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]

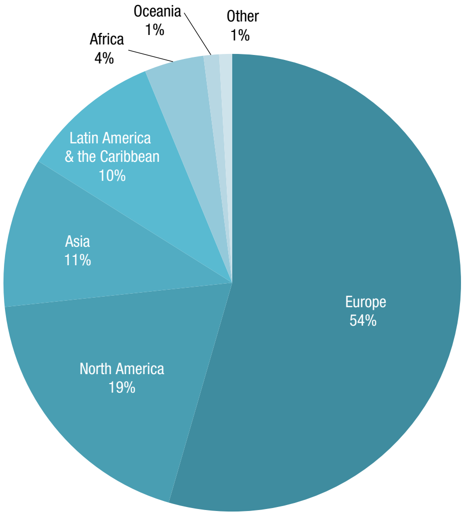
As for the personal 3D printing market segment, the development of open-source 3D printing initiatives and the expiry of related patents have lowered the cost of printers, making them more accessible (see subsection 3.1.3 on the role of patents).[8] Low-cost printers and fabrication labs for personal 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.

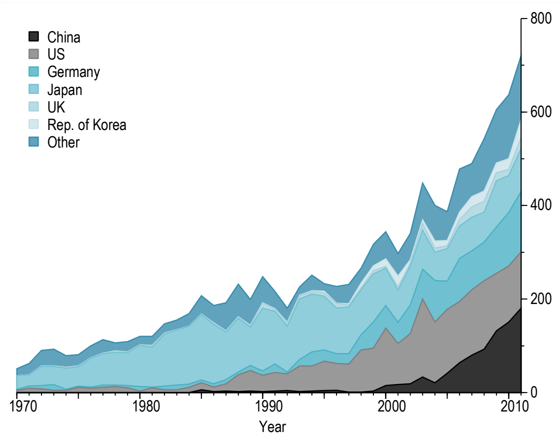
Figure 3.2 shows the evolution of patent filings over the years by applicants' residence in the top six countries. In the early 1980s, Japanese applicants were prolific in filing for patents on their 3D printing inventions, but by the 2000s they had been overtaken by US applications. By 2010, Chinese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

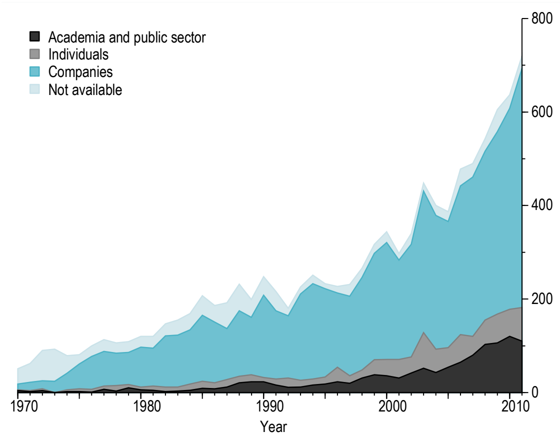
First patent filings by origin, 1970-2011



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.

