1 Big Science and Society as Seen through Research Lenses

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1.1 Introduction

For decades, debates raged over Big Science operations and the support given to fundamental research. In his 1945 report to President Truman, 'Science, the Endless Frontier', the first presidential science adviser, Dr Vannevar Bush advocated for an expansion of government support for science and recommended the creation of the National Science Foundation.

The report was highly influential in underpinning public support for fundamental research. Several scholars have also examined the role of fundamental research (also known as basic research or pure basic research), its social and economic impacts, tensions, and relevance for security and global peace. Such research enhances our understanding of nature and its laws. How science functions as a social institution was explained by several scholars (Polyani, 1962; Kitcher, 1993; Gibbons, 1994; Pavitt, 1998; Aronova, 2014).

Big Science refers to large-scale instruments and facilities, funded by national and international governments and agencies where research is conducted by specialised teams or groups of scientists and technicians on a common and significant problem. Large-scale public investments enable Big Science to produce public goods (Weinberg, 1961). Particle physics is a good example with significant social implications, but it is not the only one. Developing nations such as India provide evidence for this. Homi Bhabha, for instance, who was a theoretical physicist, initiated the revival of Big Science programmes (in relative terms) at the Tata Institute of Fundamental Research in 1945 to support physics research (Wadia, 2009).

Big Science investments grew further over time. It was a growth driven by the need to enable large numbers of scientists to assemble diverse expertise to collectively resolve major research questions. The establishment of international science organisations such as CERN in 1954, for instance, opened space for an extensive research community. The acronym CERN is also used to refer to the laboratory; in 2021, it had 2,676 scientific, technical, and administrative staff members and 783 fellows. In addition, CERN hosted about 12,731 associated members and users from institutions in more than 110 countries with a total number of personnel recordings

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16,190 by 2021[1]. The CERN experiments are supported by a larger group of scientists and engineers from various countries, the majority of whom are connected to national laboratories and institutions in their home countries.

The demonstrated success of laboratories like CERN suggests that reliable collaboration is possible with advanced communication tools, structured workshops, and effective interactions among the Big Science research community and technical staff. How Big Science operates and continues to function efficiently, nonetheless, remains yet another puzzle for many.

1.2 Big Science as Described in the Literature

Big Science, breakthrough innovation, and societal benefits are often tightly linked with each other (Bach and Lambert, 1992; Autio et al., 2004; Vuola and Hameri, 2006; Liyanage et al., 2007). In fact, the term 'Big Science' was coined into the vocabulary of scientific enterprise in the last century. Lawrence's Cyclotrons and the University of California Radiation Lab established in 1930 are classic examples of the emergence of Big Science concepts. The advent of Big Science is a major step forward in human inquiry into nature and it extends beyond what individuals can do with structured and organised exploration of nature and nature's phenomena including the existence of life and biomedical and astronomical events.

The term Big Science specifically originated in the US during World War II. However, it was subsequently used in more general expressions to refer to significant scientific advances, which, when considered by their order of magnitude, achieved complex goals that otherwise would have remained unattainable (Bush, 1945; Price, 1963; Weinberg, 1968; Etzkowitz and Kemelgor, 1998). Naturally, Big Science demands big investments, intense international collaboration, and the complex organisation of leading scientists, which entails some risk-taking that can be overcome by carefully crafted collective decisions. Collaborative organisation of science thus has its inherent advantages (Hicks and Katz, 1997; Etzkowitz and Leydesdorff, 2000; Giudice, 2012). Typically, Big Science projects require dedicated and technologically advanced infrastructure and a set of project management skills which were new at the time to the contributing scientists and engineers. Although their research goals could be described as 'high risk, high gain', these laboratories and collaborations were assigned oversight structures to ensure that adequate risk mitigation practices were in place. Collaborations in Big Science require building connections with leading scientists (see Figure 1.1).

[1] CERN Personnel Statistics 2021, Human Resource Department, March 2022—https://cds.cern.ch/record/2809746/files/CERN-HR-STAFF-STAT-2021-RESTR.pdf.

