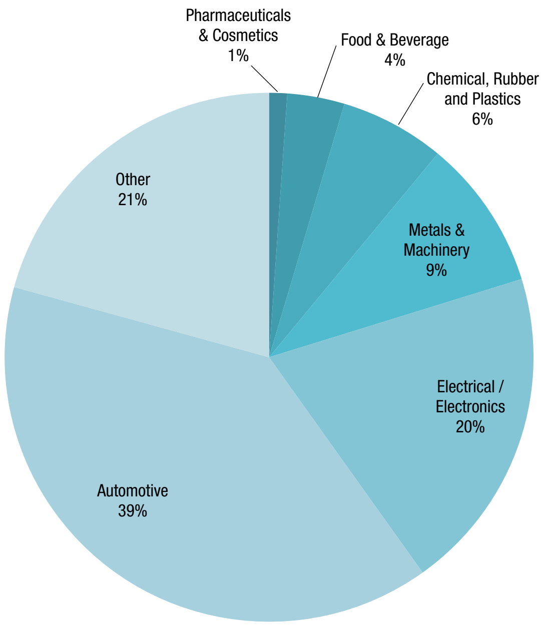
In terms of sectors, the automotive industry continues to be the main driver of automation, followed by the electronics industries (see figure 3.11, bottom). Innovation will enable more flexible and small-scale manufacturing.

Figure 3.11: Worldwide shipments of industrial robots on the increase, led by Asia and the automotive sector

Shipments in thousands of units, 1995-2014 (top)



Share of sectors as percent of total shipments, 2014 (bottom)



Note: The regions as shown here follow the definition of the IFR.

Source: IFR World Robotics Database, 2014.

102. In terms of robotic density, as at 2014 the Republic of Korea had the highest robot density in the world, with 437 units per 10,000 persons employed in the manufacturing industry, followed by Japan (323) and Germany (282). In comparison, China's density was 30, Brazil's 9 and India's 2 (IFR, 2014a).

A novel robotics field is the production and use of service robots in areas outside of manufacturing. This category includes robots intended for "professional use" in agriculture, mining, transport – including the large field of unmanned aerial and land vehicles, space and sea exploration, unmanned surveillance - health, education and other fields.[103]

The total number of professional service robots reached USD 3.6 billion in 2014, projected to lead the growth of upcoming robotic use.[104] The largest markets are Japan, the Republic of Korea, the US and Europe. The sectors leading their use are defense, logistics and health. Surgical robot device markets, at USD 3.2 billion in 2014, are anticipated to reach USD 20 billion by 2021.[105] In addition, robotics in personal and domestic applications, another novel robotics field, has experienced strong global growth with relatively few mass-market products, for example floor-cleaning robots, mowers, robots for education and assistive robots for the elderly.[106] With small to non-existent sales volumes even in 2012 and 2013, the sale of these robot types took off exponentially in 2014 and onwards.

A few consultancy reports have emphasized the wide range of savings generated through advanced robotics in healthcare, manufacturing and services, producing high estimates of the benefits to economic growth.[107] But quantifying the productivity-enhancing contribution of robots in definite terms is challenging.

Robots can increase labor productivity, reduce production cost and improve product quality. In the service sector in particular, robots can also enable entirely new business models. Service robots provide assistance to disabled people, mow lawns, but are also increasingly deployed in service industries such as restaurants or hospitals.

In terms of welfare, robots help humans to avoid strenuous or dangerous work. They also have the potential to contribute solutions to social challenges such as caring for the aging population or achieving environmentally friendly transportation.

103. See IFR.
104. IFR (2014b).
105. Wintergreen Research Inc. (2015).
106. IFR (2014b).
107. The McKinsey Global Institute estimates that the application of advanced robotics could generate a potential economic boost of USD 1.7 trillion to USD 4.5 trillion a year by 2025, including more than up to USD 2.6 trillion in value from healthcare uses (McKinsey Global Institute, 2013).

In part, the economic gains of robots are directly linked to substituting – and thus automating – part of the currently employed workforce.[108] On the one hand, more productive labor helps keep manufacturing firms competitive, avoiding their relocation abroad and creating higher-wage jobs. On the other hand, the use of robots is certain to eliminate both low-skilled but also some types of higher-skilled jobs hitherto unaffected by automation. On balance, the employment effect of robotics is currently uncertain, however.

In terms of overall economic benefits, another question is whether robotic innovation has diffused to low- and middle-income countries already with meaningful impacts. The installed base of robots outside a few high-income economies and a few exceptions such as China is still limited, including in countries such as Brazil or India, but in particular also in less developed economies. It is expected, though, that firms involved in manufacturing and assembly activities for global or local supply chains will need to upgrade their use of robots, including some in middle-income or even low-income economies that have so far competed on cheap labor alone. Robots are also gaining ground in low-income countries to address quality issues in local manufacturing.

3.3.2 – The robotics innovation ecosystem

As it evolves from the era of industrial automation to the use of advanced robotics across the economy, the present-day robotics innovation system can be characterized by a few key traits.

Concentration in key countries and narrow robotics clusters with strong linkages

Robotics innovation mainly takes place within a few countries and clusters.[109] These clusters thrive on the interface between public and private research, with firms commercializing the resulting innovation.

108. Metra Martech (2011), Miller and Atkinson (2013), Frey and Osborne (2013) and Brynjolfsson and McAfee (2014).
109. Green (2013).

An analysis of robotics company databases shows that robotics clusters are mainly located in the US, Europe – in particular Germany, France and to some extent the UK – and Japan, but increasingly also in the Republic of Korea and China.[110] Relative to GDP or population size, Canada, Denmark, Finland, Italy, Israel, the Netherlands, Norway, the Russian Federation, Spain, the UK, Sweden and Switzerland stand out as economies with a big presence of innovative robotics firms.

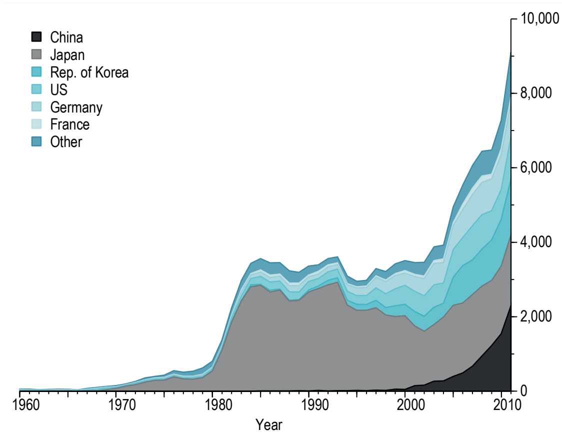
This picture of inventive activity concentrated in a few nations, also now broadening to include Asian innovative nations, is also mirrored by patent data. Figure 3.12 depicts the number of first patent filings worldwide in the robotics space between 1960 and 2012. It shows the importance of US and European and later Japanese inventors at the outset, the emergence of the Republic of Korea in the early 2000s and more recently China.[111] While the share of Chinese patents in total robotics patents in 2000 was only one percent, that figure had risen to 25 percent by 2011. The Republic of Korea's share stood at 16 percent in 2011. Japan's share fell from 56 percent in 2000 to 21 percent in 2011.