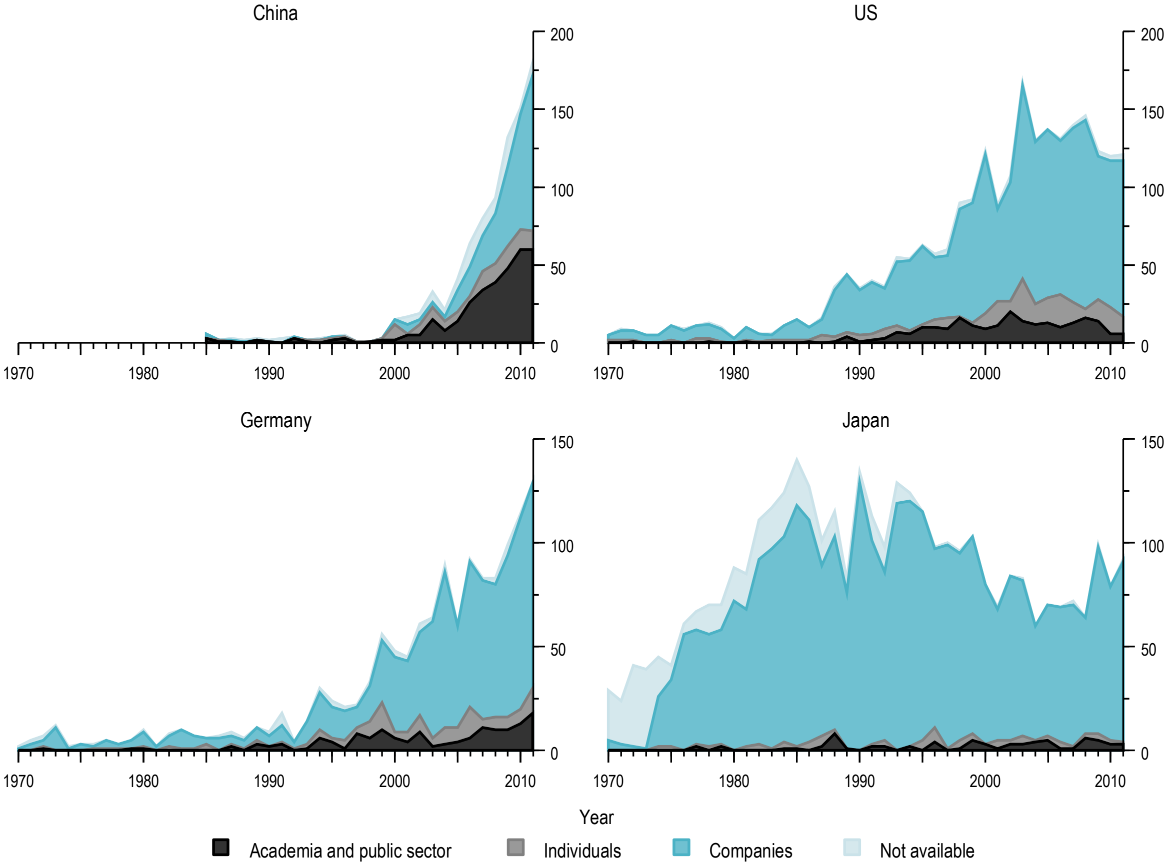
Within this ecosystem, innovative advances can come from consumers as well as the firms producing 3D printers.[34] Users can explore new applications for 3D printers and the few that are sophisticated enough may even be able to alter and improve upon existing hardware and software. This user role in 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.

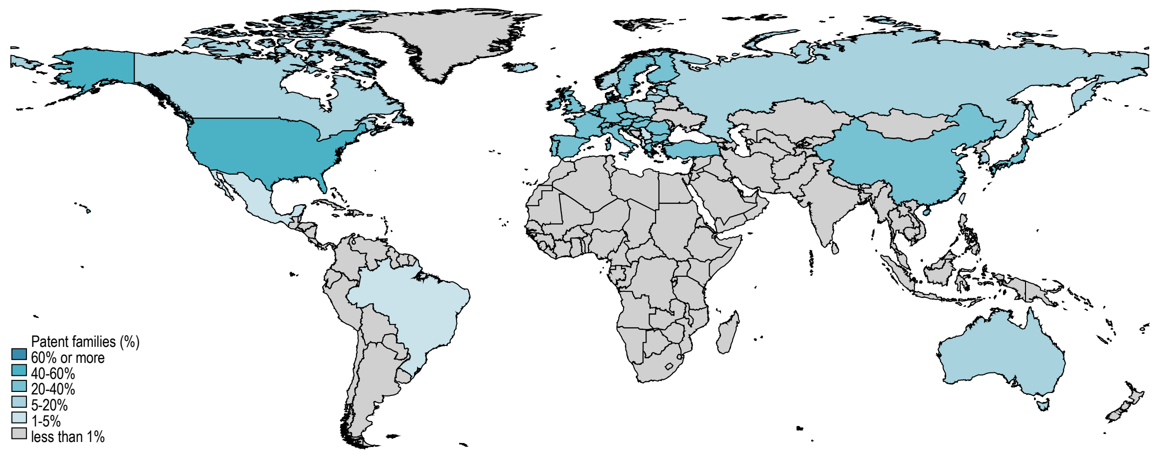
How important patents may have been to prevent rivals from imitating the technology is difficult to ascertain. For one thing, 3D printing systems – both in the industrial and personal market segments – are relatively difficult to reverse engineer.[41] Even the raw materials, which tend to be proprietary, 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.

