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The Future of Big Science and Social Impacts

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15.1 Introduction

The examples and practitioners' views shared throughout the previous chapters offer four key takeaways. First and foremost, the focus on fundamental knowledge is the main generative mechanism in Big Science. To qualify as Big Science, the scope and intent of these projects by the scientific community need to be focused on significant fundamental science issues and problems. It could be about testing a specific grand unification theory, hypothesis, or experimental verification of the Higgs boson, understanding gravitational waves, or dark matter and dark energy. Contemplating even larger, more technically challenging attempts, like the Future Circular Collider (FCC) at CERN, serves as an indispensable example of the build-up of cumulative scientific knowledge, technological capability, and the synthesis of human ingenuity.

How large collaborations are successfully put together is a culmination of many factors and is an arduous process that depends on the drive, determination, and commitment of key individuals. It can be regarded as a churning process that requires a continuous cycle of systematic formulation of project ideas, engaging with different people and organisations, and refining theories and experiments. In addition, such ideas need to obtain political and organisational support. Sometimes, the state of technology can be a barrier. For example, for both ATLAS and CMS, developing radiation-tolerant electronics remained a major hurdle towards functioning signal processing systems for a long time (Brianti and Jenni, 2017).

The second key takeaway is the path dependence of Big Science. Big Science ideas can be described as an extension of both theoretical and instrumental dependence (Peacock, 2009). Many examples discussed in this book reveal a particular pattern, organisation, and design that is noteworthy in the development of experimental physics research. The case of ATLAS and CMS at CERN, for instance, suggests that instrumental or experimental dependence is necessary for the falsification or confirmation of a theory—in this case, the Standard Model of particle physics, which is a theory concerning electromagnetic, weak, and strong nuclear interactions developed throughout the latter half of the twentieth century. This raises further questions:

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Where do big ideas come from? What is the process of selecting those ideas? and how to fund and take those ideas forward?

Third, as this book highlights, Big Science differs from more traditional science in view of its complexity in organisations and management. In a resource-intensive environment, Big Science projects appear to run with responsible leadership and management processes requiring systematic, clear reporting, and documentation. These mechanisms are indispensable to ensure scientific rigour and accountability to international partners, to circumvent any potential pitfalls and to deal with uncertainty. Careful planning, resource allocation, teamwork, and dynamic leadership processes are key success criteria for successful Big Science operations.

Big Science also involves careful management processes to draw on the right types and levels of collaboration that allow building interdisciplinary teams and groups to last over decades. One of the main challenges is the effective management of communication and coordination among team members spread across various research organisations in different geographic locations. ATLAS, CMS, and LIGO had thousands of scientists working from different laboratories across the globe.

The capability of dealing with diverse epistemic cultures requires significant personal skills. Above all, managing complexity in these experiments can be difficult due to the sophistication of the technologies. For example, the ATLAS inner tracking system (ITS) is a highly complex detector system that requires effective management to ensure efficient operation and maintenance. ITS is also a modular system that needs careful engineering integration and installation, requiring expert knowledge to deal with various components, testing, continuous monitoring and reliable operations. Such insights ignite more important discussions and raise the following questions: How can we manage knowledge generation and translation processes?; What has learning or networking got to do with Big Science operations?; and How do we determine what works and what does not?

Fourth, Big Sciences give rise to new disciplines and novel knowledge systems. In fact, a discipline is a body of knowledge that is practiced by a group of scientists who are disciplined to adhere to standards for the creation and dissemination of knowledge in a particular field. As complexity grows, Big Science experiments in high energy physics, advanced telescope projects, astrophysics experiments, and molecular biology experiments use some of the most complex and deep scientific and technological techniques, knowledge, and skills.

Big Science initiatives are designed to solve grand challenges and find answers to very complex problems. Naturally, this requires bringing together diverse groups of talented scholars from varied disciplines converging from different nations all around the globe. Big Science undertakings thus unite countries and scientific communities irrespective of their individual political or national, geographic interests.

CERN, for example, has developed competencies over 70 years, building effective international collaborations even among fierce adversaries. Similarly ESO established in 1962 operated over 60 years. Building effective collaboration is the most difficult challenge in Big Science operations. Many protocols need to be put in place for diverse groups to work together. Time will reveal how the global community will unite to tackle future Big Science challenges. There is potential for countries in Asia, Europe, Africa, Central America, or North America to work together despite cultural and geopolitical differences.

When working on Big Science projects, trust becomes an essential ingredient for effective international collaborations. Collaborative efforts at each stage of the development of complex experiments need transparency, good communication, and open discussions. In this modern world, the prospects for establishing and sustaining cooperative Big Science initiatives have been negatively impacted by ongoing conflicts, a lack of trust, commitment, transparency, and accountability. To maintain support for Big Science initiatives, science diplomacy is essential to building success in collaborative scientific efforts.

