10
Big Science as a Complex Human Enterprise

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10.1 Introduction

Open science is the fabric of making scientific research and research data available to every user irrespective of their role and contribution to research endeavours. The design or the rubrics of the scientific ethos and process constitute two starting reference realms for undertaking the complex task of analysing the contribution of Big Science to society. Open science facilitates ready access to scientific research and the wider dissemination of data and information. Such open science objectives are to enhance and accelerate learning and innovation and benefit society. This, in turn, increases trust in science and builds the credibility and reliability of scientific enterprises, invigorating a better understanding of the role of science in society.

This chapter offers yet another set of interlinked facets aiming to illustrate that scientific activities are complex and multifaceted human enterprises that escape closed and rigid definitional frameworks.

Thus, the first section starts by offering a view of science, society, and values in a historical context. Given the inescapable interdependence between science and society, this historical reflection also includes a social dimension. In this sense, the central issue being thought through is how science should advance in society and which social values should be cherished. Although answers to this complex question are far from straightforward, it is clear that science should engage holistically with the many aspects of engaging the norms and values of society embedded, for example, in politics, the arts, the economy, wellbeing, etc.

Using these factors as a foundation, the second section examines Big Science from the viewpoint of aiding in the emancipation of humanity, or the less fortunate and disadvantaged people of the world. Big Science produces both direct and indirect social benefits, particularly when it comes to major challenges and issues like climate change.

In light of the upcoming challenges to our society's future, the third section examines how scientific and artistic endeavours can energise one another by fostering

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interdisciplinary forums for discussion and experimentation. Humanity needs to search for opportunities to launch ambitious and ground-breaking projects in order to respond in a way that disrupts systems and technology. The final section considers whether strictly neoclassical economic frameworks are adequate or even suitable for valuing Big Science given how diverse it is and especially how historically entwined it is with society.

10.2 The Social Value of Big Science

Given the various paths from fundamental science to experimental development, contributions to society can be viewed as a common denominator linked to the characteristics of research organisations. Indeed, the increasing high-technology requirements of research provide a fertile ground for technology and knowledge transfer, promoting the injection of science into all levels of daily life in a variety of ways.

Consider, for example, quantum entanglement, a physics phenomenon based on quantum theory. Who could have imagined the practical applications of cryptography and computing would result in the formation of companies to protect information sharing?

When organisations dealing with fundamental sciences permit 'freedom' to think, do, and discuss freely, it is possible to find fundamental research as a common denominator for technological development and applications. If so, is it not possible to provide non-science organisations with some basic guidance that will help them achieve this 'freedom' and teach them how to use it for themselves? The answer to these questions was well illustrated by Sir Ben Lockspeiser, the first President of the CERN Council in 1954, who stated: 'Scientific research lives and flourishes in an atmosphere of freedom—freedom to doubt, freedom to inquire and freedom to discover. These are the conditions under which this new laboratory has been established' (Lockspeiser, 1954).

In the case of CERN, high energy physics stimulates the continuous production of innovative technological development. In the quest to find out what matter is made of and how its different components interact, these organisations need to develop highly sophisticated instruments, in which technology as well as required performance often exceed the available industrial know-how. This is why, since its creation in 1954, CERN has pursued the tradition of collaborative partnerships with industry and making CERN's technologies available to third parties. In the LHC experiments, almost half of the participants are from non-member states of CERN. As a result, the technological learning from high energy physics has spilled over worldwide.

This worldwide spill over concerns not only technological learning but also the development of frontier technologies required in Big Science and their utilisation in fields other than those they were originally developed for. Scientific organisations are constantly improving their capabilities for making real-time observations, interactive data analysis, and automated processes.

The LHC experiments, astrophysics experiments, and gravitational waves laboratories have knowledge reservoirs that bring significant benefits to society. The recent

Covid-19 was an example of how knowledge reservoirs in physics and medicine at EMBL-EBI (PDBe-KB Covid-19 Data Portal) and the Repository of Corona Disease Research Community made available through Zenodo, which is a multi-disciplinary open repository maintained by CERN, were linked.