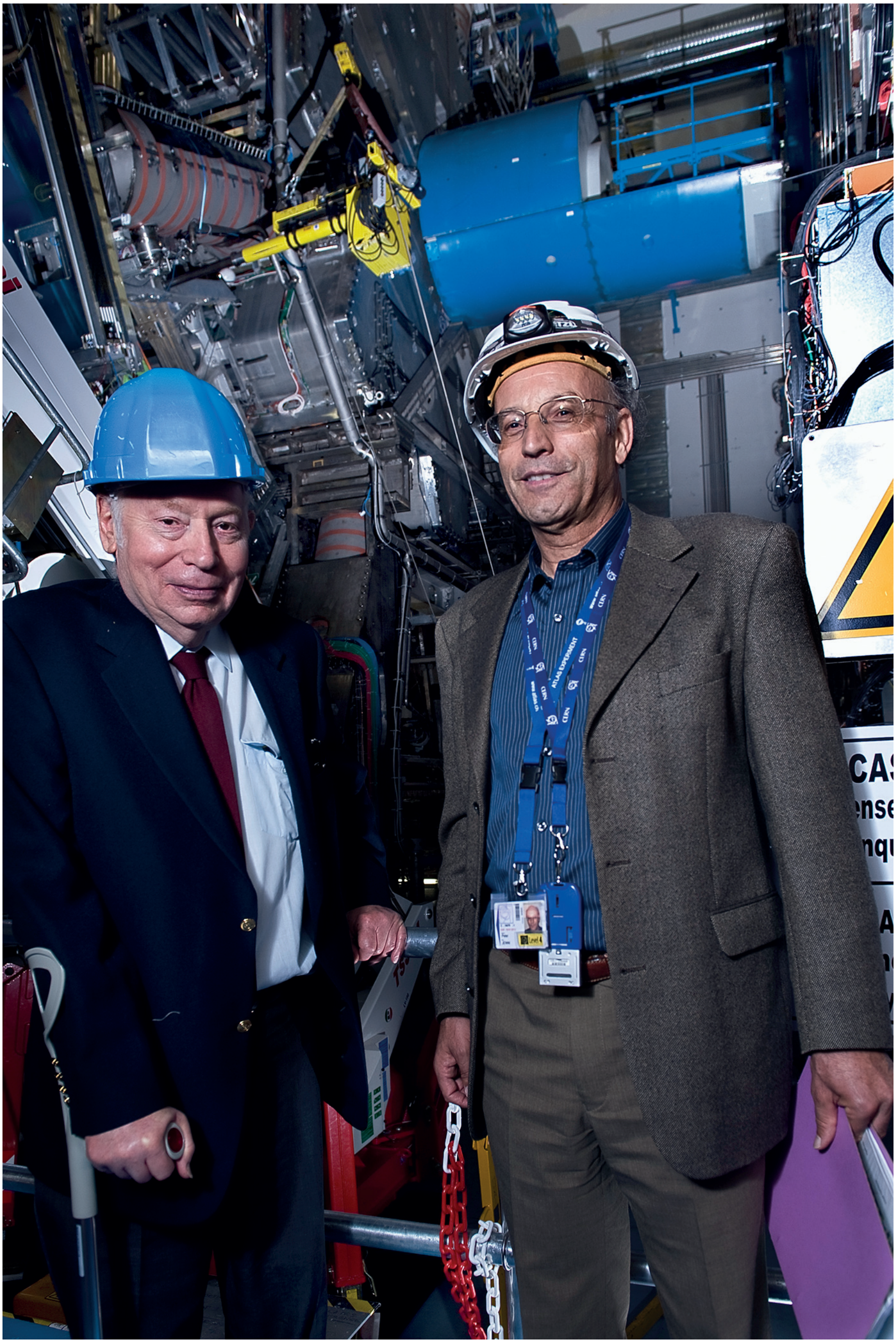

Figure 1.1 Master Builders of Big Science—Steven Weinberg visiting CERN and ATLAS (with Peter Jenni, former ATLAS spokesperson)
Source: © CERN

Big Science laboratories are clustered around nuclear and later particle physics research, astronomy and, more recently, in areas of the life sciences (Galison and Hevly, 1992). These dedicated, large-scale technological infrastructures also offer potentially interesting opportunities for industries interested in advancing R&D (Hameri, 1997). Most of these laboratories are geared towards solving some of the most challenging scientific puzzles of today. They probe into the origin, density, structure, and distribution of mass (energy) in the universe and explore the early stages and structure of space–time, the origins and evolution of massive stars, and the origins of life on Earth. These research questions, among many others, bring together hundreds of research institutions, creating complex, interacting networks across diverse disciplines (Nature Index, 2019).