Considering all chapter contributions, we present the following conclusions to explain the Big Science processes and develop the Collaborative Innovation Framework, a general purpose framework to illustrate factors that contribute to knowledge generation, development, and diffusion (COIF).

15.2 Chapter Reviews and Findings

15.2.1 Connecting the Dots: Big Science, Breakthrough Innovation and Society

We have come a long way in appreciating the historical roots of Big Science; learning with respect, how it takes decades to build a world-leading facility, building advanced technical infrastructure, and forming outstanding scientific teams. The ultimate success of all these entities relies on unity amongst dynamic networks of universities and supportive industrial bases across nations around the globe, along with a substantial degree of political support.

The Introduction (Chapter 1) provided an overview of the Big Science concepts covered in this book. It addressed the following questions: Why is Big Science important? How does it contribute to novel scientific knowledge and how does it impact public goods and social benefits? Based on a sample of practitioner accounts of Big Science endeavours, we identified missing links between integrating Big Science methods that are dispersed among technological tools, industrial opportunities, educational possibilities, and broader societal considerations.

The following are some of the most important lessons from Chapter 1:

1) The historical roots behind Big Science indicate that it takes several decades to build a world-leading facility with supporting technical infrastructure and future projects will require an even longer timescale;
2) Although a Big Science facility is typically centrally located, its success relies on building a dynamic network of (international) universities for carrying out the projects, data sharing, analysis, and a supportive industrial base; and

3) Big Science's contributions to society seem to be primarily serendipitous, meaning that their full societal ramifications have been rarely correctly predicted in advance.

15.2.2 Isn't it the Difficult Journeys that Lead to Beautiful Destinations?

As Richard Feynman, Nobel Laureate and a well-known physicist, said: 'It doesn't matter how beautiful your theory is, it doesn't matter how smart you are; if it doesn't agree with experiment, it's wrong.'

The iconic success stories of LHC's ATLAS and CMS experiments provide vivid perspectives on how Big Science projects come about: how they evolve from pushing the frontiers of science, driven by ambitious scientific goals and producing advanced technologies.

Chapter 2 describes how these experiments work in tandem with one another while also using various technologies and methods on their own. The genesis of ATLAS and CMS confirms that big ideas and concepts come from individuals (not necessarily laboratories where they work) and epistemic culture is the magnet that creates teams and groups who want to work together. The collaborations build around such individuals and teams that complement each other intellectually and socially. Collaborations naturally build around them. It is, however, naive to believe that all good ideas will receive funding and that the ability to attract funding support will determine which idea is a winner. There is always healthy competition among scientists, laboratories, and technologies (e.g. circular and linear colliders). Competing groups are working in a wide range of fields such as astrophysics, dark matter, and dark energy.

As explained in Chapter 2, the capital-intensity and complexity of these projects require long time frames for research inquiries and investigations. These experiments have a specific scientific and technological scope, complex design, and advanced engineering know-how that require the collective expertise of some of the best brains in the field of high energy physics.

Some of the key lessons from Chapter 2 are noted below:

1) The CMS and ATLAS experiments contributed to the development of new technologies and techniques in detector design, microelectronics, data processing, and computing;
2) Big Science projects are inherently complex undertakings and no individual can expect to solve all issues;
3) The level of precision and accuracy required is immense, with very high energy, radiation, and the intensity and speed of collision rates;
4) Lean engineering of the overall concepts of the ATLAS and CMS detectors was of paramount importance. In that sense, one can say that each one of them was its own prototype; it has a pre-determined specific task and implied life

cycle, not designed to be identically copied or replicated but to allow possible upgrades; and

5) Developing and scaling up Big Science experiments require innovative thinking, human and financial resources, time, multiple iterations and building strategic partnerships. They also require collaborating with leading experts in science and engineering to address specific scientific scope with due consideration to limitations (e.g. current and evolving science policies, geopolitics, and economic and funding cycles).

15.2.3 A Handful of Wisdom from a Success Story

To provide the reader with an understanding of the depth and scope of Big Science projects, the book has zoomed in, on the illustrative example of the LHC machine, which marks the successful culmination of over 80 years of continuous and tireless development of new technology in particle accelerators. Naturally, the LHC played a pivotal role in the discovery of the Higgs boson. It was a massive collaborative effort and a true reflection of what humans can accomplish when they collaborate. The Higgs boson discovery is not an isolated single event. It was the culmination of decades of both theoretical and experimental research.

Even with comprehensive mitigation mechanisms in place, Big Science projects are risky. However, the rewards can be significant: the discovery of the Higgs boson and the associated Nobel Prizes are examples of the latter. The joint discovery of the Higgs boson by ATLAS and CMS in 2012, a missing piece of particle physics' Standard Model (SM), is a significant recent achievement.