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.

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).

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

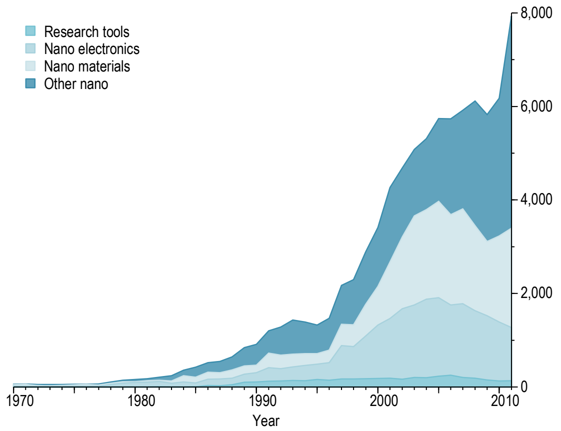
In which ecosystem does nanotechnology flourish? As a first step, it is useful to look at the patent landscape for nanotechnology. While not offering a perfect mirror of the innovation landscape, patent data provide rich information about some of the key innovation actors – especially those involved 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).

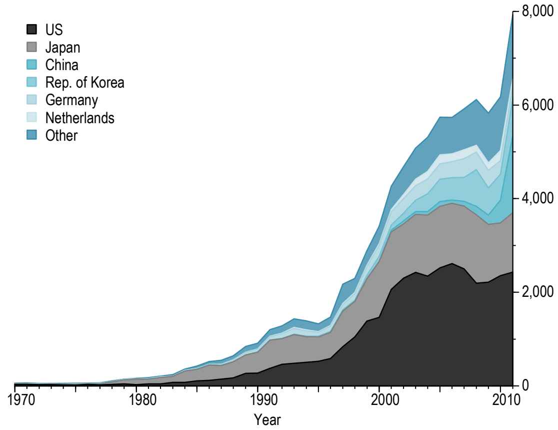
Figure 3.7 shows the same patent filings as figure 3.6, but offers a breakdown by origin of the patent applicant. It shows increasing geographical diversity. Up to the late 1990s, US and Japanese residents accounted for most nanotechnology patent filings, but since then other origins have gained in importance. 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