Within these few countries, robotics clusters are concentrated around specific cities or regions – and often around top universities in the field. For example, in the US, Boston, Silicon Valley and Pittsburgh are generally regarded as the three main robotics clusters. In Europe, the Île-de France region in France (particularly for civil drones), Munich in Germany, Odense in Denmark, Zurich in Switzerland and Robotdalen in Sweden are prominent, among others. In Asia, Bucheon in Korea, Osaka and Nagoya in Japan and Shanghai and Liaoning Province in China are key robotics clusters.

Some companies that excel in robotics innovation are located outside these clusters. They are usually established large companies in the automotive sector, or increasingly also Internet companies, that are well-established in their own field. They have the financial means and the skills to hire robotics experts and to use knowledge developed elsewhere, also often by acquiring newer firms.

Figure 3.12: Fast growth in robotics patenting, especially in the late 1980s and as of 2005

First patent filings by origin, 1960-2011



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

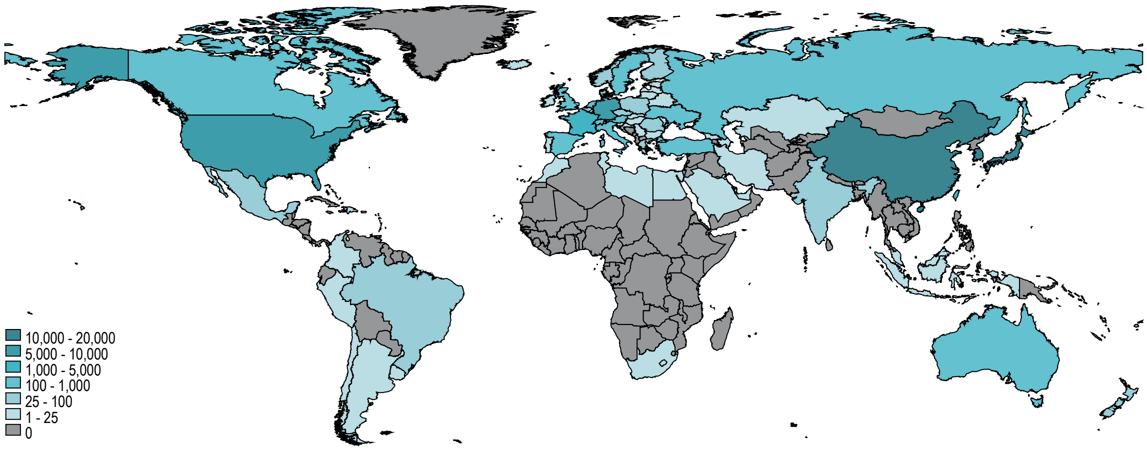
Figure 3.13 indicates the origin of first patent filers in 2000-2012. The countries with the highest number of filings are Japan, China, Republic of Korea and the US, which each filed more than 10,000 patents and together account for about 75 percent of robotics patents, followed by Germany with roughly 9,000 patents and France with over 1,500. Other countries such as Australia, Brazil, a number of Eastern European countries, the Russian Federation and South Africa also show newer robotics patenting activity, although on a low level.

Indeed, in terms of robotics innovation and company startups, the majority of activity is in high-income countries, except for China again. China has seen a strong surge of robotics patents and hosts some of the fastest-growing robotics companies such as DJI (Drone Company), and new industrial robot manufacturers such as Siasun and Estun which are driving down the cost of robots.

110. See Tobe (2015) at *www.therobotreport.com/map*.
111. See also UKIPO (2014).

Figure 3.13: Increasing but limited geographical diversity in robotics innovation

First patent filings by origin, 2002-2012



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

Highly dynamic and research-intensive collaborative robotics innovation ecosystem

The robotics innovation ecosystem comprises a tight and cooperative network of actors, including individuals, research institutions and universities, and large and small technology-intensive firms. Robotics brings together diverse science and technology breakthroughs to create new applications; while long established, it continues to deliver new inventions as new materials, motive power, control systems, sensing and cyber systems kick in.

As evidenced in section 3.3.1, individual entrepreneurs and their startups played a critical role in kick-starting and further developing the robotics industry.

Select public research institutions are also crucial actors in the robotics innovation ecosystem. Examples of leading universities include McGill in Canada, Carnegie Mellon in the US, ETH in Switzerland, Imperial College in the UK, Sydney University in Australia, Osaka University in Japan, and the Shanghai Jiao Tong University in China. PROs such as the Korean Institute of Science and Technology, Fraunhofer in Germany, the Industrial Technology Research Institute in Taiwan (Province of China) and the Russian Academy of Sciences are notable too.

Traditionally, these science institutions play an important role in innovation generally by conducting long-term research whose commercial applications will only be realized far in the future. In addition, however, in robotics specifically they had and continue to have a major role in furthering development by creating spin-outs and spin-offs, by patenting (see section 3.3.3), and through close collaboration with firms.[112] Examples of spin-offs include Empire Robotics, a spin-off of Cornell University, and Schaft Inc., a spin-off of the University of Tokyo. Collaboration between firms and PROs is tight too, with, for instance, KUKA developing lightweight robots with the German Institute of Robotics and Mechatronics. Furthermore, their increased offering of formal robotics degrees has been critical in the development and diffusion of skills, as corporations hire recent graduates.

When it comes to inventive robotics firms, three main types can be identified.

First, there are small company startups or specialized robotics firms which are often created by individual inventors affiliated to academic robotics centers or robotics clusters, sometimes with significant direct or indirect government support. An example is Universal Robots, which emerged from a robotics cluster in Demark with links to the Danish Technological Institute, receiving initial government and seed funding.

112. Nof (1999).

Although parts of the industry are more mature today, the potential for small robotics startups is still large. In the early stage of radical innovation, small startups demonstrate more agility and speed, and closer interaction with academia. Also, innovation ecosystems are becoming more specialized, allowing for niche specialist companies. Third-party external developers are increasingly part of the robotics innovation system, as robotics platforms, often based on open-source software architectures, are the starting point for further development. Also, a growing number of companies provide robotics-related services – mobility or machine management systems. Moreover, the rise of new, more consumer-oriented robotics firms and new funding mechanisms allow for small initial start-ups. Play-i, now called Wonder Workshop, for instance, which focuses on creating educational toy robots, recently raised money through crowd-funding platforms.

Second, large, established robotics companies, initially focused on industrial robot research and production alone, such as ABB (Switzerland), Kawasaki Heavy Industries, Yaskawa and Fanuc (Japan) and KUKA (Germany) are active in robotics R&D. Scale matters, as innovating in the field of industrial robotics hardware is particularly capital-intensive; research takes years to materialize. Large clients in the automotive sector, for instance, are only willing to buy from large, trusted, established companies to avoid safety risks. In addition, large robotics firms are emerging from the novel trend toward service and household robots. iRobot (US) is one such example. Initially a spin-off from MIT, it is now a large company producing robots for business, private households and for security purposes, but making most of its revenues from the development of military applications.

Third, large firms outside the robotics industry have also gained related competencies. Firms such as BAE Systems (UK) in the area of defense, aerospace and security have always and continue be important players for robotics innovation. In addition, firms in the automotive sector continue to be significant, not least due to their own important use of robots. A newer development is the increasing involvement of electronics and ICT firms such as Samsung (Republic of Korea) and Dyson (UK). As robotics becomes more reliant on connectivity and ICT networks, Internet or IT-related firms such as Amazon, Google and Facebook but also the Indian ICT services firm Infosys, Alibaba of China and Foxconn of Taiwan (Province of China) are joining the fray, often acquiring shares in or taking full ownership of established robotics firms. Moreover, firms in the health sector are also increasingly prominent in robotics research. Market leaders in the area of surgical robots, for instance, include Intuitive Surgical, Stryker and Hansen Medical.

