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Technology strata: A framework distinguishing between technologies

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Summary

- The term technology conflates various technological entities by grouping them according to their underpinning science or application sector. This often leads to ambiguity that can negatively impact government technology strategies and lead to suboptimal composition and size of R&D investments as each technology type has its own unique problems and needs. Thus, **a common framework distinguishing between technological entities** has wide ranging implications for innovation policy.
- There are **several technology strata** as technological entities evolve over time, starting from underpinning science, through the application of scientific principle into a core technology and integration into a larger system forming an integrated technology, which then can have different final use applications.
- **Final use applications** are highly dependent on one's **frame of reference**. These include solutions (product/service) technologies, process technologies, R&D and engineering tool technologies, external infrastructural technologies – where the latter three groups play a vital role in technology lifecycles as they feed back into technology development despite often being neglected during strategic development.
- **Interdependencies** between these strata are based on a shared and evolving knowledge and technology base, which is why at the highest level of generalization, there is the **technology family** that encompasses these different technology strata.

1. The problem: There is a need to differentiate between technology strata

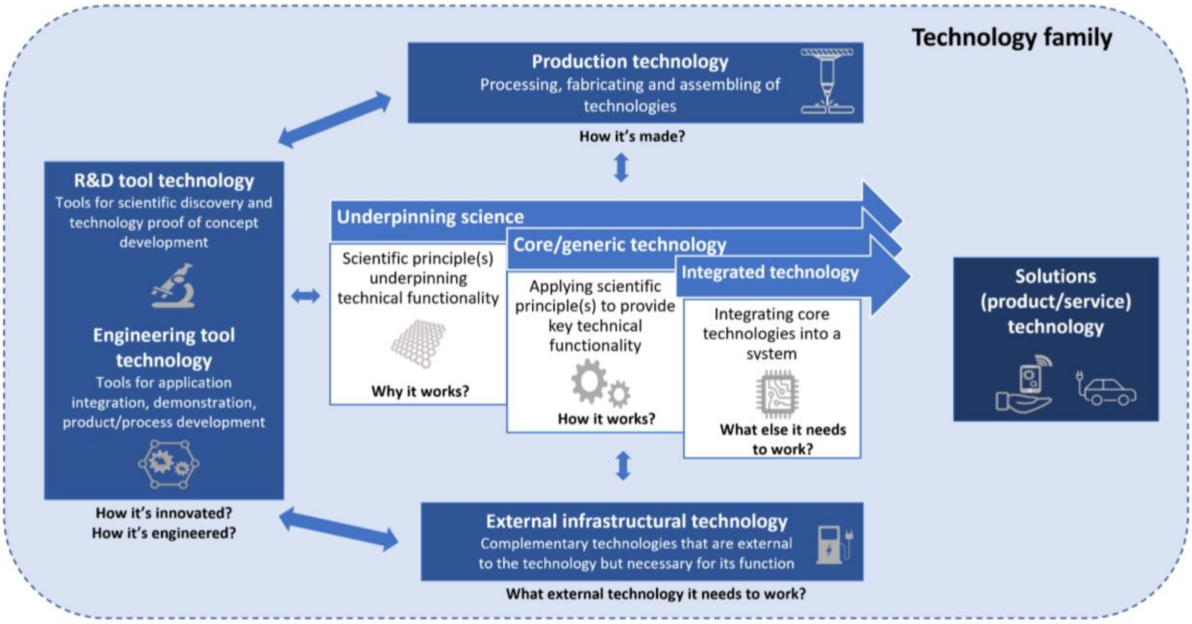
Is a smartphone at the same level of generalization as a microchip, a transistor, a scientific principle underlying semiconductor material, a photolithography machine, or a laser dicing machine? What about an ultra-responsive hearing aid, a pressure sensor, engineered graphene, or an atomic force microscope? This list suggests that technologies, or more precisely **technological entities** understood as self-standing physical and non-physical devices, processes and scientific knowledge resulting from created competence, can be grouped into a number of logical and distinct categories. **They can be grouped according to technology strata through which they evolve and draw upon during their lifecycle** yet distinctions between these strata are rarely made in both informal and formal communication. This ambiguity especially when referring to emerging and complex technologies can lead to miscommunication between the wide range of actors that take part in innovation and industrial processes. Furthermore, as each technology stratum faces its own unique challenges with specific needs, uncertainty around terminology can negatively impact the speed and efficiency of developing technologies and relevant industries, for example, through suboptimal composition of R&D funding due to inappropriate strategizing across different technology strata. There is a need to deconstruct technology to its basic levels and to create a common vocabulary to clarify which is at focus with potentially wide-ranging implications for those involved in funding, developing, manufacturing, and using technologies.

2. The technology strata framework

As shown in Figure 1, the framework proposed here suggests that every technological entity evolves through and can be classified across different technology strata starting from its *underpinning scientific principles*, through the application of this principle into a *core technology* and integration into a larger system forming an *integrated technology.* Technologies can furthermore have different final use applications, but their classification is highly dependent on one's frame of reference. Some technologies become *final use technologies* in the solutions (product/service) technology sense – e.g., a smartphone or an ultra-responsive hearing aid. Others become production technologies, R&D and engineering tool technologies, or external infrastructural technologies – all playing a vital role in other technology lifecycles despite often being neglected during strategic development.