The following lessons can be derived from Chapter 3, which deals with the construction of the world's largest machine—the Large Hadron Collider:

1) Big Science projects must be willing to take calculated risks in order to realise their scientific goals. When incidents happen, problems must be addressed quickly, openly, and collaboratively as a team and new approaches may not always succeed. Everyone collaborates and works together to solve the problem, avoid cost escalation, mitigate risks, and manage them effectively;
2) Responsible governance is to work out all possibilities and remedies to protect researchers, organisations, and public safety in a high energy and radiation environment;
3) Governance structures need to consider the project's overall life-cycle stage and the complexity of each part of the connected system, for example, upgrade projects may require separate management structures from those involved in daily operations;
4) Organisational structures are streamlined to facilitate project work packages with overall directors taking consultative approaches while ensuring a rapid and effective decision-making process; and

5) Due to the complexity and advanced level of selected technologies, Big Science projects can protect themselves against massive, unforeseen effects through partitioning and securing them in 'blocks' or 'sectors' that will contain any unanticipated damages.

15.2.4 Versatile Big Science

Chapter 4 describes the various disciplines and associated technologies of accelerators and detectors that have enormous economic and societal benefits. Distinctive examples were drawn in this regard from medical, biomedical, energy generation, energy transmission, space, computing, and other industrial fields.

The following related lessons can be derived from Chapter 4:

1) A strong relationship exists between Big Science and innovation. Partnership with industry benefits both collaborating parties with innovative practices that combine creativity and intellectual diversity;
2) Human aspects such as multi-ethnic and multinational environments, as well as cultural differences between research organisations and industry, should not be overlooked in Big Science projects;
3) Big Science projects are sources of ground-breaking technologies. Partnerships evolve over time from idea refinement to the final stages of industrialisation, including the R&D and prototype phases;
4) Development of new technologies from Big Science requires new approaches to innovation: pushing the frontiers of superconducting electrical transmissions for the HL-LHC suggests potential benefits and applications for society; and
5) Practical applications that go far beyond the accelerator fields, for example, range from climate change to cultural preservation.

15.2.5 Here and Now Determines the Future

Chapter 5 leapfrogs into the future to illustrate how CERN's past experience can shape future high energy research frontiers. Aside from particle physics, other fields such as astrophysics and cosmology must collaborate in order to fully understand the big, open questions about the nature and behaviour of the universe. Scientists in general collaborate to develop new and more efficient scientific tools that pave the path for major discoveries. Progress in science certainly calls for unity among the different communities, including not only particle physicists, information technology professionals, and other professionals, but also a multitude of other stakeholders, including industry personnel.

The lessons that can be derived from Chapter 5 are:

1) Future Big Science initiatives like the FCC, coordinated by CERN, can potentially keep pushing the frontiers of science well into the twenty-first century;

2) Effective collaborations need to be open, transparent, and diverse. A collective understanding of Industry and academia from an early stage in the life cycle of long-term projects is necessary to facilitate technology development and rapid diffusion;
3) New types of organisational management approaches are necessary to ensure continuity, as well as new approaches to reward and motivate the young generation of researchers in long-term experiments and projects;
4) In designing the next generation of Big Science projects, the evaluation of the socio-economic impact should be integrated from the early phases of the project life cycle; and
5) Continuous review, evaluation, and monitoring of projects will maximise returns from such large public investments.

Big Science projects typically attract large numbers of leading researchers, engineers, technicians, and students from thousands of universities, and research laboratories all around the world. There is a strong chance that these intellectual powerhouses will want to work more closely with businesses and governments to form alliances that will help them tackle other complex or urgent problems.

The painstaking process of extrapolating from past experiences to future situations can be useful and rewarding because no individual—certainly not only the project leaders—can anticipate all the risks and rewards of complex experiments.

15.2.6 Creative Constructs: Big Science, Learning Cycles, and Design

A number of chapters covered designs, leadership, medical technologies, and examples from astrophysics to show how innovation works in Big Science organisations and experiments.

Simplicity and Significance

All complex research, like detector-based technologies, can be simplified with creative designs, simplifications, and innovation. To this end, the concept of Social Learning (SLC) presented in Chapter 6 provides valuable insights into how design thinking can be used to solve Big Science complexity and how, if more widely used, it can support innovation processes involving both particle physics and astrophysics experiments.

SLC simplifies and structures the innovation process. These learning cycle approaches extend beyond the academic domain and, when combined with an interdisciplinary approach, can even bring together distinctly different domains such as science and the humanities, as well as levels and domains of expertise.

Such an open innovation approach can assist in understanding the current operations of Big Science and in planning for future research projects, for instance, in the search for dark matter and dark energy, where the use of open data sources and the sharing of information are becoming increasingly crucial.