Each year hundreds of young people join organisations like CERN, as students, fellows, associates or staff members taking up their first job. This continuous flow of people, who come to these research centres, are trained by working with experts, and then return to their home countries, exemplifies knowledge and technology transfer via people. However, when it comes to industry, the potential of organisations such as CERN may be underutilised. It would be possible to enhance the spectrum of their technological impact by paying attention to their technological learning management.

Several studies provide evidence that the socialisation of participants in meetings leads to the acquisition of skills in various areas (Bressan, 2004; Bressan et al., 2008; Bressan, 2010). The development of interests through interaction with colleagues is a critical element in the learning process. The learning processes extend from tacit knowledge, which is essentially personal and hard to share, to explicit knowledge, which can be easily shared.

Individual and organisational learning is a core asset of research organisations, the latter being the social process by which a group of people collectively improve their capacities to produce an outcome. The creation of organisational knowledge amplifies the knowledge that is created by individuals who spread it at the group level through dialogue, discussion, experience, or observation (Nonana and Takeuchi, 1995).

Big Science research organisations must provide a context in which individuals can hold both formal and informal discussions to steer new ideas and foster collective learning if they are to be effective in the process of knowledge translation. This type of knowledge generation is regarded by economists and sociologists as significant, because such processes support organisational and technological innovation relevant to industry and society.

Scholarly studies (Kogut et al., 1992; Grant, 1996; Spender, 1996; Autio et al., 2003, 2003b, and 2011) have confirmed that knowledge acquisition in a multicultural environment is linked to interactions between social capital components (social interaction, quality of relationships, and network connectivity) and competitive advantage (development of inventions and uniqueness of technology).

Large experiments, such as those at the LHC, serve as the hub of an institutional and organisational network at CERN. Interactions between individuals and experiments, enabled by the collaboration's organisational structure and the frequent use of modern communication tools such as emails and websites are important routes for knowledge translation.

The fertile environment such as the LHC experiments fosters a dynamic, interactive, and simultaneous exchange of knowledge both inside and outside the collaborations, allowing individuals to create and expand knowledge through their social networks while also involving industry at various stages of project development.

Thus, when working in scientific environments, if the development of personal skills is well managed, used, and catalysed to target individual development, it is possible to improve labour-market opportunities. Individuals with a sense of entrepreneurship may want to consider working for a company that promotes learning and innovation in science enterprises, which can also be used for social business purposes (Bressan et al., 2008).

Nobel laureate Muhammad Yunus, a Bangladeshi social entrepreneur, banker, economist and civil society leader founded the Grameen Bank and he was awarded the Nobel Peace Prize in 2006, 'for their efforts through microcredit to create economic and social development from below'. The social business income is reinvested in the business itself with the aim of increasing social impacts. Yunus' philosophy was to profess the social benefit of the social enterprise and he demonstrated that it is possible to develop a social enterprise built on the selective transfer of knowledge and technology.

Such transfers can foster innovative solutions to promote good governance and develop strategies to address emerging global security challenges and the risks of over globalisation leading to inequity and social unrest. Besides Big Science initiatives, there are a myriad of other actions needed to foster innovative solutions to promote good governance and strategy to address emerging global security and economic challenges. The risks of globalisation, wars, pandemics, human rights violations, and poverty always have drawbacks.[1] In Yunus' words, 'a charity dollar has only one life; a social business dollar can be invested over and over again' (Yunus, 2009; 2011).

In doing that, Big Science organisations such as CERN in partnership with other governmental organisations such as the UN can promote emancipation processes leading to enhanced cooperation and operability for developing an intertwined framework among global members and stakeholders to make knowledge actionable from local to global. Under the 2030 UN agenda, the 17 Sustainable Development Goals (SDGs) could be a place to look for some inspiration.[2] It is possible to find actionable applications of such fertile collaborations in disadvantaged countries as well.

In his recent book on The Kyoto Post-Covid Manifesto for Global Economics, Hill and his colleagues (Hill et al., 2022) observe the underlying dynamic of the majority of contemporary global economics, self-interest, but then demonstrate the power of drawing our relationships instead from the wellspring of what makes our *humanity* work—*sharing*. The Kyoto Post-Covid Manifesto moves on to show how this alternate sharing dynamic can be built into existing and new institutional and exchange relations through 'Humanity-centred transformation'. The result is that the organisations and their exchange relationships become more productive because the participants now live and benefit from 'an increasingly broad culture of trust and cooperation rather than divisive self-interest and greed' (Hill et al., 2022: 352).