The highest level of generalization comprises the *technology family*, which encompasses various technology strata that share a common and evolving knowledge and technology base due to a common feature. The common feature can come from underpinning science and engineering (e.g., nanotechnology, biotechnology, advanced materials) or an application area (e.g., renewable energy generation, medical imaging, advanced manufacturing) depending on the direction from which innovation is stimulated. Families of technologies are particularly important as references to technologies are usually made at this level across government technology strategies. For example, critical technologies in the UK Science & Technology Framework (DSIT, 2023), technology families in the UK Innovation Strategy (BEIS, 2021), critical and emerging technologies in the US Critical and Emerging Technologies List Update (NSTC, 2022) or key enabling technologies of the European Commission (European Commission, n.d.) – all refer to emerging technology families as opposed to an individual technological entity yet no previous theoretical conceptualizations are available.

Figure 1 Simplified framework distinguishing between technology strata and final use applications.



Notes: The number of technology strata increases horizontally with increasing complexity of the final use application and vertically with increasing top-level boundary. The organization of framework parts depends on systems complexity and frame of reference.

As presented in Table 1, there are at least four dimensions on which technology strata differ: 1. economics of innovation – i.e., the public-private good content of technologies with implications for the role of different actors in developing and funding technology; 2. resources and capabilities needed for R&D and production; 3. stage in technology, product or industry lifecycle; and 4. technology complexity. As each dimension can have several degrees, this could easily lead to a many-dimensions matrix of technology types, but instead a simplified yet comprehensive version of technology strata distinguishing on these dimensions is presented in the above framework. The last section (Section 7) elaborates on these dimensions in more detail and shows that differentiating between technology strata has wide-ranging implications for strategic development and competitive advantage.

Table 1   Dimensions on which technology strata differ.

Dimension	Degree		
Public-private good content of technology	Public	Quasi-public	Private
Underlying resources and capabilities	Research	Technology engineering	Manufacturing
Maturation - **Technology** - **Product** - **Industry**	Lifecycle_t	Lifecycle_{t+1}	Lifecycle_{t+n}
Technology complexity	Simple	Intermediate	Complex

3. Background

There exist many conceptualizations of how a technological innovation proceeds from research laboratories to the market, whether that is from an evolutionary (i.e., technological trajectories, lifecycles), systems (i.e., innovation systems) or management (i.e., readiness levels) perspective. There are also various definitions of what constitutes a technology and technological innovation. Yet, references to different technology strata are often made colloquially using the same broad terms, e.g., semiconductors, chips, biotechnology, nanotechnology, artificial intelligence (AI), big data. However, the use of these terms suggests that a technology is a homogeneous entity omitting consideration for its changing and dynamic nature. During the lifecycle of a technology and industry emergence, technological entities evolve through different strata, in an iterative and recursive process drawing upon each other and forming through combinations and integration (Arthur, 2006; 2009; Schumpeter, 1934).

Consider the example of a multifunctional product technology – a smartphone. It is made up of various self-contained technological entities such as a microchip, battery, operating system, touch screen, etc. that do not particularly have a specific use on their own. While references are often made to the 'smartphone', its building blocks are based on different underpinning science, core technology, tool technologies, production technologies and external infrastructural technologies (see Figure 2). A microchip exploits the physical and chemical properties of semiconductor materials as its underpinning science, transistors as its core technology, photolithography machines as one of its production technologies or electron microscope as one of its R&D and engineering tool technologies. While a battery is based on the flow of electrons between electrodes as a result of a chemical reaction as its underpinning science, the electrochemical cell as its core technology, the roll-press for manufacturing batteries, etc.

