Big Science in the 21st Century

Economic and societal impacts

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Economic and societal impacts

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In loving memory of Steven Weinberg (1933–2021)

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Part II Economic and innovation impact of Big Science projects [Editor: Jason Li-Ying]

Preface

Last year platoons of scientists discovered exoplanets orbiting distant stars, successfully launched the James Webb Space Telescope, our latest state-of-the-art 'window' into deep space, finished sequencing the human genome, publicly offered generative AI tools, while accelerated innovation in vaccine technologies and promising therapeutics for other diseases pushed into new territories. Answering big questions often requires scientists and institutions to pool resources and data, whether the research involves detecting gravitational waves in deep space, understanding the interactions between elementary particles that are the fundamental constituents of matter, or investigating the genetics of brain development.

Impressive by any standard, such achievements nonetheless raise questions about the direction of 21st century science. The 20th century saw the rise of Big Science with its roots traced back to the First World War. Subsequently, the Second World War led to the Manhattan Project's development of the atomic bomb, which is widely considered to be the dawn of the Big Science era. Following the end of the war, intensive globalisation led to the foundation of international laboratories such as CERN in Switzerland, as well as many international collaborations led by NASA, ESA, ESO, EMBL and other Big Science organisations worldwide. Big Science projects were often perceived as the key to pushing back the frontiers of science as well as to a nation's prestige. Over the past years, Big Science has also changed phase, becoming not simply larger in scale but even more interdisciplinary and international. The open questions and mind-bending concepts explored by big scientific instruments in particle physics and astronomy also serve to draw bright young minds into science, even if some of them will later work in other areas. Fundamental science has to make its case not only on the basis of the cultural value of fundamental knowledge, but also in terms of the socioeconomic benefits that it brings to society. The impact of Big Science on economic prosperity becomes more evident if we consider its cumulative contributions to the 21st-century knowledge economy, which relies heavily on research and innovation. However, Big Science has also drawn criticism due to its long timelines and consumption of significant resources, as well as the view that large projects may reduce innovation or lead to 'group think'.

These tensions, articulated at different levels within the scientific community and the public sphere, have been transforming the scope and the characteristics of the Big Science model. Capturing these changes, and how they are manifested in different areas, is one of the motivations for this volume. The volume is organised in five parts. The first looks at lessons from Big Science organisations and best practices in increasing the return of benefits to society. We have strived to include a variety of Big Science facilities, at different levels of maturity, offering an overview of the challenges linked to planning, building, and operating these facilities. The second part presents the view of economists working in relevant fields and includes case studies that illustrate previous socioeconomic impact assessments for large-scale research infrastructures, offering new insights into the impact of Big Science organisations. The third part takes a historical perspective on Big Science, tracing its development in the aftermath of the Second World War. The essays, extending over several thematic and geographical boundaries, discuss the ways and whys that shaped the evolution of Big Science in different disciplines (e.g., physics, biology and engineering) and offer valuable insights into the modern debate about the challenges and merits of Big Science. The fourth part explores the wider cultural and educational impact of Big Science projects over the past decades. The essays discuss the potential of Big Science projects to inspire and alter how we look at our world through different media, from documentaries to Hollywood's blockbusters, and from museums to the classroom. The last part of the book offers a broader and more global perspective, by widening the discussion to cases beyond North America and Western Europe. The essays in this part examine the different challenges that Big Science projects face in other parts of the globe, while reminding us of the synergies and collaborations developed between laboratories and academia at a global scale.

Undeniably, Big Science has transformed the world in which we live and will continue to do so even if its character is transformed. The different viewpoints in this book demonstrate the ways in which Big Science has delivered intellectual, cultural and economic advancement, while reminding us that this path is not always linear. Furthermore, the blend of historical and contemporary perspectives reminds us that science is not only about discoveries but is also about the collection, replication and corroboration of results with new and more powerful instruments. A finding that seems mundane or trivial may become immensely important years later, when a parallel discovery contextualises or clarifies its implications, or by adding more precision that reveals small deviations compared to our present theoretical models. It's like exploring an unknown land; we can never know in advance whether over the next hill lies a new ocean or just another hill.