The quest to understand the birth of the universe builds upon and complements research data created by big accelerators like the LHC at CERN, arrays of telescopes operated by ESO and research operated by ESA and NASA such as the Hubble Telescope. Recent Planck results (Planck, 2019) of the cosmic microwave background (CMB) fluctuations support, among other things, the Standard Model of neutrinos consolidated by recent results found by the particle physicists at the LHC and elsewhere (DUNE, 2020; IceCube, 2020), the concept of an accelerating expansion of the universe measured by the SCP astronomer community in the early 1990s, and the absence of spatial curvature suggested by the earlier CMB measurements. The results, in fact, reveal deeper connections between the Higgs particle and the accelerating universe (Steinwachs, 2019).

Several communities are working on the connections between black holes, space–time curvature and gravitational waves, most notably the LIGO experiment (Gregoris et al., 2019). The thresholds of the formation of massive early stars which end up in Black Holes once they have run out of the nuclear fusion processes combine a wide range of communities across astronomers and nuclear physicists and they are addressing fundamental questions in the emergence of visible matter, the organisation of subatomic matter, and their interactions within (NRC, 2013). Such studies are possible thanks to a few accelerators and instrumentation available in nuclear physics facilities, such as HIAF in Australia (HIAF, 2020).

Large-scale facilities like ESRF in France are running experiments to reveal the fundamental nature of space–time symmetries and are working together with life-science laboratories like EMBL in Europe (EMBL, 2020) on the exploration of living matter in diverse disciplines such as chemistry, structural biology and medical applications, environmental sciences, information science, and nanotechnologies (ESRF, 2020). Powerful X-ray lasers at large facilities such as the European XFEL in Germany (XFEL, 2020), LCLS (SLAC, 2020), and SACLA in Japan (Riken, 2020), unveil the composition and structure of complex biomolecules and materials on the atomic scale.

Big Science laboratories thus act as catalysts for the many different scientific communities using them. These laboratories offer shared technical and scientific facilities providing necessary technological infrastructure and knowledgical knowhow.

These laboratories provide instrumental support for scientific and technological investigations (Beck and Charitos, 2021).

Yet, in the light of history, the processes and interconnections between science, innovation, and society are not very easy to untangle, despite several compelling examples provided. Electricity and radio waves were harnessed in the early part of the twentieth century based on experimental work carried out some half a century earlier; the transistor and the laser were developed after World War II based on observations and theories made decades earlier about the behaviour of atoms and molecules (Johnson, 2010). These disruptive innovations resulted mainly from sequential contributions made by individuals and small teams. Big Science laboratories provided advanced technical facilities and dedicated teams to leapfrog and scale up discoveries and technological advances of much grandeur. In that sense, Big Science facilities herald as next-generation investments in technological innovation.

A rapid and steady growth of more complex scientific collaborations, therefore, took place forming new and expensive laboratories and partnerships, involving industrial companies (Krige, 1993; Kronegger et al., 2011; Qi Dong et al., 2017). At the forefront were the versatile domains of physics, biomedicine astrophysics, and data science. In time, Big Sciences model rapidly expanded to include climate sciences, ecology, oceanography, astronomy, gravitation, neutrons, synchrotron light and laser physics, fusion research, artificial intelligence, and other disciplines.

Noteworthy among the more recent examples is the unravelling of the composition of the human genome in 2000, paving the way for new drug discoveries. This discovery relied on the foundations of genetics dating back half a century and the use of massive computing power made possible by advances in computer chip development (Davies, 2002). A second example is the discovery of the Higgs-particle at CERN (Figure 1.2) in 4th July 2012 (jointly announced by both the CMS Collaboration, 2012 and the ATLAS Collaborations, 2012), than half a century earlier and using a massive amount of computing power to analyse and find the particle which stimulated the development of cloud computing (Chandrasekaran, 2015). The discovery of the Higgs boson was a major achievement in the field of particle physics because the Higgs boson is extremely unstable and rapidly decays into other particles (see Figure 1.2).

Big Science stretches across borders with laboratories and collaborations having a global reach because of the nature of the scientific work they foster (Holden, 1985). In most cases, the host labs act as the host organisation for their research community and connect with several other research laboratories and universities. At least in the domain of physics, it is not unusual that different Big Science labs host overlapping scientific visitors and users. For example, the ATLAS and CMS collaborations have more than 180 institutions each, including all major Big Science labs in particle and nuclear physics from over 40 countries from all continents (ATLAS Collaboration, 2020; CMS Collaboration, 2020).