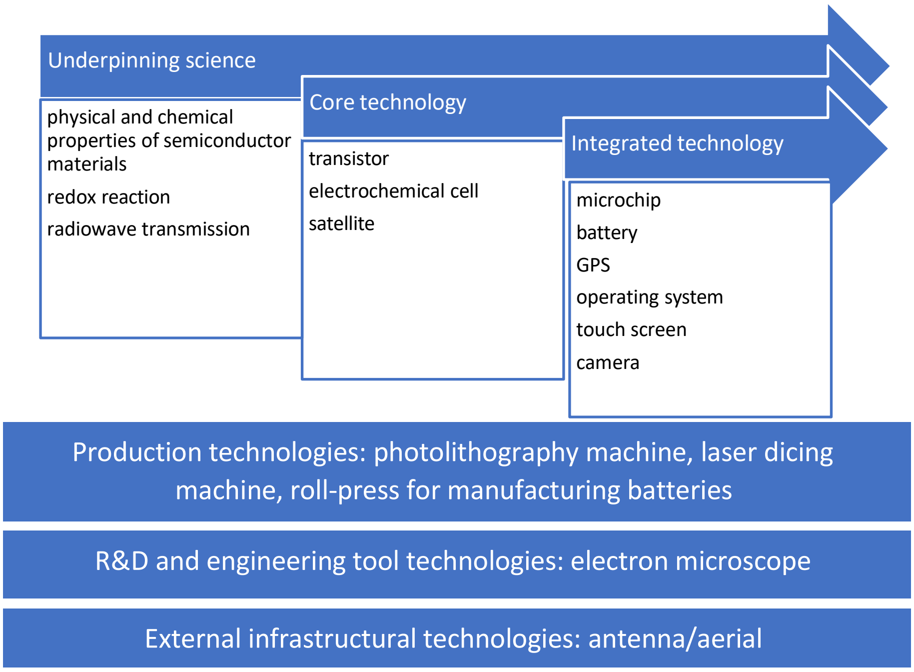


Figure 2 A non-exhaustive list of different technology strata making up a multifunctional product technology – a smartphone.

4. Existing definitions of technology

Definitions of technology often start with a list of elements that make up technologies followed by a statement describing technology as a means to fulfil a certain purpose. For example, Brooks (1980) defines technology as a 'subset of knowledge that includes the full range of devices, methods, processes, and practices that can be used to fulfill certain human purposes in a specifiable and reproducible way'. Similarly, Arthur (2009) refers to technology as 'a means to fulfil a human purpose', 'an assemblage of practices and components' or 'the entire collection of devices and engineering practices available to a culture'. These definitions list the different elements necessary to develop a new technology that are intrinsically also technologies or knowledge, however they do not provide a systematic view of these elements that indeed are very different in their nature.

For example, the *science underpinning final use technology X* can be distinct from the *science underpinning its production technology Y* and therefore may require different research knowledge base, facilities, tools, standards, test equipment, materials, skills, and the involvement of different actors. Likewise, understanding the *science underpinning the final use technology X* is likely to run into different problems and requirements – e.g., lack of laboratory equipment or shortage of R&D workforce – compared to the problems and requirements of a *production technology Y* used to *manufacture technology X*, both evolving through and relying on different technology strata. Thus, distinctions between technology strata enable understanding the unique challenges and needs – such as technical, organizational, financial, and physical resources and capabilities in relation to industry and market structures – that emerge during technology and industry lifecycles.

The categorization of technologies as either 'product' or 'process' technology (e.g., Rosenberg, 1982) is widely used and the view of a technology as one or the other depends on the **frame of reference** of the user and producer. In other words, a product technology is someone else's process technology. For example, an atomic force microscopy is a product technology for those who developed and manufactured it but a process technology for those who use it for atomic manipulation of a sample. Commonly, process technology is believed to come at play at later stages of technology development. However, the case is very often that new, especially emerging and radical, product technologies require novel process technologies to be also scaled up. This means that process technologies must also undergo their own technology lifecycles (with their maturity often being characterized using the manufacturing readiness levels as opposed to technology readiness levels used for product technologies). In summary, while the categorization of product vs. process technologies is widely spread and useful to some extent, references often do not take into consideration the fact that the view of a technology depends on the frame of one's reference, process technologies often also have to undergo technology development, and it does not consider other vital technology levels and elements: underpinning science, tool technologies, and external infrastructural technologies that have their own unique challenges and needs.

5. Defining technology strata

While the proposed framework of technology strata is different from the innovation stages, they align to some extent as technologies evolve from scientific principles to final use technologies in a recursive process. In other words, technologies go through technology strata starting from underpinning science, through core technology and integrated technology, to final use technology in a dynamic process of combination and integration (Schumpeter, 1934). This process draws on other final use technologies such as production technologies, tool technologies and external infrastructural technologies, all being part of a wider family of technologies with a shared knowledge and technology base. The following definitions of technology strata aim to clarify semantics, while drawing from the diverse literatures of innovation economics, technology development and systems dynamics. Table 3 demonstrates the application of the technology strata framework applied to the nanotechnology family as an example.

5.1 Underpinning science

Underpinning science refers to scientific principle(s) that explain why a technology works. It is concerned with understanding scientific principle(s) that underpin the technical functionality of a technology. It is important to understand the underlying science of each technology, as different technologies can be based on different scientific principles. These differences have significant implications for the development of each technology stratum, including the required knowledge, skills, tool, external infrastructural and production technologies, etc. For example, medical imaging technologies such as computerised tomography (CT) scanners, ultrasound scanners, and magnetic resonance imaging (MRI) machines are based on different scientific principles (see Table 2). CT scanners are based on the interaction of electromagnetic radiation with matter – i.e., X-rays. Whereas ultrasound scanners are based on the scientific principle of soundwaves being reflected by matter. Likewise, MRI is based yet on another physical phenomenon: nuclear magnetic resonance (NMR).