Generally speaking, the exchange of knowledge within the robotics ecosystem currently seems extensive and fluid. This is benefited by the science-intensive nature of robotics innovation and the strong role of science and research institutions, but also the admittedly nascent phase of many advanced robotics strands. Scientific papers and conferences – such as the International Symposium on Industrial Robots – play a key role in the transfer of knowledge. Moreover, robotics contests and prizes rewarding solutions to specific challenges enable researchers to learn and benchmark their progress, and to close the gap between robotics supply and demand. Collaboration among the three types of firms mentioned above is extensive.

Finally, decentralized, software-enabled innovation is likely to increase in the future as robots become more widespread, and robot platforms and systems more standardized. In practice, a wider set of external firms and partners will be able to deliver customized solutions to existing proprietary robotic software platforms. This will enable greater modularity in innovation.

The substantial role of government in orchestrating and funding innovation

Governments and their institutions have played a large role in supporting robotics innovation. The standard set of technology-neutral government innovation policies has strongly supported robotics innovation, in particular through supply-side policies taking the form of research funding or support for business R&D.

Beyond important research funding and standard innovation support measures, a few specific support measures deserve mention:

Creation of special research institutions or research networks: Examples include the Swiss National Centre of Competence in Research Robotics, which federated research labs, and the Korea Robot Industry Promotion Institute, set up to promote technology transfer.

R&D funding, grants and public procurement: Governments, and often the military, fund robotics innovation and create demand by the means of grants or – often pre-commercial – procurement. In the US, R&D contracts, including from the National Institutes of Health or DARPA, are the foremost catalysts.[113] Pre-commercial procurement of robotics solutions for the healthcare sector, for instance, is part of EU Horizon 2020 grants.

Organizer of contests and challenges and prizes: Governments have played a role as organizer of robotics contests. Japan has announced a Robot Olympics, the UK recently held a competition for driverless vehicles and the DARPA Robotics Challenge is a landmark.

Incentives for collaboration, technology transfer, finance and incubation: Through grants or contracts, governments will frequently require collaboration and technology transfer. The EU Horizon 2020 Robotics project, for instance, stimulates public-private collaborative projects of a multi-disciplinary nature. In addition, government activities aim to facilitate cluster development, entrepreneurship and industry networking. Governments also ease the financing of robotics innovation, for example, the French government's seed fund "Robolution Capital".

Regulations and standards: Finally, regulations created by governments, in the form of standards, testing and security regulations, impact the diffusion of robotics technology.

In addition to the above, many high-income countries and China have announced special robotics action plans in recent years (see table 3.9). Mostly, these plans announce specific monetary investments in support of robotics research and innovation, including improving robotics education and technology transfer.

Table 3.9: National robotics initiatives

National Robotics Initiative Advanced Manufacturing Partnership	US (2011)
France Robots Initiatives/*Feuille de Route du Plan Robotique*	France (2013/2014)
Robotics project Horizon 2020	EU (2015)
New Industrial Revolution Driven by Robots ("Robot Revolution")	Japan (2015)
Next-Gen Industrial Robotization	Republic of Korea (2015)
Robotics technology roadmap in 13th Five-Year Plan (2016-20)	China (2015)

3.3.3 Robotics and the IP system

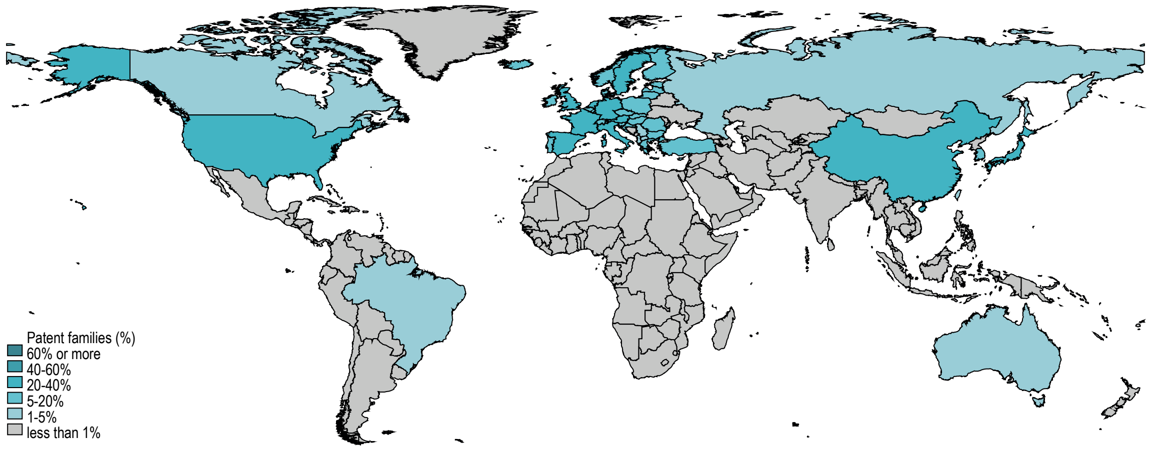
The focus of robotics innovation is shifting from industrial automation to more advanced robotics involving various technological fields, actors and economic sectors. As a result, related IP and other strategies to appropriate returns on innovation investment are embryonic; our understanding of them is incomplete.

Some tentative findings on appropriation strategies do, however, emerge on the basis of the existing literature, data and insights from industry practitioners and robotics researchers.

113. Mireles (2006), Springer (2013) and Siegwart (2015).

Figure 3.14: Robotics patenting focused on a few selected destinations only

Share of patent families worldwide for which applicants have sought protection in a given country, since 1995.



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

The increasing role of patents; their valuable function and potential challenges

Two forms of IP protection play a particularly important role in helping firms appropriate return on their investments in R&D: patents and to a lesser extent industrial designs protecting the ornamental features of a robot.

Key robotics inventions were frequently patented by their original – often academic – inventor, who often also started a corresponding company or actively transferred the IP to existing manufacturing firms.

As a result, robotics patents increased strongly in the late 1980s, as broad-based automation of factories flourished and robotics research was ramped up (see figure 3.12). Then, after relatively flat patenting activity between the 1980s and 2000, the shift to more advanced robotics has given another boost to robotics patenting which continues to this day.

Figure 3.14 shows that actual robotics patent exclusivity is geographically highly concentrated. Japan is the leading destination with around 39 percent of global robotics families having an equivalent there, followed by the US and China with close to 37 percent, Germany with 29 percent, other major European countries and the Republic of Korea. In turn, only 1.4 percent of robotics patent families have equivalents in low- and middle-income countries other than China.

Automotive and electronics companies are still the largest filers of patents relating to robotics (see table 3.10), but new actors are emerging from different countries and sectors such as medical technologies. These firms' robotics patent portfolios are growing in size, as firms grow them organically or purchase companies with a stock of granted patents.