The following related lessons can be derived from Chapter 6:

1. Design concepts offer new and innovative ways of codifying the process of how knowledge generated in Big Science projects could be disseminated for the benefit of society (e.g. experiments carried out at IdeaSquare at CERN are provided as examples);
2. Design artefacts, demonstrate the importance of incorporating the (end) user experience in the design process as early as possible and call for a multidisciplinary approach;
3. Design practices can codify, abstract, and generate new meaning for Big Science knowledge by synthesising human, technical, and economic considerations into tangible design artefacts. Social Learning Cycles (SLCs) can be expanded beyond the scope of Big Science projects (e.g. ATLAS to why they were originally applied) to the level of knowledge and technology transfer impacting applied sciences beyond the hosting organisations;
4. Designs have taken on a major role in Big Science in the visualisations and image reconstruction of events in LHC experiments and astrophysics; and
5. Beyond detector and accelerator technology, design concepts, engineering prototypes, and artefacts have contributed to innovations in various components and devices.

15.2.7 Driving the Vision to Reality

Human interactions and leadership, which have long been central interests in Big Science operations, were covered extensively in this book. Chapter 7 discusses leadership from the perspective of complexity and its application to Big Science projects. Leadership demands versatility in new skills. Big Science leadership requires skills that go beyond those of a typical leader and the usual project management skills that call for a combination of complex knowledge and abilities.

Big Science ethos reminds us of the need to place emphasis on transparency, empathy, ethical behaviour, as well as building trust. A common emphasis on collaborative leadership was then observed, on the scientific and technical credibility of the elected spokesperson as well as the responsibility of the leader towards the scientific community.

The following lessons can be derived from Chapter 7:

1) Leaders of Big Science need to be inspirational, credible, and competent;
2) Leaders across Big Science experiments can have diverse and different leadership approaches due to the size of the collaboration, geographical location, and disciplinary orientation;
3) Leaders have to deal with complex project structures, diversity of technology, and budgetary constraints;

4) Leadership traits include ethical, authentic, and shared leadership, stakeholder management, listening to employees, valuing diversity, building trust, empathy, and having diverse leadership culture to foster innovation; and
5) Leaders need to pay attention to gender issues: the participation of females in high energy physics is still relatively low. Efforts to increase diversity in leadership roles and to increase female participation will bring unique perspectives, creativity, and insights into scientific endeavours.

15.2.8 Never Believe the Sky Is the Limit

The marvel of astrophysics discoveries is another important pillar of Big Science. Using significant examples, Chapter 8 demonstrated the critical role of technological innovations in astronomical discoveries.

The complexity, cost, and audacity of these investigations require large collaborations modelled on high energy physics collaborations, regarded as pioneers. The astrophysics community displays a unique epistemic culture, in which data and analysis sharing has become the norm, with open access and open communication.

The authors describe the spectacular discoveries ranging from the search for Earth-like planets—the existence of life in nearby solar systems—to measuring subnuclear scale displacements that capture the wisps of passing gravitational waves produced in cataclysmic black hole collisions or attempting to identify the elusive nature of dark matter through the presence of neutron stars.

These discoveries take decades in parallel with the development of new technologies, techniques, and leading research. Hence, sustained long-term commitments from all stakeholders, particularly governments and funding agencies, are necessary for breakthrough innovation in Big Science.

The following lessons can be derived from Chapter 8:

1) Pushing audacious ideas results in ambitious Big Science astrophysics projects that rely heavily on observational science;
2) Technology development in the field of astrophysics contributes to fundamental research through extensive data collection using big telescopes, satellites, and radio astronomy to study the universe;
3) The path to discovery can extend over decades due to technological change and the use of new techniques such as multi-wavelength;
4) Astrophysics involve multiple stakeholders around the world and has complex data sharing and analysis functions. Sustained long-term commitment to all stakeholders, particularly governments and funding agencies, is necessary for long-term success; and
5) Astrophysics and particle physics research communities have complementary epistemic goals and cultures with common interests in the study of the universe.

15.2.9 Breakthroughs in Medical Technology

Chapter 9 traces the development of detector technologies in medical applications, which have been in use since the early days of Big Science and have thus contributed and will continue to contribute to societal well-being. Using examples of medical technology such as radiation therapy and cyclotron-based proton therapy, the authors focused on the technological trajectories and potential infrastructure contributions to miscellaneous fields of medicine using specific combined treatments, such as Neutron Enhanced Captured Therapy where Big Science may well play a role.