Underpinning science usually takes up an intangible form of scientific and technical knowledge that can be either easy to formalize and communicate (codified/explicit knowledge) or more difficult to formalize and transfer due to its embeddedness in actors (tacit knowledge). Organizing and developing knowledge to understand scientific principles forms the basis of technologies and thus it is the first stratum. This generally includes formulating, testing, and predicting hypotheses about scientific principles, most often at a theoretical level. Interest in understanding scientific principles can begin due to either identifying a need for a new or improved technology or observation of a new scientific phenomenon (Arthur, 2006; 2009).

Underpinning science of technologies is embedded in scientific domains such as mathematics, physics, chemistry, life sciences, engineering, materials science, etc. (Featherson & O'Sullivan, 2017). However, it is not as broad as a scientific domain. Instead, it refers to specific scientific principle(s), which could come from various scientific domains, that underpin a technology.

Table 2 Underpinning science of medical imaging technologies.

	Family of technology		
	Medical Imaging Technology		
	CT SCANNERS	ULTRASOUND SCANNERS	MRI SCANNERS
Underpinning science	**X-rays** Interaction of electromagnetic radiation with matter	**Soundwaves** Reflection of soundwaves by matter	**NMR** Different magnetic moments of atomic nuclei

5.2 Core technology

Once scientific principles are understood and theoretically described, **core technologies arise from the application of scientific principle(s), which leads to their key technical functionality.** Technical functionality provides a technology base or platform on which potential applications are based upon – even though potential applications are often not immediately clear or are limited to a couple of applications at the early stages of core technology development. Core technology research including proof of principle and proof of concept, prototyping and demonstration are used to explore and confirm potential market applications and provide a set of technical conceptualizations for these applications (Tassey, 2005; 2014). **The right question to ask here is how a technology works.**

While all core technologies lead to technological dynamism through ongoing technical improvements and complementary innovations in application sectors, their impact on the economy depends on their level of pervasiveness in application sectors. The steam engine, electric generator, electric motor, transistor, and the internet are examples of core technologies that have led to large-scale changes in the organization of the whole economy (also referred to as general purpose technologies – GPTs) (Teece, 2018; Bresnahan & Trajtenberg, 1995; Tassey, 2008). However, core technologies can eventually become GPTs when their economic impact is considered large enough, usually assessed retrospectively. In other words, every GPT is a core technology, but not every core technology is a GPT. The technology strata framework proposed here can therefore be used to define GPTs as it is concerned with technical principles (while that of GPT with economic impact).

There are several closely related terms to core technology, e.g., generic platform, enabling, fundamental and horizontal technology, that are however not well defined and often used ambiguously or interchangeably.

5.3 Integrated technology

Integrated technologies are derived from and based on core technologies, often disparate technologies or subsystems, that are integrated into a system. This system is selectively and purposefully directed at a potential application but does not have to be configured for final use – depending on the complexity of a technology. System integration comprises the joining of different pieces of hardware and/or software into a technology that works as a whole. As this technology level is about integration, **it is important to understand if there are any other technologies or subsystems that are needed for it to work or to be usable.** For example, a large number of transistors and other electronic components are integrated on a microchip (also referred to as integrated circuit) in a complex design often using electronic design automation (EDA).

5.4 Final use technology/application

Final use technologies can be grouped as either product/solution technologies, production technologies, R&D and engineering tool technologies, or external infrastructural technologies. The three latter groups usually undergo their ‘own’ technology lifecycles and play an essential role in other technology lifecycles.

5.4.1 R&D and engineering tool technologies

Tool technologies are a set of technical tools that support the R&D and production of novel technologies. They are often presumed to be readily available as part of laboratory and production equipment. However, they need to undergo their ‘own’ technology lifecycles. They allow analytical testing, measurement, modelling, process and quality control, data collection, etc., for the other technology strata both during R&D and production. For example, the Nobel Prize winning infratechnology inventions of scanning tunnelling microscope and atomic force microscope enabled nanotechnology developments through atomic-scale imaging of various surfaces (Palmberg et al., 2009).

Given that infratechnologies are necessary throughout all phases of technology and industry development including innovation and production, they can be further divided as R&D tool technologies and engineering tool technologies. **R&D tool technologies are tools used for scientific discovery, exploration and understanding of scientific principle(s) as well as technology proof of principle and concept development. Engineering tool technologies are tools used for application integration, demonstration and development of technologies.**

5.4.2 Production technologies

Production technologies is another group of technology elements that is an inevitable part of innovation and industrial systems as it refers to the processing, fabrication and assembling of technologies. It includes both the processes of material manipulation and the equipment itself.

5.4.3 External infrastructural technologies

External infrastructural technologies are complementary technologies that are external to the technology but necessary for its functioning. Some examples are antenna, roads, etc.