Table 3.10: Top 10 robotics patent filers, since 1995

Company name	Country	Number of first patent filings
Toyota	Japan	4,189
Samsung	Republic of Korea	3,085
Honda	Japan	2,231
Nissan	Japan	1,910
Bosch	Germany	1,710
Denso	Japan	1,646
Hitachi	Japan	1,546
Panasonic (Matsushita)	Japan	1,315
Yaskawa	Japan	1,124
Sony	Japan	1,057

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

The large and growing stock of patents owned by universities and PROs is noteworthy too. Table 3.11 lists the most important patent holders, now largely dominated by Chinese universities. While industry experts note a strong move towards "open source" in the young generation of roboticists at universities, the IP portfolios of universities are also growing strongly, possibly facilitating the commercialization of new technologies as described in earlier sections, but possibly also creating new challenges for universities and PROs in managing and utilizing these sizeable portfolios.

Table 3.11: Top 10 robotics patent holders among universities and PROs, since 1995

Top 10 patenting worldwide			Top 10 patenting worldwide (excluding China)		
Shanghai Jiao Tong University	811	China	Korea Institute of Science and Technology (KIST)	290	Rep. of Korea
Chinese Academy of Sciences	738	China	Electronics and Telecommunications Research Institute (ETRI)	289	Rep. of Korea
Zhejiang University	300	China	National Aerospace Laboratory (now JAXA)	220	Japan
Korea Institute of Science and Technology (KIST)	290	Rep. of Korea	KAIST	188	Rep. of Korea
Electronics and Telecommunications Research Institute (ETRI)	289	Rep. of Korea	*Deutsche Zentrum für Luft- und Raumfahrt*	141	Germany
Tsinghua University	258	China	*Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung*	91	Germany
Harbin Engineering University	245	China	University of Korea	85	Rep. of Korea
National Aerospace Laboratory	220	Japan	Hanyang University	84	Rep. of Korea
Harbin Institute of Technology	215	China	Seoul National University	77	Rep. of Korea
KAIST	188	Rep. of Korea	National Institute of Advanced Industrial Science and Technology (AIST)	69	Japan

Note: Academic inventors file under their own name or the spin-off company name in certain countries. They are not captured here.

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

It is challenging to understand the various factors leading firms in the field of robotics to file for patents, given the current evidence base. No large-scale survey of robotics firms or other solid quantitative work exists that would shed light on this question. Providing a definitive answer on the impacts of robotics patents on follow-on innovation via disclosure, licensing and IP-based collaboration is also difficult.

However, a number of findings emerge from the views of industry experts, including both lawyers and roboticists.[114]

As in other high-tech sectors, and in anticipation of significant commercial gains from the robotics industry, robotics firms seek to use patents to exclude third parties, to secure their freedom to operate, to license and cross-license technologies and, to a lesser extent, to avoid litigation. For small and specialized robotics firms in particular, patents are a tool to seek investment or a means of protecting their IP assets defensively against other, often larger, companies.

In terms of the impacts of the patent system on innovation, at present the innovation system appears relatively fertile.[115] Collaboration – including university–industry interaction – is strong, and there is extensive cross-fertilization of research. Patents seemingly help support the specialization of firms, which is important for the evolution of the robotics innovation system.

114. Keisner *et al* (2015).
115. Keisner *et al* (2015).

It is also hard to argue that patent protection is preventing market entry or restricting robotics innovation more generally by limiting access to technology. The available evidence shows little or no litigation occurring in the field of robotics. Indeed, most of the disputes over robotics IP in the past 10 years have involved just one company, iRobot.[116]

The importance of particular patents for robotics innovation is hard to verify too. Currently, no patents have been flagged as standard-essential; no known patent pools exist in the area of robotics. And there are few formal and disclosed collaborations or exchanges in which IP is central. Only one major licensing deal in the recent history of robotics has received much attention.[117] That said, company acquisitions involving the transfer of IP are growing strongly.[118]

116. Keisner *et al* (2015).
117. Keisner *et al* (2015).
118. The most prominent agreement in recent history was the July 2011 joint development and cross-licensing deal between iRobot Corp and InTouch Technologies.

As regards disclosure, firms use patents to learn of new technology developments, to gain insight into competitors' plans to improve or create products, but also to learn if a competitor is attempting to obtain patent protection that should be challenged.[119] Forward patent citations within and outside robotics are often used as a sign that incremental innovation taking place; earlier inventions are built upon. Often, however, and in particular in the US patent system, they are a mere legal obligation, making impact assessment more difficult. As a result, the overall value of patent disclosure in the area of robotics remains largely unassessed.

Many of the above questions will only be resolved over time. Arguably, IP is not yet fully used in advanced robotics and so its potential impact remains to be realized. Compared with the standard industrial robot innovation of the past, today's robotic innovation system involves more actors, various technology fields and significantly more patent filings. One can start to see the more intensive offensive and defensive IP strategies that are present in other high-technology fields.[120]

A vital question is whether the increased stakes and commercial opportunity across various sectors will tilt the balance toward costly litigation, as in other high-tech and complex technologies. There have been cases – though not many to date – in which non-practicing entities have targeted robotics companies with a lawsuit.[121] In particular, press reports mention the possibility of negatively perceived patent troll activity in the field of surgical robots and medical robotics more broadly.[122]

Two elements could increase the likelihood of disputes. First, experts consulted in the course of research for this report have raised concerns that overly broad claims are being made in the case of robotics patents, especially with respect to older patents. Second, in certain countries the patentability and novelty of computer-related inventions generally are a matter of debate. This is particularly true in the US, where the recent Supreme Court decision in *Alice Corp. v. CLS Bank* seems to have reinforced a restrictive approach on the patent eligibility of software.[123] Given the large and growing software-related component of robotics innovation, concerns about software patentability may pose a challenge in relation to current and future robotics-related patents.

Robotics platforms and the coexistence of IP and open source

As described in section 3.3.2, robotics platforms used in universities and businesses are increasingly central to robotics innovation. Increasingly, too, they are open platforms, often based on open-source software such as the Robot Operation System (ROS). These open-source robotics platforms invite third parties to use and/or improve existing content without the formal negotiation or registration of IP rights. Instead, software or designs are distributed under Creative Commons or GNU General Public License, a free software license. This allows for rapid prototyping and flexible experimentation.

119. Keisner *et al* (2015)
120. Keisner *et al* (2015).

121. See the Siemens AG litigation with Roy-G-Biv. See also Hawk Technology Systems LLC filing suit against Fanuc Robotics Corp, and Sonic Industry LLC filing against iRobot Corp.
122. Sparapani (2015).
123. Thayer and Bhattacharyya (2014a, 2014b).

The idea is simple. Actors distinguish between two levels of innovation. On the one hand, there is the collaborative development of robotics software, platforms and innovation. Such innovation may be substantial, but it is essentially precompetitive because the fields of use are relatively basic and do not serve to differentiate products. Actors therefore apply cooperative open-source approaches to obtain common robotics platforms, as this allows them to share the substantial up-front investment, avoid duplication of effort and perfect existing approaches.

On the other hand, however, innovative firms invest in their own R&D efforts and look to protect their inventions far more vigorously when it comes to those elements of robotics innovation that differentiate end-products.

This parallel application of cooperative and competitive approaches results in a coexistence of competitive and open source-inspired approaches to handling IP.

Various non-profit organizations and projects support the development, distribution and adoption of open-source software for use in robotics research, education and product development. The iCub, for instance, is an open-source cognitive humanoid robotics platform funded by the EU which has been adopted by a significant number of laboratories. Poppy is an open-source platform developed by INRIA Bordeaux for the creation, use and sharing of interactive 3D-printed robots. Other examples include the Dronecode project and the NASA International Space Apps Challenge.