Another example is Australia's Nuclear Science and Technology Organisation (ANSTO). ANSTO occupies much of Australia's landmark infrastructure including

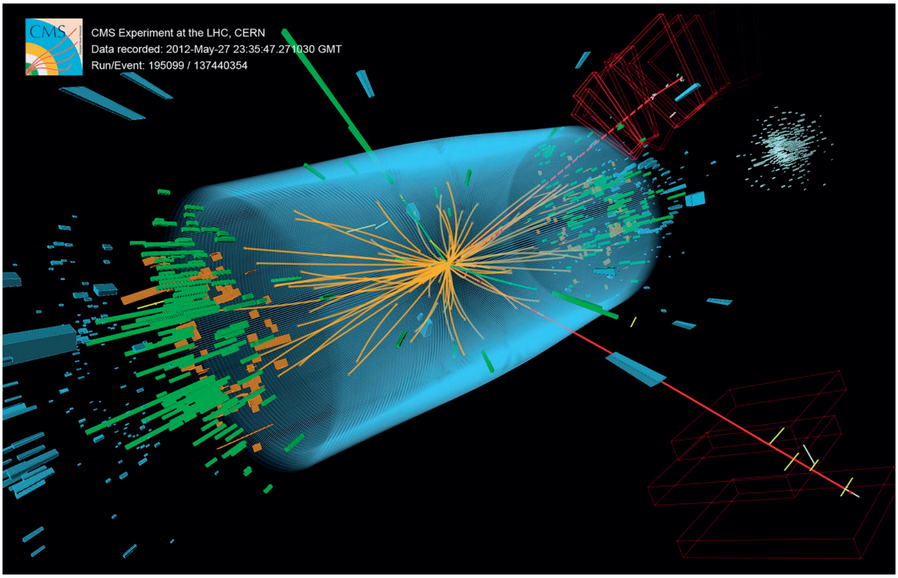

Figure 1.2 Tell-tale sign of the Higgs boson
Source: © CERN- CC BY 4.0

modern nuclear research reactors, a comprehensive suite of neutron beam instruments, the Australian Synchrotron, the National Research Cyclotron, and the Centre for Accelerator Science. It has over 60 research, technology, and regulatory partners all over the world, including CERN and ATLAS (ANSTO, 2020).

A third example that depicts the nature of interconnectivity and embedded network structure linked to Big Science is ATTRACT,[2] an EU-funded framework for promoting early-stage detection of the pathology of disease and the associated imaging technologies in Europe (ATTRACT, 2020). It is coordinated by six leading European Big Science facilities with the intent to seed-fund and cross-link the different stakeholders across detection and imaging, with the objective of creating an innovation platform for Europe. These types of activities are expected to breed innovation through collaborative research networks (Liyanage, 1995; Liyanage et al., 1999).

Understanding how Big Science collaborations are structured and managed is also becoming increasingly important in gauging their effectiveness (Bammer, 2008; Hsu and Huang, 2011; Canals et al., 2017). Obviously, that needs to take into account cultural, geographical and historical factors (Gazni et al., 2012; Ortoll et al., 2014), nonetheless that alone is not enough. It should be equally taken into consideration how they manage to scale up, how individual researchers can act and respond within the project structures and finally how to arbitrate possible internal disputes or conflicting requirements.

[2] The ATTRACT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No. 101004462 and No. 777222.

Some insights have been offered in the context of CERN (Knorr-Cetina, 1999; Tuertscher et al., 2014; ATLAS, 2020) and LIGO (Collins, 2003) and the emphasis is on the well-articulated and strong shared goals, well-crafted procedures of conduct and collegial, and lastly the rotating management structures. However, having a better understanding of how processes work—or do not work—within collaborations, as well as how they deal with unforeseen problems or unpleasant surprises, is more important. For example, the LHC uses dipole magnets (see Figure 1.3) to bend the paths of circulating high energy proton beams which generate enormous energy, hence these superconducting magnets need to be cooled to extremely low temperatures (about −271.3 degrees C).

It should be noted that the management structures of—and leadership issues related to—Big Science labs differ from those of the scientific collaborations they foster. Running large-scale laboratories is a more top-down approaches where the governances is determined by the funding agencies and governments, and where adequate resources are allocated for supporting infrastructure and research projects (Mark and Levine, 1984; Kinsella, 1999; Geles et al., 2000; Anadon et al., 2016; Fabjan et al., 2017). In contrast, management of individual projects—even if large in scale—is more bottom-up, and often governed by the network of contributing universities and funding agencies; in the capacity of users of these large facilities (Robinson, 2021).