The following lessons can be derived from Chapter 9:

1) LINACs and medical detectors have revolutionised medical diagnostics, radiation therapy, and cancer treatment. Due to high capital costs, accelerator, and detection technologies have a long adoption curve;
2) Big Science has contributed to the development of imaging technologies used in medical diagnosis such as CT, MRI, and PET scans that have not only assisted in detecting accuracy in (e.g. beam-based methods and algorithms) the LHC, ATLAS and CMS and other experimental technology components for any defects but also contributed to significant advances in medical applications;
3) Once a new technology is adopted, there is a long tail of continuous improvements that follow and are used in various interconnected disciplines;
4) Technologies that are not clinically applicable may still be useful in addressing changing needs in both established and developing science and technology sectors; and
5) Advances in accelerator technology are making medical technology more affordable and accessible, lowering capital costs, and thus making these medical treatment types more accessible to a larger number of people.

15.2.10 Multiple Perspectives: Big Science and Society

Several chapters addressed the organisational and social construction of knowledge and all emphasise the importance of embedding learning in Big Science projects to translate knowledge into usable forms and learning experiences for future generations.

Chapter 10 explored the multifaceted and entangled relationships between Big Science and society, offering varied perspectives on its complexity and richness. The authors note that this avoids the use of single-lens, closed, and rigid valuation frameworks. The challenge therefore remains to capture both ontological and epistemological aspects of the scientific activity, as well as the idiosyncrasies of the individual actors and communities taking part in it.

A potential starting point could be to consider why and how scientific activities emerge out of fundamental characteristics of human nature, such as curiosity, imagination and serendipity and how they are capable of generating collaborative communities and, ultimately, collective and individual value. The widespread Covid-19 pandemic has already demonstrated that the knowledge produced by Big Science is not a luxury but rather a necessity for addressing both current and upcoming problems facing our planet.

The following related lessons can be derived from Chapter 10:

1) Big Science knowledge production is complex and multifaceted; it is an interdisciplinary human enterprise;
2) Human complexity in networking and relations is path-dependent and evolutionary;
3) The outcomes of Big Science need to be judged from various lenses without prejudice;
4) Big Science experiments are open to scrutiny and constructive criticism for their simplicity and effectiveness; and
5) Curiosity, imagination, and serendipity are intertwining forces for solving complex problems and Big Science knowledge and technology are global public goods.

15.2.11 Facing Big Data Challenges

Chapter 11 shows how data modelling, artificial intelligence, and data mining have hugely contributed to data analysis in Big Science projects. As the next-generation Big Science instruments are going to be loaded with ever-massive data generators, the quest for collection, storage, and analyses of data are challenging tasks. Currently, the impact of newly developed algorithms, rare signal discrimination, and methodologies to reconstruct images in high energy physics and astrophysics is visible.

Even more intriguing questions have been asked about how to share, manage, and use massive amounts of data generated in particle collisions and astronomical observations. Open access will remain a requirement for publicly funded research data, regardless of the scientific domain or geographical boundaries. The data life cycle is increasingly becoming valuable for science while making inroads to contribute to social, educational, and economic development. Artificial intelligence and quantum technologies are starting to have an impact on research fields.

The following related lessons can be derived from Chapter 11:

1) Big Science acts as a stimulus for science–industry interactions and has an impact on society as a co-developer, lead user, and a source of inspiration;
2) Big Science and big data techniques are intertwined, and techniques such as machine learning, grid computing, data mining and modelling, predictive analysis, and artificial intelligence will enable new technological discoveries and innovation;
3) Concepts such as openlab at CERN and Open target and Industry programme at EBI-EMBL can be used to test the organisational transition of multidisciplinary science–industry interactions;

4) Big Science can foster interactions between scientific progress and technological needs, as well as between technological solutions and new scientific pathways; and
5) Big Science can serve as a testbed for the transition of data gathering, analysis, programming, and algorithm developments from scientific applications towards broader societal impact. It may also be able to aid in a change of mindset.

15.2.12 Big Science's Call for Entrepreneurs for the Common Good

Although not strategically targeted, the impacts of Big Science connect with centralised economies and have the potential to generate large-scale prosperity in society through the development of enterprises. The authors of Chapter 12 have recognised that these enterprises need social equity mechanisms based on Big Science collaboration and values for cultural transformation.

The following related lessons can be derived from Chapter 12:

1) The positive impact of fundamental science in Big Science is connected with centralised economies that have brought large-scale prosperity through free enterprise, which is used as a social equity mechanism for transformation;
2) Big Science can transform research into social good and give it a direction, for example, in achieving universal developmental aspirations by using reliable, circular models and contributing to the achievement of the Sustainable Development Goals of the United Nations;
3) By collaborating with different stakeholders (such as in ATTRACT), Big Science has the potential to address social issues;
4) Innovation serendipitously ignites by using knowledge management tools with social capital, thereby overcoming obstacles to achieving quality of life; and
5) Serendipity can initiate the process of transforming fundamental science into breakthrough commercial innovation, and it may be possible to 'systemise' serendipity (e.g. CBI process at IdeaSquare at CERN).