5.5 Technology family

A family of technologies is an umbrella term that encompasses various technology strata based on shared feature(s) either stemming from underpinning science and engineering or sectoral application, where such definitions may not arise immediately when new technical functionalities and technologies are discovered and explored. A technology family can be characterized by a shared knowledge and technology base with high learning rates between different technology development cycles within the family. For example, nanotechnology is a family of technologies that groups all technology strata (e.g., nanoparticles used for drug delivery to treat spinal cord injuries, engineered graphene used for sensors in ultra-responsive hearing aids, atomic force microscope, photolithography machine) that have at least one physical dimension below 100 nanometres or are used to develop and manufacture them. Thus, a family of technologies is made up of a complex interplay of many lifecycle journeys that emerge and re-emerge during a longer time period continuously requiring different complementarities, support and involvement of various actors.

Table 3   Examples of technological entities within the nanotechnology family classified using the technology strata framework.

Underpinning science	Core technology	Integrated technology	Final use technology	Production technology	Tool technology	External infrastructural technology
Semiconductor physics	transistor	microchip	computer memory	photolithography machine	scanning tunnelling microscope	
Crystal Chemistry	quantum dots	sensor	ultra-high definition displays and televisions	laser dicing machine	atomic force microscope	
Surface science	carbon nanotubes	thin film device	flash memory chips for smart phones and thumb drives			
Functionalisation chemistry	engineered graphene	microphone in auditory bandwidth	ultra-responsive hearing aids			
Organic chemistry	cellulosic nanomaterials	drug delivery	antimicrobial coatings on keyboards			
Materials science	gold nanoparticles	air filters				
Molecular biology	nanoparticles	liposome-loaded devices	cancer treatment			
Molecular engineering			repair spinal cord injuries			
Microfabrication						
Medicine		probes for the detection of targeted sequences of nucleic acids				

6. Application of the framework for technology strategizing

The two below examples (see Figure 3) show that it is possible to use the above technology strata framework for assessing technological entities starting from any stratum. This is particularly important as most commonly technology prioritization and foresight exercises are concerned with novel and emerging technologies, whose potential market applications and economy wide impacts are uncertain during early and mid-stages of technology development. Differentiating between technology strata, however, does allow a better understanding of the necessary complementarities, infratechnologies and production technologies, etc.

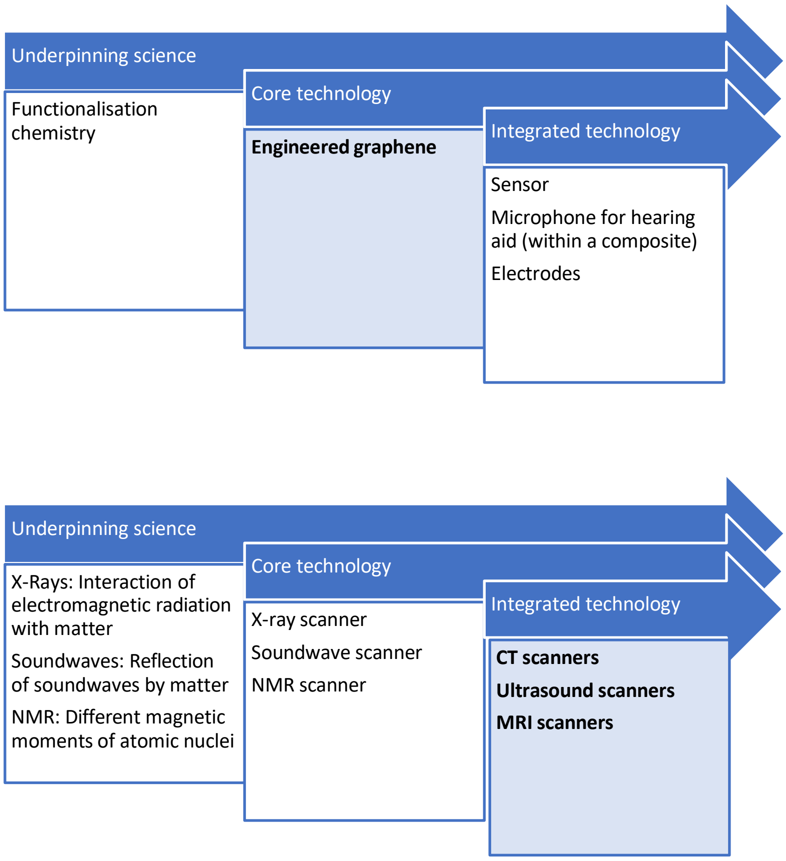


Figure 3 Technology strata framework can be used from either direction.

7. Dimensions distinguishing technology strata and why distinctions matter

The following section elaborates on the dimensions that show why distinctions between technology strata are essential for strategic development and competitive advantage (as summarized in Table 1).

7.1 *Underlying resources and capabilities*

Technology does not arise in isolation, and neither is it a homogeneous entity as described by the early conceptualization of technology as a black box. Technologies are developed and diffused in innovation systems that can be defined as complex interactions between a diverse set of actors, such as firms, universities, public research organizations, government agencies, etc., shaped by institutions (Edquist, 1997), endowed with different resources and capabilities, and supported by different infrastructure (Featherston & O'Sullivan, 2017). Therefore, there are differences in terms of the resources (e.g., knowledge base, infrastructure, workforce skills, processes, routines) and capabilities (unique combinations of resources) available to different actors in various innovation systems and across its disparate stages. The same holds for industrial systems that are an intrinsic part of innovation systems despite often being omitted from considerations or only explicitly implied.