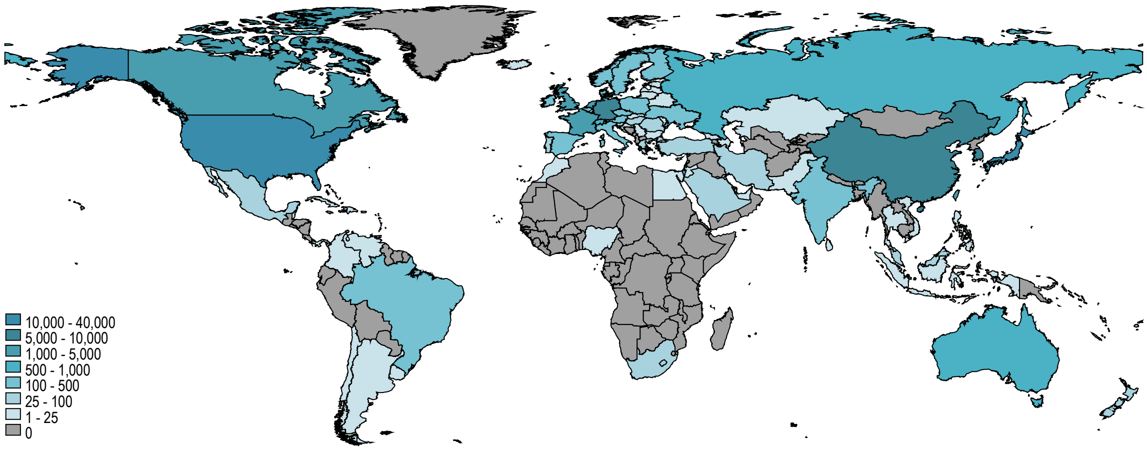
Governments support innovation in nanotechnology through a variety of mechanisms, including direct R&D spending using grants and procurement contracts, innovation prizes and R&D tax incentives. Quantifying the importance of these mechanisms is not straightforward. Available data sources often do not 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

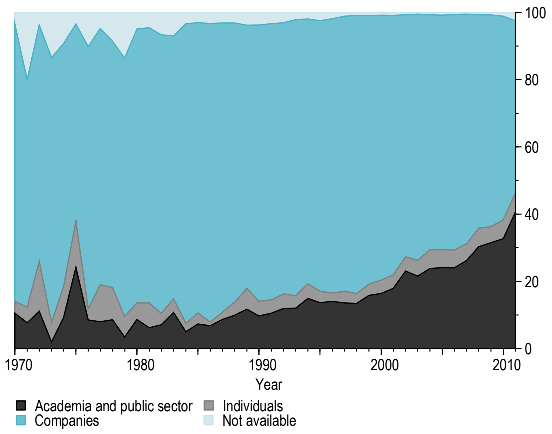
First patent filings by origin, since 1970



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.

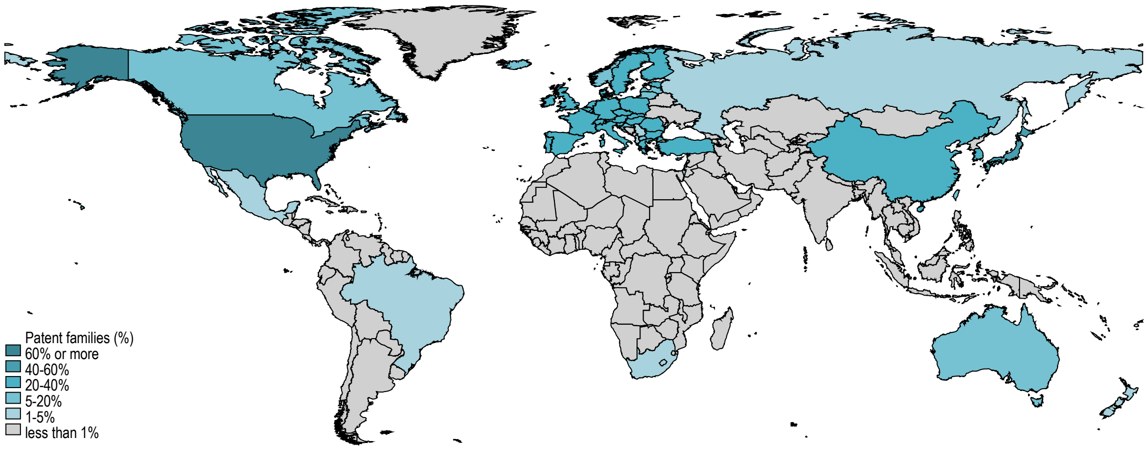
75. This figure refers to nanotechnology patents filed since 1995.

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]

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.

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).
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.