15.2.13 An Outlook on Asia's Positioning in Big Science

The authors in Chapter 13 look ahead to the possible leadership role Asia may assume in the future in Big Science projects in particle physics. Asia has been strongly involved in front-line particle physics research for some time, like in the US and Europe. Despite some Asian countries making large investments in Big Science projects, they are still lagging behind their US and European counterparts in attaining scientific excellence in high energy physics and/or astrophysics.

The following related lessons can be derived from Chapter 13:

1) Although several Asian countries are actively involved in major Big Science projects in particle physics, there does not so far appear to be a strong common foundation or consensus to take on leadership in Big Science;
2) Japan and China are both signalling intent, but their approaches and motivations appear to be very different;
3) Concrete initiatives from Asian countries are necessary to spearhead Big Science initiatives (e.g. LIGO-India) collaboration;
4) Collaborative Big Science initiatives in Asia are necessary to combine growing talents in the region while pursuing fundamental scientific ambition and keeping technological and economic growth in perspective.

15.2.14 The Future of Big Science Stands on Shared Wisdom

The majority of Big Science organisations are focused on producing fundamental scientific knowledge. However, these projects have had significant direct and indirect spill over effects on the public good in terms of knowledge dissemination and learning.

Learning is recognised in Chapter 14 as a crucial element that influences peer-to-peer learning, academic learning, and the success of many postgraduate students through initiatives like the CERN summer programmes and other initiatives. Outreach activities can provide significant benefits and contribute to the development of a strong epistemic culture in specific areas of science.

The following related lessons can be derived from Chapter 14:

1) Large-scale international collaborations have developed structures and processes that facilitate the flow of information and knowledge. A mixture of competition and cooperation, driven by shared curiosity in diverse mindsets, helps to optimise this flow and can be an example for others;
2) Education and public engagement are critical for garnering support for large-scale scientific projects (e.g. the FCC);
3) Educational and outreach programmes facilitate two-way interactions between scientists and the general public, fostering future research; and
4) Big Science can thrive with public support and engagement, particularly in the recruitment of young scientists to take over future high energy physics development.

A strong commitment to education and learning is a key feature of Big Science. The development of the next generation of scientists, engineers, and technicians is crucial, but it is not the only factor driving the internal work that Big Science organisations must do. Moreover, there is a need to instil faith and interest in fundamental research, as well as to teach and share the methodologies that go with it, to help future generations develop interest and engagement in science.

15.3 Towards an Analytical Framework

The findings outlined in these chapters suggest that Big Science should be viewed as a complex system that interacts with its own components (Robertson and Caldart, 2008; Palmieri and Jensen 2020). Big Science displays elements of complexity, serendipity, open nature, networking, social design, and creative thinking that connect to society. Big Science complexity is highly structured and process-driven, as demonstrated in Big Science experiments. There are many subsystems within the complex structures, like the Inner Detector, Calorimeter, Muon Spectrometer of the ATLAS and CMS detectors. Some of these complexities increase as energy levels and the sophistication of experiments increase.

Multidisciplinary teams and groups must work together in order to solve some of the most complex operational system problems while staying within budget. Big Science creates vast knowledge networks and an innovation ecosystem that is characterised by knowledge-based and knowledge-driven open innovation.

The findings also support the view that the rationale for public expenditure and political support for large-scale science infrastructure underpins Big Science's benefits and outcomes (Wagner et al., 2015; Gastrow and Oppelt, 2018; Hallonsten, 2021).

Big Science collaborative processes seem to facilitate the seamless transfer of fundamental knowledge to the technology development of initiatives. Useful outcomes trigger as a result of cumulated knowledge on working with complex systems and subsystems. The diffusion of Big Science knowledge into useful outcomes is never a linear process.

The fundamental characteristics of research prevent too much simplification of meaning and translating knowledge across the social learning cycle (SLC). It is therefore necessary to untangle the underlying epistemological and ontological positions as to what scientific knowledge is feasible to transfer, what is not, and under what conditions. The question then remains: how to effectively integrate such processes within scientific collaborations. That is, how to explain the complex processes involved in the collaborative work of epistemic groups such as scientists, social scientists, and business managers and how useful ideas get translated from Big Science facilities such as CERN and ESO.

Based on the insights gained from the previous chapters, some of the key issues to consider here include:

a) How much does Big Science contribute to the common pool of public resources?
b) How does it promote greater collaboration?

c) How does it produce primarily non-excludable and non-rivalrous pure public goods, allowing anyone to use them without restriction regardless of whether they contributed to their creation? and
d) How does it create, to a certain level, intellectual property that can be developed in conjunction with public goods?