This has implications for technology strata in the sense that their underlying needs and challenges differ. For example, production technologies require different resources and capabilities, and their development is often undertaken and funded by different actors as opposed to core technologies (this is also the case when comparing any other technology strata). During the initial stages of production technology development, global trends in material and process approaches, material effects and availability, potential supply chains, and other engineering principles and knowledge are investigated (DOD, 2020). Whereas these undertakings are less of a concern during the initial stages of core technology development and more focus is placed on the scientific principles underpinning its technical functionality and proof of principle and concept. Moreover, the development and funding of production technologies has traditionally been undertaken by private actors, who compete based on their manufacturing capabilities (DOD, 2020), with recent increases in policy support for scale-up facilities (e.g., Revitalizing the U.S. Semiconductor Ecosystem (PCAST, 2022)).

Likewise, the capabilities of semiconductor foundries that are predominantly occupied with the fabrication of semiconductor chips is very different to those of fabless semiconductor companies that focus on designing and testing them. The facilities of companies – or other actors – and their respective capabilities therefore could differ from those needed, for example, for basic research and core technology development – i.e., engineering vs. scientific knowledge, industrial vs. innovation workforce skills. This is not to say that different resources and capabilities cannot coexist or be available at the same time, but that there are unique and specialized mixes of capabilities available to different actors and required by each technology strata.

7.2 Public-private good content of technology

Related to the argument on underlying resources and capabilities, the public-private good content of technologies influences investment incentives and therefore the involvement of public and private actors in both funding, developing, and manufacturing technologies. This is also closely linked with the strengths of the intellectual property rights regime (Teece, 1986). For example, the incentive to support scientific knowledge is low for private sector actors as it is a public good. In other words, investments into knowledge creation cannot be fully recovered (appropriated) by the investor as it can be used by various individuals beyond its creator/investor. Therefore, knowledge creation and especially basic research are often undertaken by universities and public research organizations.

As technologies emerge from underlying science through core and integrated to final use technology, engagement from the private sector increases as the appropriability issues diminish and knowledge becomes more appropriable – i.e., shifting from public to private good (Tassey, 2005). The case of core technologies (that could in retrospection be recognized as general purpose technologies – GPTs – if they have economy-wide effects) is interesting here as these are often funded by the public sector and only to some extent by the private sector. This has to do with uncertainty around market application of core technologies and appropriability issues as core technologies can be so pervasive that a single investor/innovator/firm could not possibly cover all potential market applications and therefore capture their full value (Teece, 2006). Larger diversified R&D companies tend to invest in core technologies but these investments are managed quite differently to investments that go into application and use technologies (Tassey, 2005; Teece, 2006). Whereas, core technology research is generally not feasible for smaller companies, which generally focus on application and use technology development (Tassey, 2005).

Tool technologies (supporting R&D and production), which are essential across all steps of technology and industry development, can be characterized as quasi-public goods (Tassey, 2005). Many of these technologies have a public good content like measurement tools, test methods, data, quality control techniques and industry standards, yet they lower transaction costs for companies, which is why both public and private investments in their development can occur. There is therefore a balancing act between public and private investments in technology and industry development that are motivated by different incentives and closely related to appropriability regimes. There is a need for optimal investment in different technology levels and elements but also sustaining and improving complementarity between public and private investments in both innovation and industrial systems.

7.3 Technology, product or industry maturation

The dimension of time plays an important role when it comes to technology development. As suggested earlier, technologies evolve through different strata in a dynamic process of combination and integration. Various theoretical frameworks and management tools – including product, technology and industry lifecycle theories, evolutionary perspectives, technology and manufacturing readiness levels – have attempted to capture these dynamics. They all point to the fact that technology and industry emergence and development are evolutionary and changing processes.

While product, technology and industry lifecycle theories do not share a unified terminology as their units of analysis differ, they all describe that over time there are different factors that are important in the emergence and development of products, technologies and industries. The unit of analysis of product lifecycles is the market share of a product over its lifetime usually depicted as an S-curve going through the stages of development, growth, maturity, and decline (Levitt, 1965). The product lifecycle, however, does not differentiate between technologies that actually matter with regards to the type and number of users, marketing channels to be used, need to achieve economies of scale or scope, etc. For example, the market for consumer goods will be larger than for capitally intensive production technologies.

Over time, incremental improvements across technology strata can lead to the emergence of competing and improved technologies. Each of these improved technologies has its own S-curve, with technological discontinuities in between their S-curves (Foster, 1986). This is in accordance with industry life cycle theories, that observe that in the early stages of industrial evolution, there are many competing technology designs emerging until one or a small class of designs starts to emerge as superior due to some aspect. When a dominant design emerges, competition moves from technology design to lowering unit costs through economies of scale or scope and learning – i.e., to production technologies (Teece, 1986; Abernathy & Utterback, 1978).