We would like to thank the authors who kindly accepted our invitation and joined us in this amazing journey. Balancing different projects and approaches and striving for an inclusive representation of the many facets of Big Science has been an arduous task for us as editors. This task was further complicated by the global pandemic, as many of us faced lockdowns and shared stories about losses and grief. As we went through different phases of the pandemic certain authors had to withdraw while delays were introduced. We are also grateful to the Institute of Physics (IOP) team, who encouraged us from the first moment and steered the production of this volume smoothly and efficiently. We would also like to thank the external reviewers who evaluated our original proposal for this book, providing invaluable feedback and further guidance. We dedicate this work to the memory of Steven Weinberg, who had kindly supported the work that became this volume. Weinberg, who died in July 2021, was not only a Nobel laureate physicist but also a prolific public intellectual who greatly supported the development of Big Science.

This volume aspires to offer a comprehensive overview of the different ways in which Big Science has impacted our society and, consequently, to open new perspectives on how to evaluate its societal benefits. It offers a glimpse of the complex realities that characterise the development and present status of Big Science. A central theme of the volume is that the impact of Big Science should be considered beyond its economic benefits to industry and innovation, or the opportunities that its facilities offer for smaller experiments, but also via its interaction with society at large, including the training of new scientists and broader cultural benefits for new generations. We hope that these essays will encourage a dialogue with other scientific communities and bring new connections between people working in science and technology studies and economists and historians.

Editor biographies

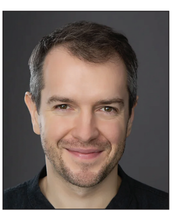
Panagiotis Charitos

Panos holds a bachelor's and a master's degree in astrophysics from Imperial College London and an MSc in Media and Communications from the London School of Economics. He joined CERN in 2011 as a member of the ALICE Outreach Group and since 2013 he has also served as co-editor of CERN's Physics Department newsletter. From 2015 to 2020 he was in charge for the communications of the Future Circular Collider project exploring the feasibility of a next generation of circular colliders at CERN. Before that, Panos had worked for major daily newspapers and publishing houses in London and Athens, and was the founder of ROPI Publications, a niche publishing house specializing in the history and philosophy of science.

Theodore Arabatzis

Theodore Arabatzis holds a Diploma in electrical engineering from Aristotle University of Thessaloniki, and an MA and a PhD in history of science from Princeton University. He was awarded fellowships from Princeton, MIT, and the Max Planck Institute for the History of Science. His research has focused on the history of modern physical sciences and on historical philosophy of science. He has published numerous articles in these areas and the monograph *Representing Electrons: A Biographical Approach to Theoretical Entities* (University of Chicago Press, 2006). He has served as co-editor of the journal *Metascience* (2010–2014). In 2017 he was awarded the IUHPST Essay Prize in History and Philosophy of Science by the International Union of History and Philosophy of Science and Technology. He was president of the European Society for the History of Science (Sept 2020–Sept 2022). More detailed information about his work can be found at http://scholar.uoa.gr/tarabatz/home.

Harry Cliff



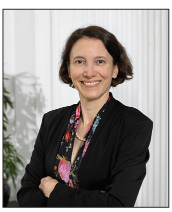
Harry Cliff is a particle physicist at the University of Cambridge's Cavendish Laboratory working on the LHCb experiment, a huge particle detector buried 100 metres underground at CERN near Geneva. He is a member of an international team of around 1400 physicists, engineers and computer scientists who are using LHCb to study the basic building blocks of our universe, in search of answers to some of the biggest questions in modern physics. His research is focussed on the very rare decays of exotic fundamental particles called beauty quarks, which have the potential to reveal evidence of hitherto undiscovered particles or forces.

Cliff is also an active communicator of science. From 2012 to 2018 he held a joint post between Cambridge and the Science Museum in London, where he curated two major exhibitions: Collider (2013) and The Sun (2018). He gives a large number of public talks, including two at TED and the Royal Institution that have each been viewed millions of times, alongside appearances on television, radio and podcasts. His first popular science book, *How To Make An Apple Pie From Scratch*, was published in August 2021 and a second, Space Oddities, will be published in 2024.

Günther Dissertori

Günther Dissertori studied Physics at the University of Innsbruck. From there, he moved to work as a doctoral student at CERN in Geneva, where he began his research career. In 2001, he was offered an assistant professorship at ETH Zurich, and six years later was made a full professor. At CERN, he was strongly involved in the CMS experiment, one of the two experiments at the Large Hadron Collider that discovered the Higgs boson. With his group, Dissertori also developed new positron emission tomography (PET) devices, including a cost-efficient brain PET scanner, which was brought to the market by the spin-off company Positrigo AG. In February 2022, he took up the role of Rector of ETH Zurich.