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

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,

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)

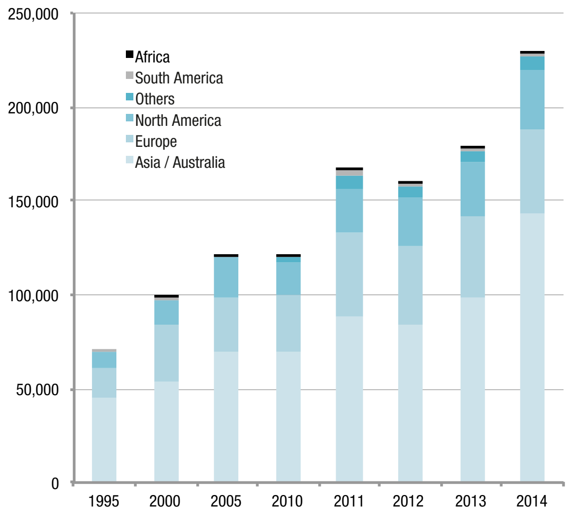
As illustrated by figure 3.11 (top), the number of robots sold is increasing, reaching about 230,000 units sold in 2014, up from about 70,000 in 1995, and projected to increase rapidly in the next few years. Japan, US and Europe were the initial leaders in terms of market size.

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]

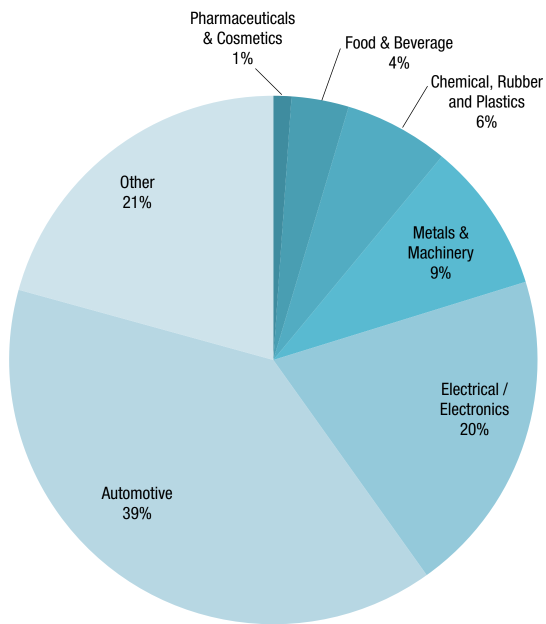
In terms of sectors, the automotive industry continues to be the main driver of automation, followed by the electronics industries (see figure 3.11, bottom). Innovation will enable more flexible and small-scale manufacturing.

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.

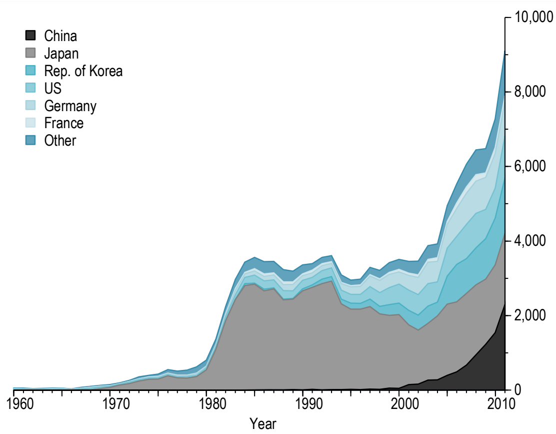
This picture of inventive activity concentrated in a few nations, also now broadening to include Asian innovative nations, is also mirrored by patent data. Figure 3.12 depicts the number of first patent filings worldwide in the robotics space between 1960 and 2012. It shows the importance of US and European 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).