In addition to the observed time-lag of decades between scientific theory formulation, discovery and ultimate recognised value for society (Goddard, 2010), the process from discovery to practical use is often non-deterministic or could be

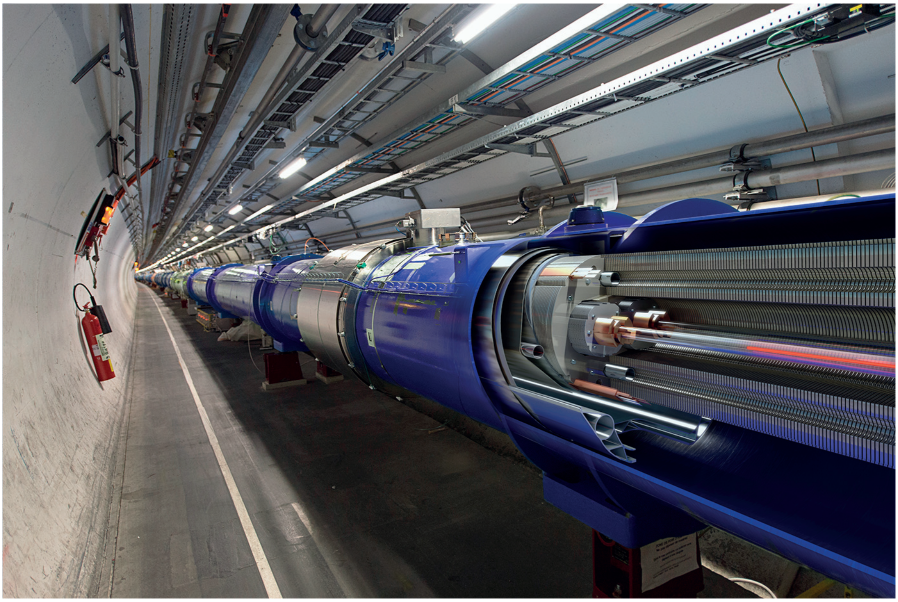

Figure 1.3 LHC dipole magnets in the underground LHC tunnel
Source: © CERN- CC BY 4.0

serendipitous by nature. Well known and often cited examples are the discovery of penicillin (ACS, 1999) and the invention of the World Wide Web (Hameri and Nordberg, 1998; Gillies and Cailliau, 2000), where the final, revolutionary product resulted from addressing initial needs or challenges elsewhere. The importance of understanding serendipity in scientific discovery or innovation processes is well known (see e.g. Merton and Barber, 2004; Garud et al., 2018; Yaqub, 2018) but it has not been given due consideration with regard to the societal impact of Big Science.

Provided that the Oxford English Dictionary definition of serendipity is ‘the occurrence and development of events by chance in a happy or beneficial way’ (Oxford English Dictionary, 2020), this approach has so far not been essentially included in studies on the economic or societal value of Big Science, although its presence has been acknowledged (OECD, 2008, 2014).

A more classic, cost-benefit analysis approach has been applied to estimate the economic returns of investment in Big Science laboratories and collaborations (Science Business, 2015; Florio, 2019). Although these methods consider variations in the Net Present Value (NPV) and rate of return criteria, the actual benefits of investing in Big Science research are difficult to quantify. For example, somewhat unexpectedly, the single most significant generator of socioeconomic impact from such endeavours is training. This finding emerged from Cost-Benefit Analysis studies for the LHC and the High-Luminosity LHC (HL-LHC) upgrade as well as from lessons concerning the socioeconomic impact that these facilities have beyond the core scientific mission. (Gutleber, 2021). Other studies have shown that the applied discount rates have positive implications for big projects like the LHC at CERN (Florio and Sirtori, 2016). However, these studies do not describe the process of knowledge creation or variations within, of Big Science designing and building, and of making use of their instruments in interaction with the different stakeholders in society. Within Big Science experiments, there are sophisticated instruments and technologies. For example, the Pixel Detector of the CMS experiment at LHC consists of advanced electronics and silicon sensors as shown in Figure 1.4.

Alternative attempts have been made, for example by Boisot et al. (2011), using options thinking (McGrath and MacMillan, 1999; van Putten and MacMillan, 2004; MacMillan et al., 2015) to capture the potential future value of Big Science undertakings. This approach is based on knowledge or the information economy (Nelson and Romer, 1996, Romer, 1990; David and Foray, 2001) but assets can be described as a dynamic cycle from creation to their oblivion using the so-called Information Space (I-Space) framework (Boisot, 1998; Child et al., 2014). In this approach, Big Science projects, while pushing the envelopes of science and technology to leap forward, create options that may or may not be realised (‘executed’) by the different stakeholders, acknowledging at the same time the act of serendipity. Despite the promise of this approach, not much progress has been seen during recent years on this front, even if there are documented case studies about dynamics and structures within Big Science collaborations (Knorr-Cetina, 1999; Glänzel and Schubert, 2004; Tuertscher et al., 2008; Canals et al., 2017) and on supplier relations (Nordberg and Verbeke, 1999;