Juliette Forneris



Juliette Forneris holds a PhD in Geology from Arizona State University. From doctorate and post-doc studies focused on the thermodynamics of minerals, she transitioned into the fascinating world of Big Science through subsequent positions at Danish firms supplying goods and services to Big Science organizations. From 2010 to 2019 she was network manager for BigScience.dk, a publicly financed initiative to promote Danish companies towards the Big Science market. Throughout that period, she served as Industrial Liaison Officer for CERN and ESO, played a central role in the first Big Science Business Forum in 2018 in Copenhagen, and also chaired CERN's ILO forum from 2015 to 2018. In 2019, Juliette became the director of the International Centre at the Danish Technological Institute, while still keeping in touch with the world of Big Science through collaborative R&D projects.

Jason Li-Ying

Jason Li-Ying is a well-recognized figure in the international research society of innovation management. His research and teaching interests include technology & innovation management, innovation and organizational learning, strategic management, and technology transfer. Besides his excellence in research and education, Jason also has extensive experience in innovation strategy and business development for SMEs by acting as strategic advisors for a number of innovative companies. He also has an excellent track record in teaching, coaching, and supervising EMBA students and teaching courses at Master's and PhD level programmes in product design innovation, innovation management, and business strategy at Technical University of Denmark (DTU). Jason is also visiting professor at University of Management and Economics (ISM) in Lithuania, a faculty member of DTU Executive School of Business, and a faculty member for the 'Eurotech Universities' with respect to the Innovation Economics PhD program. His recent running research projects focus on innovation and corporate entrepreneurship at Big Science facilities (Research Infrastructures); the relationship between technology searching (through licensing) and innovation and digital business model innovation for SMEs.

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Part I

Voices from European Big Science Organizations [Editor: Juliette Forneris]

IOP Publishing

Big Science in the 21st Century
Economic and societal impacts
Panagiotis Charitos, Theodore Arabatzis, Harry Cliff, Günther Dissertori, Juliette Forneris and Jason Li-Ying

Chapter 1

Introduction to part I: Voices from European Big Science Organizations

Juliette Forneris

Big Science projects represent the scientific flagships of the twentieth and twenty-first centuries, created by the combination of intense international research collaboration and massive investment. Whether located on Earth, in space, or the virtual world, they symbolize the incredible human endeavours to understand the world around us and to solve the challenges of our times.

The common traits of Big Science projects are the level of scientific excellence, the enormous budgets to plan, build, and upgrade facilities sometimes compared to giant 3D puzzles, the huge amount of scientific, technical, managerial, and administrative staff, the engineering skills required to make the science happen, and the complexity of the project management.

There is no consensus, neither in this book nor in the existing literature, about the terminology used to describe Big Science projects and the organizations behind them. The terms Big Science projects or facilities, research infrastructures (RI), large scale research infrastructures (LSRI), and analytical research infrastructures (ARI) are some of the names that are used, sometimes interchangeably, to describe them. This is likely because they have their origins in different scientific communities but also because Big Science is a concept that has undergone evolution and diversification from the middle of the twentieth century until now:

1. *Scientific domains*: The early Big Science facilities had a strong focus on physics and astronomy. They were for the most part driven by a quest for advancing our understanding of the Universe. They are still often referred to as 'Big Physics'. Towards the end of the twentieth century, a diversification in scientific domains took place, giving rise to Big Science facilities for the life sciences, ICT, and social sciences.
2. *From fundamental to applied research*: Although many currently running Big Science facilities are still focused on producing beyond state-of-the-art

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fundamental research, more and more facilities have been built for the purpose of applied research in a broad range of scientific domains. These Big Science facilities are characterized by a large user community encompassing both academics and industrial users.
3. *From single-sited to distributed and virtual facilities*: As an effect of the increasing size and complexity of Big Science projects, together with advances in data science, distributed and even virtual Big Science facilities have emerged.

For the first part of this book we reached out to a range of both mature and newer European Big Science Organizations (BSOs) to give the reader an overview of the challenges linked to planning, building, and operating Big Science facilities, including the ever-growing demand from their stakeholders for documenting the socio-economic impacts. Several of these BSOs have ongoing collaborations established, for example, via EIROforum[1], ESFRI[2], LENS[3], LEAPS[4], CERIC-ERIC[5], or bilateral agreements. However, in 2018, the Big Science Business Forum (BSBF2018) was the first large public event to showcase the existence of a consolidated Big Science market and to create a stronger collaboration amongst BSOs. Under the leadership of the Danish Ministry of Higher Education and Science, nine BSOs (CERN, EMBL, ESA, ESO, ESRF, ESS, European XFEL, F4E, and ILL) joined forces to present future investments worth billions of euros (BEUR) for the Big Science industry. During the preparation of the event, the interest for other BSOs to participate grew and an additional nine BSOs (ALBA, DESY, ELI-NP, ENEA, FAIR, MAX IV, SCK•CEN–MYRRHA, PSI, and SKA) joined BSBF2018 as affiliated BSOs. During the three day event, over 1000 participants from more than 500 businesses and organizations representing 29 countries gathered to listen to over 100 speakers from these 19 BSOs and discuss how they could do business out of the over 12 BEUR in future investments presented. The success of this first event led to a pledge for a follow-up event in 2020, which due to the COVID-19 pandemic, only took place in 2022, in Granada. The idea of bringing some of these organizations together for part I of this book 'Voices from European Big Science Organizations' is also one of the direct impacts of BSBF2018.