Technology and industry dynamics thus have implications for the timing of various capabilities, investment in the right type of tool technologies (e.g., research tools, standards, quality control processes), management tool use (technology readiness or manufacturing readiness levels), business model selection (integrate or subcontract manufacturing and services). For example, whenever a new use for a technology is identified, there may be a need to go back to its underpinning science to understand whether integration with other technologies will work at a systems level. In other words, even though, technology may already exist at the stage of an integrated technology, there could easily be a need to revisit the underpinning science and to justify it accordingly, so that the new final use tchnologies can be developed.

7.4 Technology complexity

Technologies can differ on a fourth dimension – their complexity. This is important when it comes to complementary capabilities and technologies often geographically dispersed throughout the economy (Bresnahan & Trajtenberg, 1995) that are needed for a technology to work and be diffused. The more complex a technology, the more actors, resources, and capabilities are needed all increasing technical and market risk as well as information asymmetries (Bresnahan & Trajtenberg, 1995; Tassey, 2005). Higher complexity is especially challenging in the first stages of technology development because it often requires multidisciplinary R&D teams as well as research facilities that do not yet exist, but also during later stages when different technologies are integrated into a system.

Technology complexity has been increasing as we have been moving away from analogue and mechanical technologies to digital technologies and more recently to the digitalization of the manufacturing sector. The number of technological entities that make up a use technology has become unthinkable. This has an effect on the number of complementarities that an innovator (a firm or a country) needs to have access to in order to be able to compete, including knowledge, patents and technologies. This makes it challenging to capture value especially from core technologies because missing complements constrain their development into potential market application, which is why firms are often reluctant to invest into their development (Teece, 2006; Tassey, 2004).

In terms of technology strata, technology complexity has implications for the 'number' of technology strata through which a technology evolves. Consider the example of a hammer, laser printer, and real time fault detection as shown in Figure 4. The technology levels of a hammer – a simple technology – would be a hammer across all strata. Therefore, differentiating between technology strata is not necessarily important when strategizing for this type of technology. However, at the other extreme is the convergence of digital technologies with operations technologies (Industry 4.0). For example, predictive maintenance relies on a number of complex core and integrated technologies such as neural networks, processors, sensors and communication hardware, internet of things (IoT), etc. that are integrated in a complex system providing the final service of, for example, real time fault detection. Integration, but also customization, is an indivisible part of ever more complex technologies; however, it often leads to various scale-up challenges emphasizing the need to pay attention to technology strata when strategizing for such technologies at both firm and national level. In summary, it is important to understand whether complementarities across all technology strata are in place as well as to coordinate or incentivize missing complementarities, especially as technology complexity increases.