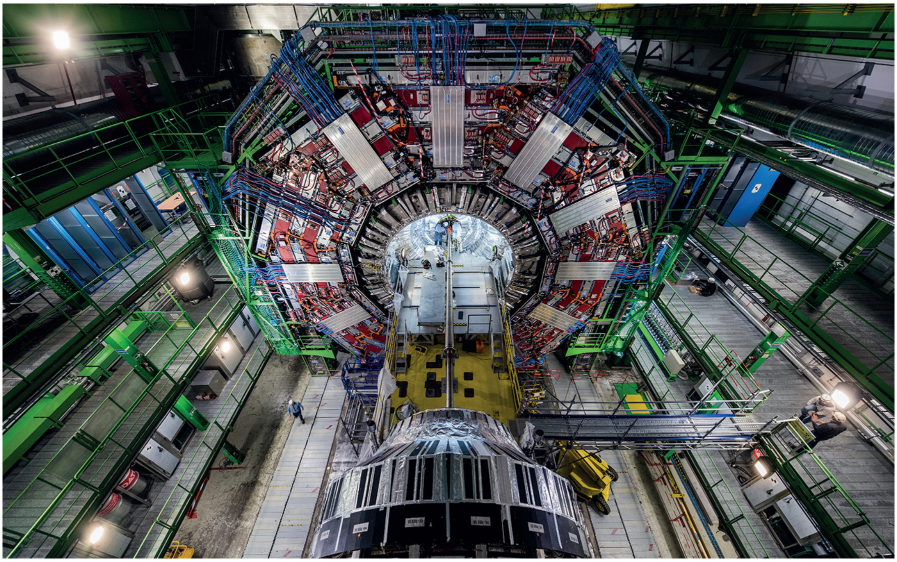

Figure 1.4 The CMS experiment at the LHC
Source: © CERN

Autio et al., 2003; Vuola, 2006). More recently, Big Science and economy were closely scrutinised from various knowledge and intellectual property angles (Beck and Charitos, 2021).

While Big Science laboratories and collaborations have been focusing on their well-defined research missions, policymakers and governments have been increasingly calling upon the scientific communities to also address pressing societal issues (EU, 2015). This is not a new call—it was noted already in the 1960s that while we can reach for the moon, we still have ghettos (Nelson, 2011). But more recently, impelled particularly by the Covid-19 pandemic, governments are increasingly turning towards scientists to know how the advancements in their respective fields help resolve complex, 'wicked' societal problems (Skaburskis, 2008), thus introducing a conditional element to their research funding. This top-down versus bottom-up projection of objectives can be hard to align because of the diversity of the dynamics of social and natural phenomena.

A leading sociologist of collaborative networks said: 'Particles do not yell back at you' (Grey, 2003). Although concepts like 'social physics' (Pentland, 2014) can be helpful in guiding how scientific methods can be used to influence human behaviour, a fundamental layer still appears to be missing, despite good efforts, that is able to capture the process of doing science itself to the dynamics of innovation and eventual societal impact (Cardinal et al., 2001; Caraca et al., 2009). Yet, the impact of public funded Big Science research has been a central concern for many scholars, policy makers, and research managers (Cohen and Noll, 2002; Mazzucato, 2013; Kokko et al., 2015; Maroto et al., 2016; Gutelber, 2021). Some of the advances in medical technology are obvious. The Linac booster (LIBO) is used to produce particle beam for cancer therapy (Figure 1.5).

There are two ingredients to consider here: the open nature of science and the design or 'fabric' of the scientific process itself. The methodology used in modern science dates back to the Greeks and was consolidated by Francis Bacon in the seventeenth century, using inductive reasoning based on data and the subsequent verification or rejection of a set hypothesis, to be openly shared with the scientific community for debate and reflection (Kuhn, 1962; David, 1998; Gribbin, 2002). Publishing in scientific journals, which offers a system of trust and earned scientific reputation, serves as the primary channel for communicating results (Merton, 1957). The impact of scientific work is also increasingly visible through this channel (Benavent-Pérez et al., 2012). This principle of 'Open Science' (David, 1998) is deeply rooted not only in the way Big Science labs and collaborations operate but also in the way they innovate their scientific instruments. The latter is captured by the principle of 'Open Innovation' (see e.g. Chesbrough, 2003; Enkel et al., 2009; Baldwin and von Hippel, 2011) which took inspiration from the practices of software communities openly sharing their code for enhanced development and applying gentle, collegial coordination—for example, the Linux operating system (Henkel, 2006). The key idea is that (external) communities are stronger than (internal) organisations in innovating new, breakthrough concepts, products, and services. This has been further enhanced by the use of online collaborative platforms that permit citizen participation to solve specific technical challenges (Seltzer and Mahmoudi, 2013;