Some of this will entail an increasing shift toward engaging end-users or amateur scientists to interact and improve on existing robotics applications. In fact, many user-oriented low-cost platforms built for home or classroom use, like TurtleBot and LEGO Mindstorms, are built on open-source platforms.

This open-platform approach is not limited to software; it can also encompass blueprints such as technical drawings and schematics, including designs. The Robotic Open Platform (ROP), for instance, aims to make hardware designs of robots available to the robotic community under an Open Hardware license; advances are shared within the community.

In general, it will be interesting to see how well the robotics innovation system can preserve its current fluid combination of proprietary approaches for those aspects of IP where the commercial stakes are higher plus non-proprietary approaches to promote more general aspects of relevant science through contests but also collaboration among young roboticists and amateurs interested in open-source applications.

Protecting robotic breakthroughs via technological complexity and secrecy

Potentially more important than patents, the technological complexity and secrecy of robotics systems are often used as a key tool to appropriate innovation. This is true for standard mechanical, hardware-related components. Robotics companies that make a limited number of highly expensive robots, including for military applications, typically do not fear that competitors will gain physical possession of such robots to reverse engineer them. Algorithms and other advanced robotics features are also hard to reverse engineer.[124]

There are also historical reasons why robotics companies choose to retain information as trade secrets.[125] In the 1980s, robotics made several significant advances and firms filed a large number of patents (figure 3.12). However, few of these inventions were commercialized quickly. As a result, firms spent large amounts of money to obtain patents that expired before their products were commercialized. They learned from this experience that patents can be costly without necessarily bringing any reward, especially for innovations that may be decades away from use in a market-ready product.

Trade secret protection is also important when employee mobility is high. There have been a few instances where robotics companies have alleged infringement of trade secrets, particularly where an employee has accepted a position at a competitor.[126]

Finally, the more recent questions around the patentability of software in the US and elsewhere could increase the incentive to protect related inventions via secrecy instead.

124. McGurk and Mandy (2014).
125. Keisner *et al* (2015).
126. Two examples from 2013 are *ISR Group v. Manhattan Partners* and *MAKO Surgical v. Blue Belt Technologies*. See Keisner *et al* (2013).

The role of being first-to-market, reputation and strong brands

Being first to market, a strong after-sales service, reputation and brand have all been critical in past robotics innovation, and they remain so today – all the more so as the industry moves out of factories and into applications with direct consumer contact.

In the case of industrial automation, only a few trusted operators able to produce a large number of reliable robots and to service them dependably were in demand by automotive companies. Initially, Unimation dominated the supply of industrial robots; later, large firms such as Fanuc held sway.

While the landscape is more diverse today, being first and having a solid reputation and brand continue to be critical. Actors such as hospitals, educational institutions and the military will want to rely on experienced robotics firms and trusted brands. In the area of medical robot makers, examples are the DaVinci surgical robot, the CorPath vascular surgery robots and the Accuray CyberKnife Robotic Radiosurgery System. Even in fields related to military or similar applications, brands matter, as evidenced by the use of trademarks such as Boston Dynamics' "BigDog". But strong brands are particularly important when robots are sold directly to end-users; for example, the "Roomba vacuum cleaner" relies strongly on its trademark value.

Most robotics companies trademark their company names and robot names, with the result that a growing number of trademarks include the term "robot".[127] Furthermore, trade dress – also a source-identifying form of IP – is used to protect the total image of a robot.

Copyright

Copyright protection is relevant to robotics too, in several respects.

Unlike a more conventional machine, a robot can have its own distinct character and persona, which can be protected by copyright, trademarks and/or industrial designs. For example, a particular design of a robot or a component may qualify for copyright protection, while a soundtrack used by the robot can be protected under copyright.

127. Keisner *et al* (2015).

Furthermore, the source code and software that run a robot will often be protected by copyright. Indeed, the most common example where robotics companies seek copyright protection is for software code that is believed to be unique and original. In practice, robotics companies typically use copyright enforcement to prevent others from copying, or simply accessing, their computer code.[128] Aside from disputes among companies, and despite the fact that national legislation often provides for reverse engineering exceptions, copyright legislation has also been invoked when an amateur scientist decrypts and changes software code.[129]

What will happen to inventions or creative works produced by robots?

In the future, robots set to accomplish a task are likely to produce new solutions to problems and in so doing create physical or intangible products or outputs that could, at least in theory, by perceived as intellectual property – new inventions, creative works or trademarks, for instance.

This element of robotics innovation could raise interesting questions as to the set-up and boundaries of the current IP system. Are objects, software code or other assets created autonomously by a robot copyrightable or patentable? If so, how? And who would own these IP rights? The producer? The user of the robot? The robot itself?[130] Some countries such as Japan and the Republic of Korea are actually considering extending rights to machines.

A full legal assessment of this question relating to autonomous robot creation is beyond the scope of this report, but who owns the IP rights over creations produced by robots will surely be a matter of much future discussion.

128. Keisner *et al* (2015).
129. In the case of Sony's robotic-dog, Aibo, users broke the original software code, made modifications and circulated the new software to other consumers enabling the latter to "teach" the robot to dance and speak, among other things. See Mulligan and Perzanowski (2007).
130. Leroux (2012).

3.4 – Lessons learned

The case studies of 3D printing, nanotechnology and robotics offer diverse insights into the nature and ecosystem of three current innovations with breakthrough potential. As in chapter 2, many of the insights are specific to the technologies at hand, cautioning against drawing general conclusions. Nonetheless, it is worthwhile pointing to commonalities and differences between the three cases, which this final section seeks to do. It follows the structure of the cases studies, first focusing on the innovations' growth contribution, then on their ecosystems and finally on the role of IP.

Growth contribution

The three innovations discussed in this chapter have already left a mark on economic activity. Industrial robots started to automatize certain manufacturing activities long ago and nanotechnology already features in numerous electronic devices. How large is the potential for these two technologies as well as 3D printing to drive future growth?

There would seem to be substantial scope for these innovations to improve productivity in manufacturing. However, given the relatively small size of the manufacturing sector in most economies (see section 1.1), the resulting overall economic growth contribution may well be small. A more substantial growth effect may stem from new products resulting from these innovations that find application throughout the economy – especially in the service sector. In addition, as the case studies demonstrated, the growing use of 3D printers and intelligent robots may prompt the reorganization of supply chains, possibly with important efficiency gains. History suggests that various forms of complementary innovation, new business models and the development of new skills would all be required to realize the implied growth potential. In addition, the diffusion of these innovations will depend on the competitive dynamics, access to finance, standard-setting and technical regulations, among other determinants.

As described in section 1.5, some economists worry that today's new technologies do not generate a large demand for new investment – possibly contributing to the low interest rate environment in many advanced economies. Worries have most commonly been expressed in relation to ICTs, and it is difficult to assess how 3D printing, nanotechnology and robotics fare in this respect.[131] One could argue that none of these three technologies requires new capital-intensive infrastructure comparable to earlier GPTs such as the railway, cars, electricity, or telecommunications. However, much will depend on the shape, capability and range of use of the innovations. New powerful technologies that find wide application throughout the economy may well generate significant investment demand, including demand for intangible capital.