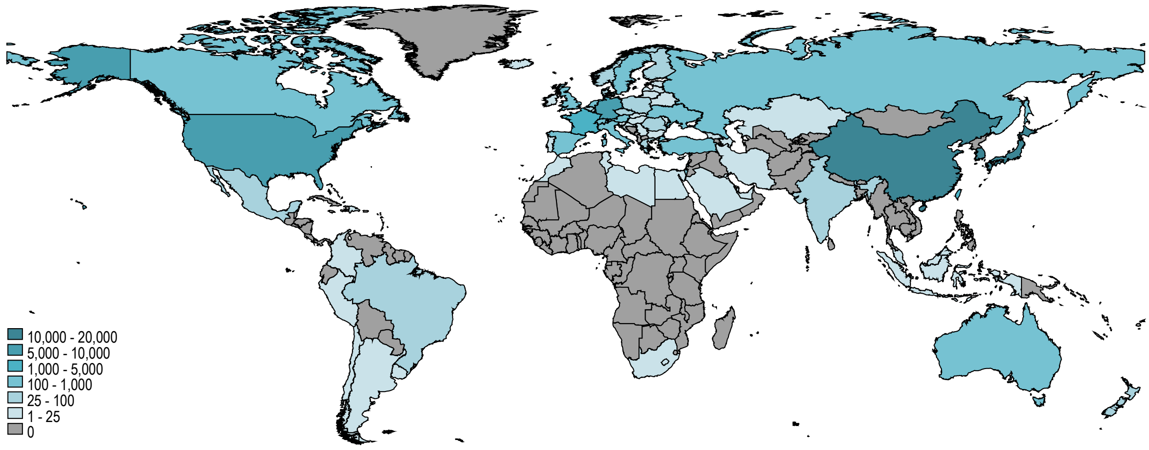
Figure 3.13 indicates the origin of first patent filers in 2000-2012. The countries with the highest number of filings are Japan, China, Republic of Korea and the US, which each filed more than 10,000 patents and together account for about 75 percent of robotics patents, followed by Germany with roughly 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

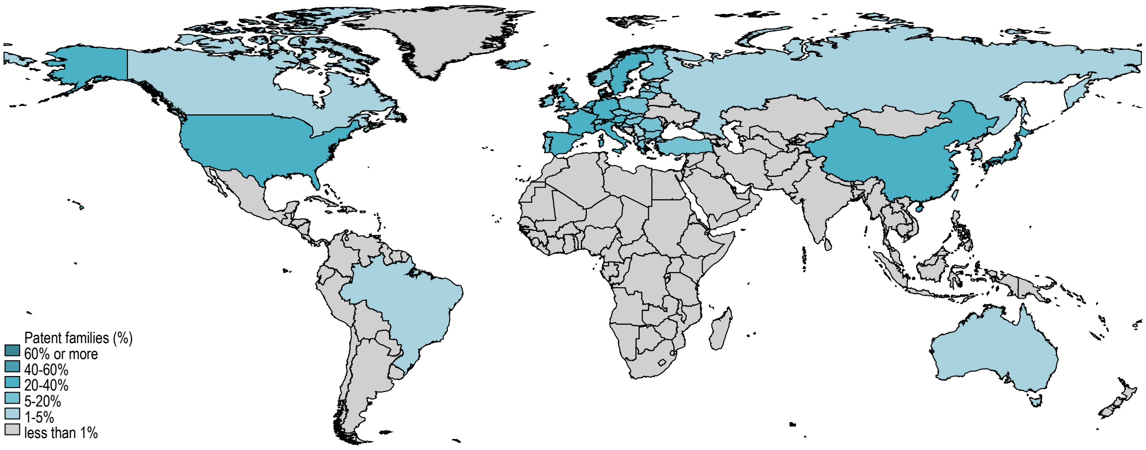
The focus of robotics innovation is shifting from industrial automation to more advanced robotics involving various technological fields, actors and economic sectors. As a result, related IP and other strategies to appropriate returns on innovation investment are embryonic; our understanding of them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

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.

127. Keisner *et al* (2015).

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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