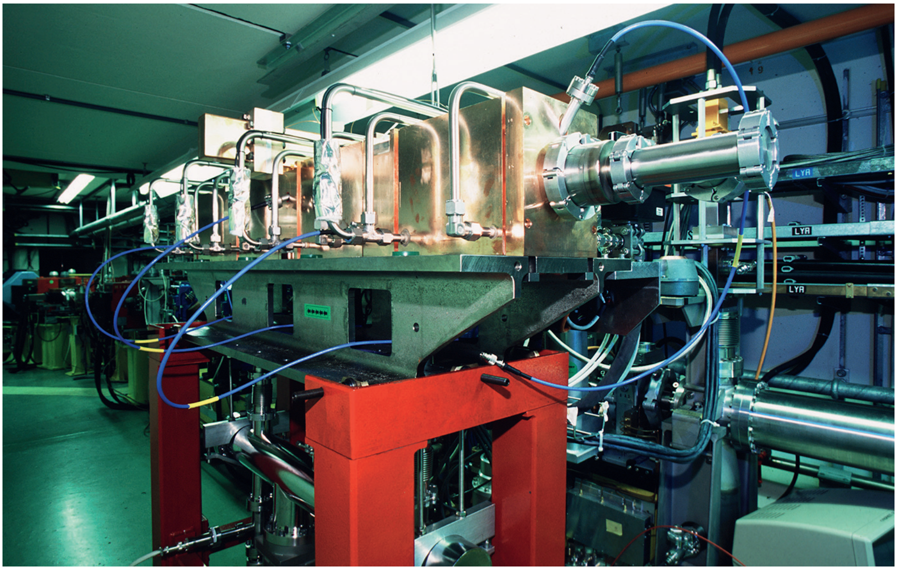

Figure 1.5 The Linac booster (LIBO) for producing particle beams for cancer therapy
Source: © CERN

Sloane, 2011). The principles of 'Open Innovation' can also be applied to support actual scientific processes as well (Beck and Charitos, 2021).

Although Big Science thrives on the above dynamics of 'Open Science and Open Innovation', which is also echoed by the science and technology policies of many countries (EU, 2016, 2020; Science Business, 2019), it can also inadvertently result in a kind of an 'innovation paradox': by openly sharing the technology to invite the research and other communities to substantially enhance its performance, making it harder for others, later on, to commercialise it due to unclaimed or diluted intellectual property rights (IPR). Putting aside here the relationship between—and implications of—open innovation and IPR policies (Bogers and Santos, 2021; Bogers et al., 2012; Granstrand and Holgersson, 2014), it is noted that in general, being publicly funded, Big Science labs and collaborations tend to follow rather loose IPR policies. They make good use of open software and hardware repositories for sharing their work in addition to their usual channels of scientific publishing (Murillo and Kauttu, 2017; Pujol, 2020). This would imply that classical measurement tools like patent-counting may not be that applicable and that the emphasis is more on the transfer of knowledge than on the transfer of concrete, identifiable products.

As noted above, the nature of the scientific process and its relevance to the design of the innovation process have not been extensively studied. The issue of design in science has been raised from an engineering perspective (Cross, 1993). The question of the architecture of complex organisational structures—which could be relevant in some Big Science endeavours—has also been addressed (Simon, 1962). Yet the role of the potential end-users has not been thoroughly examined, apart from recognising the importance of lead users in expanding the use of scientific equipment (von Hippel, 1988).

Starting with the societal challenges facing citizens, it has not been systematically examined whether the diverse cumulative knowledge and technology available in Big Science organisations and experiments can be well used in solving complex social problems. Recognising that making such a direct link between Big Science and social benefit would be difficult, user-centric techniques are available to transfer knowledge. Technology enters only at the end of the process, and not at the start, which is usually the case in the more classical thinking of technology transfer (Harmon et al., 1997).