Much uncertainty also exists as to how the three technologies will disseminate to developing economies. To the extent that technologies such as 3D printing and robotics generate savings by reducing labor inputs, there may be less of an incentive to adopt them in economies in which labor costs are still relatively low. However, such incentives are bound to differ across industries and countries, and depending on how capital-intensive new technologies turn out to be. In addition, certain applications of the three innovations may well address special needs of developing economies. For example, 3D printers may have special uses in remote areas cut off from traditional distribution channels. Similarly, nanotechnology holds promise in improving food safety, biosecurity and environmental sustainability. If such promise is to be fulfilled, history suggests that it will be important for low- and middle-income countries to develop the necessary absorptive capacity to take advantage of any technological opportunity that arises.

131. See Baldwin and Teulings (2015).

Innovation ecosystems

Interestingly, the ecosystems in which the three innovations flourish show many similarities with the historical ones presented in chapter 2. Government funding has been crucial to advance the scientific knowledge frontier, laying the ground for companies to explore commercial opportunities. Governments have also played a role in moving promising technology from the research lab to the marketplace, especially by creating market demand. However, this role appears to have been more important for robotics than for 3D printing and nanotechnology, largely reflecting the use of robotics for national defense purposes. Competitive market forces have, in turn, been instrumental in providing incentives for private R&D, the adaption of new technologies for large-scale production and the development of products to meet the needs of different consumers. In addition, as in the historical cases, the ecosystem for the current innovations has seen increased specialization over time, partly in response to increasingly complex technological challenges and partly to focus on specific applications of technology.

However, there are also important differences. To begin with, the science system and formal linkages between scientific institutions and companies appear to be more important today than they were in the past. For example, the share of university patenting varies between 15 and 40 percent among the three technologies studied in this chapter. This may partly reflect policy efforts to better harness the results of scientific research for commercial development. However, those policy efforts arguably recognize the critical role that upstream research plays in enabling downstream technological progress.

In addition, while most public and private R&D remains concentrated in a relatively small number of economies, the set of innovating economies has widened over the past decade to include several East Asian economies. Given the size of its economy, the recent rise of China as a source of significant R&D investment is particularly noteworthy. The three case studies presented in this chapter show that Chinese entities actively innovate in the fields of 3D printing, nanotechnology and robotics. Interestingly, data on patent filings suggest that China's innovation landscape differs in one important way from other R&D-intensive economies: universities and PROs account for a substantially higher share of patenting in China than in most other economies, reaching as high as 80 percent for nanotechnology. This may suggest more limited R&D capacity in Chinese firms, which may imply a lower rate of technology commercialization. At the same time, as the historical cases have shown, a strong scientific base may, in the long term, spawn new firms and industries once technological breakthroughs occur.

The role of IP

Looking at the role of the IP system, again there appear to be both commonalities with and differences from the historical cases outlined in chapter 2. To begin with, just like their historical counterparts, innovators in 3D printing, nanotechnology and robotics have relied intensively on the patent system to protect the fruits of their research activities. While one must bear in mind the absence of truly counterfactual evidence, the three case studies suggest that the patent system has played a useful role in appropriating returns on R&D investment, promoting follow-on innovation through technology disclosure and facilitating specialization.

Notwithstanding the large number of patent filings, and concerns expressed by some observers about possible patent thickets, the number of conflicts surrounding IP rights appears to be relatively small. In the case of 3D printing and robotics, open-source communities have flourished alongside more proprietary approaches to knowledge management. Overall, the IP system appears to have accommodated and supported different knowledge-sharing mechanisms. At the same time, as with the early inventor clubs in the case of airplanes, social norms appear to be important in regulating knowledge sharing within different innovation communities today.

It is important to keep in mind, however, that many of the technologies discussed in this chapter are still at a relatively early stage of development and some have yet to see any commercialization. Once the commercial stakes become higher, history suggests that there may well be greater conflicts surrounding IP. Policymakers are thus well advised to ensure a continued balance in the IP system that incentivizes knowledge creation without unduly constraining follow-on innovation. As in the historical cases, courts may at some point confront far-reaching questions about the patentability of newly emerging technology. Such questions have already arisen, for example, in relation to the patentability of nanotechnology products that exist as a product of nature or the patentability of robotics software.

Another commonality with the historical cases concerns the patent landscapes in low- and middle-income countries. Although international commercial ties are stronger than they were a century ago, innovators in the three cases have overwhelmingly sought patent protection in the high-income countries where the bulk of 3D printing, nanotechnology and robotics innovation takes place. Only a small share of first patent filings in the relevant technological fields had equivalents in low- and middle-income economies. At face value, this distribution of IP filings again suggests that technology dissemination will be determined mainly by the degree of absorptive capacity of recipient economies.

Finally, the three case studies have brought to light several new considerations that are bound to shape IP policy in the future. These include the following:

- Copyright is becoming increasingly relevant for technological innovation. This first happened with the inclusion of software in the domain of copyrightable subject matter. As software has become an integral feature of many new technologies – including 3D printers and robots – so has the role of copyright widened. In addition, copyright can protect any kind of digital expression, including 3D object designs and the design of computer chips.[132] It is as yet unclear whether this trend just signifies a shift in the use of different IP forms or whether it raises fundamentally new policy challenges.
- The emergence of low-cost 3D printing has the potential to enable the easy reproduction of any object that may be protected by industrial design and possibly other IP rights. Will this development render the enforcement of those rights more difficult – as the digital revolution did for copyright protection of books, music, movies and other creative works? Such a scenario may still be far off and there are important differences between 3D printing and digital content copying. Nonetheless, as the discussion in section 3.1.3 argues, the experience from the digital content industry holds valuable lessons on how best to manage such a scenario.
- Trade secrets have always been an important – even if not highly visible – form of IP protection. Although the three case studies offer only suggestive evidence, there are reasons to believe that trade secret policy has become more important. This is mainly because the mobility of knowledge workers has increased.[133] Despite the easy availability of codified knowledge, people remain crucial to put such knowledge to effective use. Regulating how knowledge can flow with people thus shapes both innovation and technology dissemination outcomes.

132. See section 2.3.3 on the role of copyright in the protection of chip designs.
133. For evidence relying on inventors listed in patent documents, see Miguelez and Fink (2013).