It is clear from the examples given in the previous chapters how theoretical and experimental knowledge came to be a crucial component of Big Science organisations and how these organisations developed over time. As seen, the organisation and management of this body of knowledge have complex dynamics, and not all knowledge is easily transferrable. Moreover, most of the valuable knowledge remains the tacit knowledge of the scientists and researchers who created it in the first place. They may be unavailable or unwilling to actively participate in knowledge diffusion, or they may lack the time or desire to serve as transfer agents or consultants in related technology transfer projects. It is necessary to translate tacit knowledge into useful organisational knowledge, but these processes can be quite inefficient or challenging.

In a systematic approach to the above questions and based on the findings from the previous chapters, we propose a simplistic framework called the Collaborative Innovation Framework (COIF) in order to show the connection between knowledge creation, development, and diffusion. Further work is naturally required to test the applicability of this framework. The proposed framework, captures the essential components of Big Science knowledge processes and the dynamics of fundamental

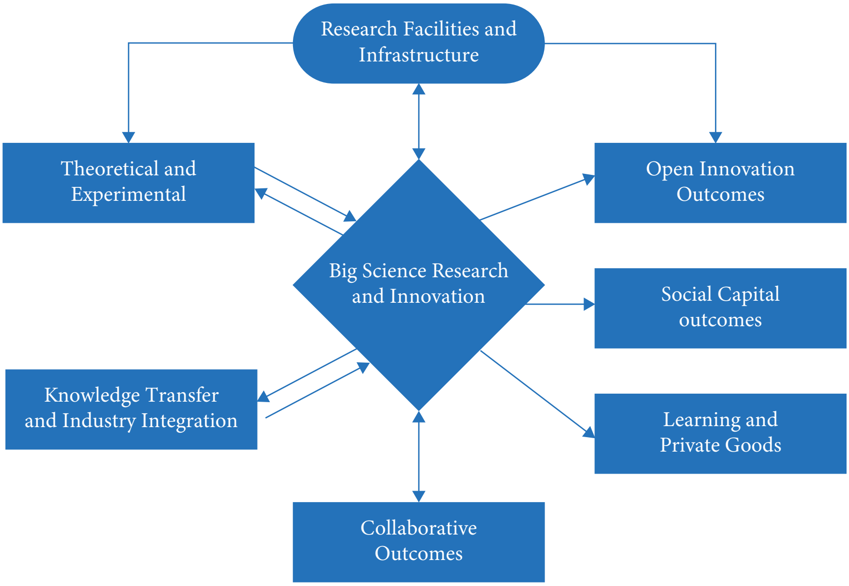

Figure 15.1 Collaborative Innovation Framework (COIF) for Big Science

Source: Created by author S. Liyanage

knowledge diffusion as illustrated in Figure 15.1. The framework exhibits the key components and dynamic relationships.[1]

The basic premise in Figure 15.1 is that in Big Science, fundamental knowledge drives open innovation, which in turn paves the way for new applications resulting from, for example, detector and magnet systems, which in turn create new fields of knowledge. The COIF model demonstrates three types of relationships: the process leading to the domain of knowledge; the knowledge validation process and the development of knowledge; and finally, the constituents of the knowledge conversions.

15.4 Concluding Remarks

The fundamental tenet of Big Science and society, is the need for collaboration, collegiality, openness and sharing benefits of knowledge. The ability of human beings to live in harmony has the potential to drive science, technology, and social change through Big Science collaborations. While Big Science collaborations have the potential to drive social change, there are scientific and technological challenges that require concerted human efforts. In this book, we have outlined, with examples, many challenges facing the progress of Big Science. Such progress is determined by complexity, serendipity, design, and knowledge diffusion processes, together with the human desire to converge intellectual power and knowledge.

Public investment and support for Big Science are essential to solve complex and growing complex problems that are worth solving. Scientists alone cannot resolve all problems without the political and social support to fund and support Big Science facilities and experiments.

Big Science collaborations have the potential to drive social benefits when effectively coordinated, managed, and supported. Big Science has the power to overcome most barriers with scientific and technical foresight and with carefully chosen research policy frameworks to strengthen its investigative powers to solve complex problems and garner the support of all nations through collective action.

Given the nature and complexity of issues such as climate change, health, social and environmental degradation that require advanced solutions with collective efforts, Big Science organisations and experiments have come to stay in the scientific landscape. Institutions such as CERN, ESO, and LIGO have shown time and time again their ability make unique contributions to scientific understanding require to solve such complex problems. Their legacies and commitment to leading-edge scientific knowledge have proven their justification for existence.

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[1] Authors would like to recognise, in particular, the contributions from the following persons: Anita Kocsis, Tim Boyle, Christine Thong, and Panagiotis Charitos.

Since their emergence in the 1960s, Big Science projects have undergone considerable development and evolutionary changes. Growing complexity with new technologies, sophistication of interdisciplinary collaborations, data-driven research, and open science initiatives have changed the nature of Big Science, leading to social renewal, human progress and social transformation. These initiatives have increase capacity to bring together interdisciplinary groups from different countries and cultures to work towards a common goal.