The approach used in this book is also inspired by Design Thinking (Brown, 2008 and 2009) where cross-disciplinary MSc-level university student teams are assigned sustainable development goals (SDG) -related projects (UN, 2020) and are then exposed to Big Science surroundings to look for potential solutions (CERN, 2019).

The students come from different backgrounds, ranging from product design to business management and engineering, and are mostly from a global network of Design Factories (DFGN, 2020). Although the primary motivation for this type of approach is educational, the project results do suggest that tools and technologies developed by Big Science labs and collaborations can contribute to pressing challenges related to topics such as climate change, pollution, and health care (CBI, 2020).

As governments are launching more Big Science-type 'moonshot' initiatives to solve societal problems such as climate change or to conquer cancer (EU, 2018), the question should be asked how current Big Science laboratories will be able to adapt, without compromising their defined scientific mission and focus. The current collaborative, bottom-up project-like structures around Big Science facilities suggest by themselves an agile approach: if participating countries are willing to fund their scientists in global projects hosted or coordinated by Big Science laboratories. But that might come with more strings attached, notably demanding that collaborations to involve societal stakeholders outside their primary scientific fields. If so, Big Science laboratories and collaborations will need to think about how these new actors could be best integrated and what the rules of engagement will be. For example, some indication of this line of thinking can already be observed in the planning of CERN's Future Circular Collider project (FCC, 2020) where different kinds of societal benefits are envisaged stemming from the technology development work, including medical applications, energy transfer, and storage and engineering software. Also, engaging a wide range of students from different fields is foreseen. In that respect, the current Sustainable Development Goals (SDG) driven student projects at CERN's IdeaSquare (CERN, 2019) might provide some insights into how this could be scaled up, if needed.

Finally, the capabilities and role of Big Science labs in responding to acute and unforeseen disruptions in society in the future need to be considered. The most recent and most vivid example is obviously the Covid-19 pandemic, which in 2020 shut down major parts of world economies, with ripple effects lasting for a long time. Although the ultimate research missions of Big Science labs will remain unchanged, the infrastructure available at Big Science laboratories could be used for rapid response to crisis, such as using scientific instrumentation and computational facilities, as was the case for Covid-19 (CERN, 2020; EMBL, 2020; ESFR, 2020; ESS, 2020; ILL, 2020; XFEL, 2020). In the future, Big Science will be able to accelerate cross-connecting of new and complementary parts of their user communities to speed up development work, i.e. contributing scientific networks in the spirit of open science and open innovation (Berkley, 2020; Chesbrough, 2003; 2017; and 2020).

1.3 Conclusions

Big Science, often refers to large-scale scientific projects, covering a broad spectrum of scientific, technical, economic, knowledge transfer, and science and society issues. Since the publication of Vannevar Bush's thesis, 'Science—the Endless Frontier' in 1945, a plethora of research publications about Big Science have covered fundamental research, the role of government and industry, the impact of science on society, and the ethics and morality of science.

The main purpose of this review is to outline some core practices, underlying theories, and concepts related to Big Science. What has been covered within a narrower scope, are accounts of Big Science undertakings from a practitioner perspective, i.e. shared experiences about the challenges faced—scientific, technological, administrative, or political—and how these are being addressed and resolved.

The literature review suggests a rather wide range of empirical evidence on the importance and role of Big Science and its impact on society. Several studies confirm Big Science projects are highly efficient, capital intensive and complex research processes. Coordinated multidisciplinary groups using the latest technology and experimental systems are necessary to solve fundamental questions attempted in Big Science organisations and experiments.

Several themes related to the future of disciplines, economics, and ethics are emerging from the literature review. Open Science and Open Innovation play a central role, and various aspects of big data and digital information systems are often highlighted. In addition, several studies outline technology transfer, design, and innovation in transferring fundamental knowledge to useful social benefits, including significant advances in medical science.

Big Science is a dominant mode of conducting fundamental research with growing international collaborations of increasing size. Indeed, there are concerns covering equity, ethics, and the role of collaboration and competition in Big Science.

The authors conclude that there is scarce literature offering examples of how Big Science can connect with society. Although there are anecdotal examples, there is scarce research literature on innovation in Big Science, future development of scientific methodology, strategic development of technological tools, recognising the role of industry, identifying educational models for the diffusion of knowledge opportunities, and impact on society.

In the light of the above review, the authors of this book saw an opportunity—that is to adopt a more holistic, process-driven practitioner-approach. Based upon the literature reviewed, one can identify three phases of Big Science processes: ideation, science in progress, and as a process, connecting with society.

Our hope is that our selection of this path will inspire further research on this intriguing topic.