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Acronyms

3D	Three dimensional
AFM	Atomic force microscope
AI	Artificial intelligence
ARPA-E	Advanced Research Project Agency-Energy
ASTM	American Society for Testing and Materials
AT&T	American Telephone & Telegraph
BEA	Bureau of Economic Analysis
CARG	Compounded annual rate of growth
DARPA	Defense Advanced Research Projects Agency
DNA	Deoxyribonucleic acid
EU	European Union
FDA	US Food and Drug Administration
FDI	Foreign direct investment
GDP	Gross domestic product
GPT	General purpose technology
IBM	The International Business Machines Corporation
IC	Integrated circuit
ICT	Information and communication technology
IDM	Integrated Device Manufacturer
IFR	International Federation of Robotics
IMF	International Monetary Fund
IP	Intellectual property
IPC	International Patent Classification
MAA	Manufacturer's Aircraft Association
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
NEC	Nippon Electric Company
OECD	Organisation for Economic Co-operation and Development
PC	Personal computer
PRO	Public research organization
R&D	Research and development
ROS	Robot operation system
SCPA	Semiconductor Chip Protection Act
SEM	Scanning electron microscope
STEM	Scanning transmission electron microscope
STL	Standard tessellation language
STM	Scanning tunneling microscope
TEM	Transmission electron microscope
TFP	Total factor productivity
TNO	Netherlands Organisation for Applied Scientific Research
TRIPS	Agreement on Trade-Related Aspects of Intellectual Property Rights
UK	United Kingdom
UKIPO	United Kingdom Intellectual Property Office
UN	United Nations
UN ECE	United Nations Economic Commission for Europe
US	United States of America
USD	United States dollar
USDA	US Department of Agriculture
USPTO	United States Patent and Trademark Office
VC	Venture capital
WIPO	World Intellectual Property Organization
XML	Extensible markup language

Technical Notes

Country Income Groups

This Report uses the World Bank income classification of 2014 to refer to particular country groups. The classification is based on gross national income per capita and establishes the following four groups: low-income economies (USD 1,045 or less); lower middle-income economies (USD 1,046 to USD 4,125); upper middle-income economies (USD 4,126 to USD 12,736); and high-income economies (USD 12,736 or more).

More information on this classification is available at *http://data.worldbank.org/about/country-classifications*.

Patent Mappings

The case studies in chapters 2 and 3 rely on mappings of patents developed especially for this report. The patent data for these mappings come from the WIPO Statistics Database and the EPO Worldwide Patent Statistical Database (PATSTAT, April 2015). Key methodological elements underlying the mapping exercise include the following:

Unit of analysis

The main unit of analysis is the first filing of a given invention.[134] In consequence, the date of reference for patent counts is the date of first filing. For some historical records – for example, those older than 1930 for USPTO documents – the application date is missing. In such cases, the date of the earliest subsequent filing or the grant date of the first filing has been used. The origin of the invention is attributed to the first applicant of the first filing; whenever this information was missing an imputation strategy has been applied, as described further below.

The only departure from this approach occurs when analyzing the share of patent families requesting protection in each patent office (see figures 2.6, 3.5, 3.10 and 3.14). In this case, an extended patent family definition – known as the INPADOC patent family – has been used instead of the one relying on first filings. In addition, only patent families with at least one granted application have been considered for this analysis, and the date of reference is the earliest filing within the same extended family. The main rationale for using the extended patent family definition and imposing at least one granted patent within the family is to mitigate any underestimation issuing from complex subsequent filing structures, such as continuations and divisionals, and from small patent families of lower quality such as those filed in only one country and either rejected or withdrawn before examination.

134. Mappings include data on utility models whenever available.

Imputing country of origin

When information about the first applicant's country of residence in the first filing was missing, the following sequence was adopted: (i) extract country information from the applicant's address; (ii) extract country information from the applicant's name (see further below); (iii) make use of the information from matched corporations (as described further below); (iv) rely on the most frequent first applicant's country of residence within the same patent family (using the extended patent family definition); (v) rely on the most frequent first inventor's country of residence within the same patent family (again, using the extended patent family definition); and (vi) for some remaining historical records, consider the IP office of first filing as a proxy for origin.

Cleaning applicant names and assigning applicant types

Applicants have been categorized in three broad categories: (a) *Companies*, which includes mostly private companies and corporations, but also state-owned companies; (b) *Academia and public sector*, which includes public and private universities (and their trustees and board of regents), public research organizations, and other government institutions such as ministries, state departments and related entities; (c) *Individuals*, which includes individual first applicants who may or not be affiliated with companies, academia or other entities. A further category, (d) *Not available,* includes all unclassified first applicants.

In order to assign broad type categories to each first applicant, a series of automated steps were performed for each of the six innovation fields underlying the case studies, to clean and harmonize applicant names. The results of this automated process were cross-checked manually – particularly for the top applicants of each type – prompting revision of the strategy and adjustment of parameters in several iterations.

The starting point was the original information about the first applicant's name from the first filing. When this name was missing, the most frequent first applicant's name within the same patent family using the extended definition was considered. This list of improved first applicants' names was automatically parsed in several iterations in order to: (i) harmonize case; (ii) remove symbols and other redundant information (such as stop words and acronyms); (iii) remove geographical references (used to improve information on applicants' country of residence); and (iv) obtain any valuable information on applicant names meeting criteria to be considered as (a) *companies* or (b) *academia and public sector* types.

Subsequently, a fuzzy string search was performed – using Stata's *matchit* command[135] – in order to detect alternative spellings and misspellings in applicant names, and the types were propagated accordingly. In addition, the results of corporation consolidation (see below) also permitted recovery of some unclassified applicant names as *companies*. Finally, the category *individuals* was imputed only to remaining unclassified records when they either appeared as inventors in the same patent or were flagged as individuals in the WIPO Statistics Database for patent families containing a PCT application. Analysis of the unclassified records indicates that most of them have missing applicant names in PATSTAT. Most of these missing names refer to original patent documents not in Latin characters and without subsequent patent filings.

Consolidation of applicants

The rankings provided for the three current innovations presented in chapter 3 consolidate the patent filings of different first applicants. Manual examination and consolidation was performed for the most frequent applicants in each innovation case study. Applicants sharing a common ultimate owner were consolidated into one. In the case of the top 30 companies for each innovation, the ownership profiles in the *BvD Ownership Database* were used. Only subsidiaries that were directly or indirectly majority owned were taken into account in the consolidation.

Mapping strategies

The patent mapping strategy for each of the six innovations is based on existing evidence and experts' suggestions. Each strategy was tested against existing alternative sources whenever possible.

135. Available at the Statistical Software Components (SSC) archive and from the WIPO website.

The 3D printing mapping is based on the seminal work by the UKIPO[136] combining CPC and IPC symbols – for example, B29C 67/005 and B22F – with text terms sought in titles and abstracts, such as *additive manufacturing*, f*use deposition model*, s*elective laser sintering* and *stereolithography*.

The airplane mapping is based on existing lists of patents compiled in seminal work by Meyer (2010) and Short (2015), and public documents on the MAA patent pool and the Curtiss-Wright patent portfolio.[137] These patents made it possible to determine and assess the most relevant IPC and CPC symbols, namely B64C and B64B.

The antibiotics mapping is based on a novel combination of CPC and IPC symbols – for example, A61K 31/18, A61K 31/43 and A61K 31/7036 – with an extensive list of text terms searched for in titles and abstracts, such as *sulfa drug*, *penicillin* and *streptomycin*, among many others. The list of terms was compiled from the WHO ATC/DDD Index 2015, the Merck Index (15th edition) and the FDA's Orange Book, among other sources.

The nanotechnology strategy is based on the IPC and CPC symbols B82Y and Y10S 977, including lower levels of these. The distinction between *research tools*, *nano-electronics* and *nano-materials* exploits these lower levels.