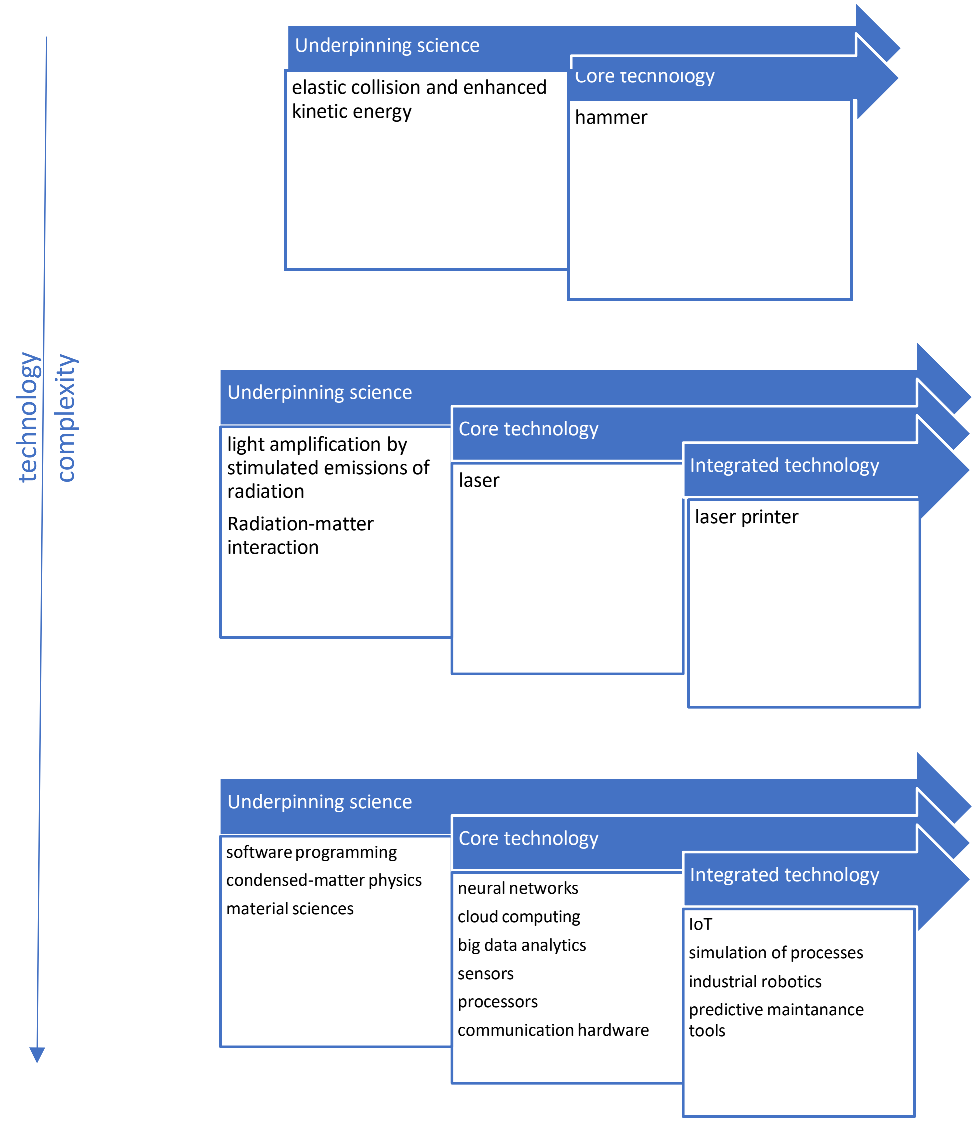


Figure 4   Technology complexity with regards to technology strata: an example of a hammer, laser printer, and real time fault detection as final use technologies.

8. References

Arthur, W. B. (2006). The structure of invention. *Research Policy, 36*(2), 274-287. 10.1016/j.respol.2006.11.005

Arthur, W. B. (2009). *The nature of technology: What it is and how it evolves.* Free Press.

Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies: 'Engines of growth'? *Journal of Econometrics, 65*(1), 83-108. 10.1016/0304-4076(94)01598-T

Brooks, H. (1980). Technology, Evolution, and Purpose. *Daedalus, 109*(1): 65–81.

Department for Business, Energy and Industrial Strategy [BEIS]. (2021). *UK Innovation strategy: Leading the future by creating it.* Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009577/uk-innovation-strategy.pdf [Accessed 11 May 2023].

Department for Science, Innovation and Technology [DSIT]. (2023). *Science & technology framework: Taking a systems approach to UK science & technology.* Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1140217/uk-science-technology-framework.pdf [Accessed 11 May 2023].

Department of Defense [DOD]. (2003). *Technology readiness assessment (TRA) deskbook*. Available from: https://apps.dtic.mil/sti/pdfs/ADA418881.pdf [Accessed 19 May 2023].

Edquist, C. (1997). Systems of innovation approaches: Their emergence and characteristics. *Systems of innovation: Technologies, institutions and organizations* (pp. 1-35). Routledge.

European Commission. (n.d.). *Key enabling technologies policy.* Available from: https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/key-enabling-technologies_en [Accessed 12 May 2023].

Featherston, C. R., & O'Sullivan, E. (2017). Enabling technologies, lifecycle transitions, and industrial systems in technology foresight: Insights from advanced materials FTA. *Technological Forecasting and Social Change, 115,* 261-277. 10.1016/j.techfore.2016.06.025

National Aeronautics and Space Administration [NASA]. (n.d.). *Technology readiness level definitions.* Available from: https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf [Accessed 19 May 2023].

National Science and Technology Council [NSTC]. (2022). *Critical and emerging technologies list update.* Available from: https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf [Accessed 11 May 2023].

Palmberg, C., Dernis, H., & Miguet, C. (2009). *Nanotechnology: An overview based on indicators and statistics* (STI working paper 2009/7). OECD Publishing. Available from: https://www.oecd.org/science/inno/43179651.pdf [Accessed 11 May 2023].

President's Council of Advisors on Science and Technology [PCAST]. (2022). Revitalizing the U.S. semiconductor ecosystem. Available from: https://www.whitehouse.gov/wp-content/uploads/2022/09/PCAST_Semiconductors-Report_Sep2022.pdf [Accessed 31 May 2023].

Rosenberg, N. (1982). Inside the black box: Technology and economics. Cambridge University Press.

Schumpeter, J. (1934). *The theory of economic development*. Harvard University Press.

Tassey, G. (2005). Underinvestment in public good technologies. *Journal of Technological Transformation, 30,* 89–113.

Tassey, G. (2008). Modeling and measuring the economic roles of technology infrastructure. *Economics of Innovation and New Technology, 17*(7-8), 615-629. 10.1080/10438590701785439

Tassey, G. (2014). Competing in advanced manufacturing: The need for improved growth models and policies. *Journal of Economic Perspectives, 28*(1), 27-48. 10.1257/jep.28.1.27

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy, 15*(6), 285-305. 10.1016/0048-7333(86)90027-2

Teece, D. J. (2006). Reflections on "profiting from innovation". *Research Policy, 35*(8), 1131-1146. 10.1016/j.respol.2006.09.009

Teece, D. J. (2018). Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy, 47*(8), 1367-1387. 10.1016/j.respol.2017.01.015

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega, 3*(6), 639-656.

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