Part I is structured around four overarching themes:

1. *The efforts to assess the socio-economic impacts of Big Science projects* are at the core of the essays from Anelli, Nordberg, and Charitos for CERN, Mathieu, Laurich, and Willekens for ESA, and Williams and Ferreira for ESO. Due to the maturity of these three organizations, a large amount of data is available to identify the long-term impacts measured after years of operation of their facilities. The conceptual frameworks and methodologies

[1] https://www.eiroforum.org/
[2] https://www.esfri.eu/
[3] https://lens-initiative.org/
[4] https://leaps-initiative.eu/
[5] https://www.ceric-eric.eu/

for impact assessment are discussed by the authors specifically for each of their organizations and Big Science projects. The essays cover a broad range of benefits from Big Science projects: scientific, technological, strategic, societal, and economic. Socio-economic impact assessments are increasingly important to BSOs and their funding bodies in light of future investment needs, but are complex analyses requiring important efforts and a systematic approach.

2. *Developing business cases for new Big Science facilities and measuring short-term impacts*. Not all Big Science projects are currently at the operation stage. Nevertheless, investigating the shorter-term impacts resulting from the construction of a Big Science facility before it even starts producing scientific results illustrates other benefits to society, as argued by Biagioni (Fusion for Energy (F4E)) in the case of ITER. The question of how to develop business cases for new Big Science facilities is addressed from different angles by Womersley for the European Spallation Source (ESS) and by Weeks, Gliksohn and Schmidli for the Extreme Light Infrastructure (ELI ERIC). While the science case is still at the heart of the decision-making process to build a new Big Science facility, key requirements are placed on the funding, governance, project management, stakeholder engagement, and cost–benefit analysis.
3. *Big Science engaging with industry*. Big Science facilities are typically planned by and built for scientists but much of the engineering work behind the science is done in collaboration with industrial suppliers (the Big Science industry). This covers a broad range from unique products based on state-of-the-art R&D work (e.g. detectors, superconducting cables, and neutron guides), to the supply of high-tech products (e.g. high-precision mechanical components, special coatings, and power supplies) to completely off-the-shelf products. Verhoeven *et al* explore how industrial liaison officers act as key intermediaries between BSOs and their industrial suppliers to ensure the best match between the demand and the supply. In their essay 'Analytical research infrastructures and industry engagement: drivers, challenges, and impact' Appleby *et al* explore the complex ecosystems for industry engagement around ARIs focusing on three paths of engagement: industry as a user, industry as a technology partner, and enterprises and research technology organizations (RTOs) as intermediaries.
4. *Big Science: constantly morphing to adapt to scientific and societal challenges*. In addition to being measured against their socio-economic impacts, BSOs are also under constant pressure to reinvent themselves to stay at the forefront of scientific developments. A prime example of this long-term sustainability is illustrated by Haid and Lehner through the almost 40 years of operation and three 'lives' of the DORIS storage ring at DESY in Hamburg. In their essay von Bredow *et al* investigate how the European Molecular Biology Laboratory (EMBL) and by extension other BSOs can affect and also respond to changing societal, scientific, and cultural norms in areas such as bioethics, data privacy, environment policies, and research integrity.

Part I, 'Voices from European Big Science Organizations', was not conceived to present an exhaustive catalog of the largest European BSOs. The purpose was instead to give the reader an idea of the scientific and technological complexity combined with the socio-economic accountability that comes with investments in Big Science. We hope that we have succeeded in giving these insights and that this work will inspire further studies encompassing more ESFRI landmarks and projects[6], and potentially exploring the specificities of the growing number of virtual infrastructures in the context of the socio-economic impacts.

[6] https://roadmap2021.esfri.eu/media/1251/rm21-part-2.pdf

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