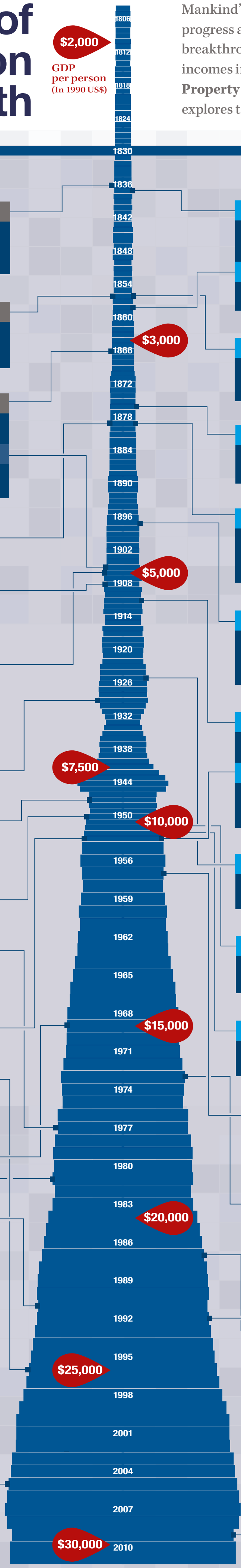
The robotics strategy is adapted from the seminal work by the UKIPO[138] combining CPC and IPC symbols – for example, B25J 9/16 and Y10S 901/00 – with text terms searched for in titles and abstracts, such as *robot* and *robotics*.

The semiconductor mapping is based on the IPC and CPC symbol H01L, including all lower levels.

136. See UKIPO (2013) *3D Printing: A Patent Overview*. Newport: UK Intellectual Property Office.
137. Meyer, P. B. (2010). *Some Data on the Invention of the Airplane and the New Airplane Industry.* Unpublished manuscript. Office of Productivity and Technology, US Bureau of Labor Statistics, Washington, DC, US. Short, S. Simine's US Aviation Patent Database 1799-1909. Retrieved August 25, 2015, from *http://invention.psychology.msstate.edu/PatentDatabase.html*
138. See UKIPO (2013) *Eight Great Technologies: Robotics and Autonomous Systems – A Patent Overview.* Newport: UK Intellectual Property Office.

200 Years of Innovation and Growth

Mankind's pursuit of innovative solutions has powered human progress and transformed our world. Two centuries of breakthrough innovations have seen a 15-fold growth in per capita incomes in frontier economies. WIPO's **2015 World Intellectual Property Report** looks at six transformative technologies, and explores the role of intellectual property in innovation.



1836 Steam Locomotive
1st numbered US patent on the *locomotive steam-engine*

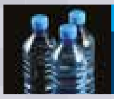


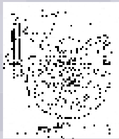
Photo: Depositphotos.com

1856 Plastics
1st man-made plastic invented, patented and trademarked as *Parkesine*

Photo: Depositphotos.com

1866 Scientific Plant Breeding
Mendel's scientific publication on plant hybridization

1905
First succesful high-yielding wheat hybrid



1879 Automobiles
Benz patents *Vehicle with gas engine*

1908
Ford mass-produces the *Ford T*

Photo: John T. Daniels (US Library of Congress)

1906 Airplanes
Santos-Dumont flies his *14-bis*
Wright brothers patent the *Flying machine*

Photo: © IWM (TR 1468)

1929 Pharmaceuticals
Fleming discovers *Penicillin*

1947
Mass production of *Penicillin*

Photo: Frank Hoffman, DOE

1950 Semiconductors
Bell Labs' *Semiconductor patent*

1977
1st Commodore PET sold

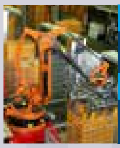


Photo: KUKA Roboter

1954 Robotics
1st industrial robot

1996
Deep Blue beats chess master Kasparov

Photo: Depositphotos.com

1969 Internet
ARPANET network deployed

1991
WWW is created at CERN

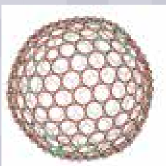


Photo: Depositphotos.com

1981 Nanotechnology
Scanning probe microscopy developed

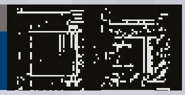
2005
Bicycle with nanotubes frame in the *Tour de France*

1837 Electric Telegraph
Cooke and Wheatstone patent the *Five needle telegraph*

1858
1st transatlantic telegraph message

Photo: Geni

1856 Industrial Steelmaking
Bessemer patents an *Improvement of the manufacture of iron and steel*



1876 Telephone
Bell patents *Improvement in telegraphy*

1879 Electric Lamp
Edison patents the *Electric lamp*

1897 Radio
Marconi patents *Transmitting electrical signals*

Photo: Smithsonian Institution

1911 Nuclear Energy
Marie Curie wins her 2nd Nobel Prize

1954
Nuclear plant APS-1 generates electricity for commercial use

Photo: Wellcome Library, London

1925 Television
Jenkins patents "*Transmitting pictures by wireless*"

1952 Supply Chain Innovations
Barcode patented

1953 Just-in-time Manufacturing
Toyota implements *Kanban* for lean production

1957 Sustainable Energy
Solar cells are patented

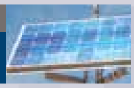


Photo: Depositphotos.com

1973 Mobile Phone
1st mobile telephone call

1992
1st SMS sent

Photo: Rico Shen

1987 3D Printing
Industrial 3D printers commercialized

2009
Low-cost 3D printers commercialized

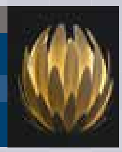


Photo: WIPO

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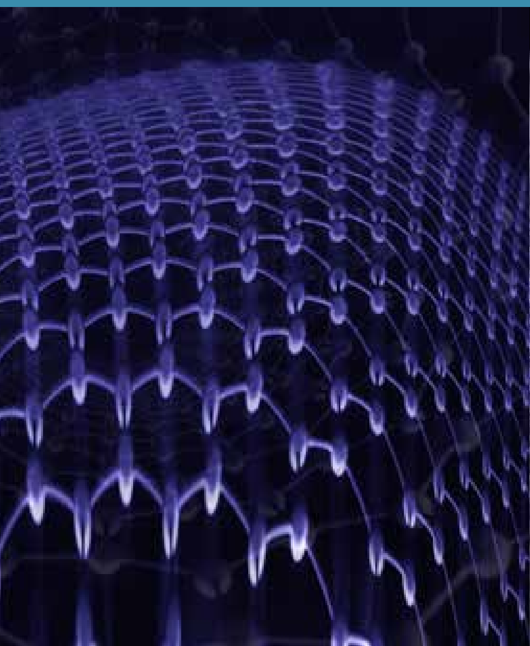
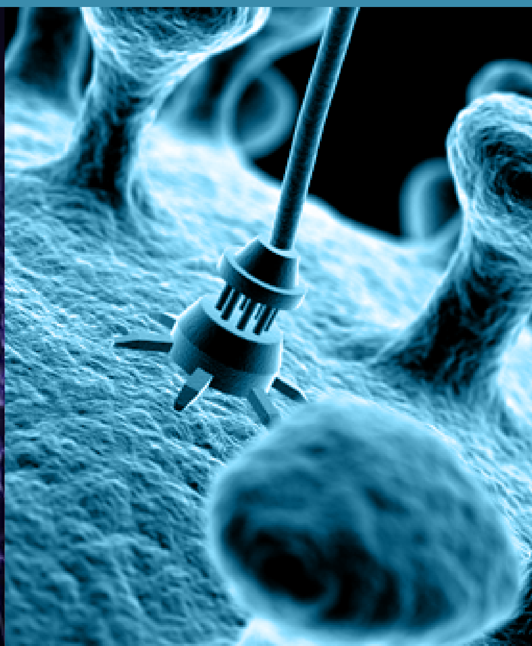


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