By nature, Big Science is a creative movement with visionary undertakings. Scientists set bold research agendas and go about designing and constructing advanced technologies with well-defined processes. Such processes, as described in this book, call for the coordinated teamwork from diverse disciplines. These organisations often engage in solving novel, fundamental and complex problems that require the application of cutting-edge scientific and technological knowledge. Hence, Big Science is a different league of its own governed by different knowledge synthesis, a philosophy of collaboration, dialogue and open discussions. Big Science also evolve through sharing of scientific and technological infrastructures, the constant search for breakthrough knowledge and the mobilisation of significant financial and human resources. It is, however, naïve to think such collaborations are easy to put together and are free from competition.

Potentially, most Big Science initiatives gives rise to useful innovation. The past decades of operations of Big Science demonstrated that scientific knowledge, methodologies, and findings together with technical instrumentation designed for purely basic research purposes have eventually ended up in elegant solutions that are fundamental to practical applications in our daily lives as well as to medical, environmental and economic developments. Numerous applications discussed in this book provide some examples. Big Science has evolved significantly over time, both in terms of the complexity of experiments undertaken and the way in which they are conducted using open science and open innovation to promote social benefits. The development of new technology for Big Science experiments can have broader applications beyond the intended use and can transform human society.

There are many future challenges for Big Science organisations. Its nature and interdisciplinarity are expected to change dramatically with grand undertakings like FCC, Linear Collider, and Dark Matter searchers. Rapid advances in technology and data-driven analytics will facilitate greater participation of multidisciplinary groups to come up with innovative solutions to the world's complex problems and challenges in climate, energy, and health.

Operations and maintenance of Big Science are quite challenging and difficult tasks. Working in these organisations can be difficult for younger and upcoming scientists to demonstrate their creative talents. Some publications have more than 1000 scientists as authors and some young people may be among the thousands of those authors contributing to a single scientific publication. Individualism and intellectual freedom can be marginalised when working among experienced and highly accomplished researchers. A continuous search for pool of talent with precision and accuracy is required for a dynamic evolution of Big Science experiments.

Moreover, there are limits and restrictions on the types of research problems that are possible to investigate. Not all ideas will become part of Big Science investigations.— In other word, Big Science is an integral part of social construction.

Big Science are also subjected to some restrictions and political pressures. There can be organisational restrictions on valuable beam time and telescope time. Politics and funding can influence the research scope and agenda. Very often, Big Science organisations have specific long-term strategies for high energy physics or astronomical research that are constantly reviewed and modified in consultation with scientists (for example the European Strategy for Particle Physics[2]).

Life cycles, capital investment sizes, and the sizes of the participating scientific communities all seem to be growing in Big Science projects. The LHC also resembles modularity in design and how various interactive components can be assembled independently like a jigsaw puzzle and bring them all together to produce the desired innovative and collaborative solutions and outcomes.

We noted that the guiding principles of Big Science initiatives are constantly evolving. Those principles promote 'open science' and 'open data' concepts that encourage transparency and make data available for public use. These principles also promote ethical collaboration and governance that uphold morality, diversity, and ethical considerations in science diplomacy.

The opportunities for Big Science to flourish are immense. We support the view that Big Science undertakings will continue to be a global phenomenon and that the most effective multidisciplinary and collaborative way to solve humanity's complex problems by combining human intelligence and resoluteness. Building a world-class scientific instrument such as the LHC, which can create extreme conditions similar to those immediately after the Big Bang and then analysing the results with extraordinary precision, is a daunting challenge for scientists and the LHC has proven that such endeavours are possible with human collaboration.

Many scientific issues that are fundamental in nature, such as climate change and the origin of the universe, are too big and are complex problems to solve by an individual, single country, one scientific institution or a nation.

Besides its contribution to scientific fundamental knowledge, Big Science can be more human-centric and the driver of humanistic-based economic principles. In a recent book, Professor Stephen Hill (Hill et al., 2022) outlined the power of human beings to assert fundamental values and build harmony across different cultures. The backdrop of unrelenting destruction caused by ongoing wars (e.g. between Russia and Ukraine in 2022) and other manufactured human conflicts and miseries serve as a stark reminder that the humanity has to be vigilant about the importance of building the spirit of sharing and collaborating for the good of society. Given the

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[2] See details in CERN documents: https://europeanstrategy.cern/european-strategy-for-particle-physics.

tumultuous current geopolitical trends, humans are urged to view human collaboration as a powerful tool to solve social problems—a tool similar to hunter-gatherers' splint stones for collective good.

We invite our fellow scientists and policymakers to contemplate either launching or participating in new Big Science undertakings to benefit from the key messages and potential lessons outlined in this book. Sharing the thrill and wonder of scientific discovery, we wish our readers a journey of learning filled with enriching and inspiring insights.