[1] W.L. Christman, *Global Resilience*: *The Manifesto* (forthcoming).

[2] CERN has observer status in the UN General Assembly.
https://home.cern/news/press-release/cern/cern-granted-status-observer-united-nations-general-assembly.

In this context, one example has been the realisation of a local IT social enterprise, a spin-off of UNRWA[3] based in Gaza, Palestine, where almost 70% of the approximately 1.000 students, who yearly graduate in Information and Communication Technology (ICT) programmes from local universities have difficulty finding a job[4] despite the rapid contextual industrial growth in this sector.[5]

Funded by the Korean government to provide short-term employment and a learning environment for young ICT graduates, this non-profit initiative aims to establish a local ICT service development business park as a hub for overseas ICT outsourcing solutions to a wide range of clients. In agreement with UNRWA, CERN invited the management of the UNRWA start-up to specific open-source software sessions in its IT Department, representing Gaza's possible solution from academia to the private sector, in order to fulfil the young social enterprise's mission and establish its high-potential socio-economic impact. The project allowed its staff to acquire the necessary knowledge and know-how to enrich their services and activities to better satisfy customers' needs and increase market segment opportunities. This is another example of how Big Science organisations can address social problems at the grass roots level.

Such initiatives between research laboratories and intergovernmental organisations like CERN and the UN will not only increase the social value of basic science but will also serve as a guidepost for future young leaders who will be able to build social businesses in order to positively impact their communities and society and to foster a new resilience culture.

As the former CERN Director General Rolf-Dieter Heuer said, 'Science has a responsibility to bring itself to the mainstream of popular culture, to engage in and shape public debate about major issues that are science based. It has the responsibility to make itself accountable, particularly if it is publicly funded. And it has a duty to work to the highest possible ethical standards. Science underpins almost every aspect of modern life, be it economic, social, cultural, or humanitarian, and it is blind to race, gender, language, and religion. In short, science represents the best in humanity' (Heuer, 2018).

10.3 Art, Design, and Science Colliders—Creating New, Young Leonardo's

The cultural convergence of art, science, and technology today is well represented by a community of international institutions that is a platform for collaboration. Exemplars such as the establishment of the Leonardo institution, the journal and book series founded (1967–1968) by Frank Malina, an aeronautical engineer and a kinetic sculptor, were important catalysts for ongoing social, political and environmental

[3] UNRWA: United Nations Relief and Works Agency for Palestine Refugees in the Near East.
[4] Mercy Corps Labour Market Needs Analysis for the Digital Economy, 2013.
[5] World Bank Ad Hoc Liaison Committee Report, covering the first nine months of 2012, estimated that the sector contributed 0.02% to Gaza's GDP growth; UNESCO Socio-Economic Report: Overview of the Palestinian Economy, 2013.

debates through the nexus of art–science interaction. One of the two key goals, as outlined by Leonardo, the International Society for the Arts, Sciences and Technology, MIT Press, and the affiliated French organisation Association Leonardo, is 'to create a forum and meeting places where artists, scientists, and engineers can meet, exchange ideas, and, where appropriate, collaborate', to tackle the 'hard problems' and bring about new agendas in science and opportunities for technological innovation.[6]

A generation later, a plethora of international organisations including science research centres like CERN, cultural institutions, universities, government, and private funding bodies are a locus for such forums.[7] This forum is a catalyst for new disciplinary collaborations, emerging theories, sharing of practices, and increased dissemination (true and false) of data across a spectrum of science. A common occurrence is the emergence of inter and transdisciplinary practices (Van Noorden, 2015; Bliemel and van der Bijl-Brouwer, 2018) through experimentation and invention.

Forums such as the European Digital Art and Science Network[8] initiated by Ars Electronica invite artists and scientists together to connect arts and cultural institutions with ESA (European Space Agency), CERN, and the ESO (European Southern Observatory). The forums are catalysts for co-innovation; multi and interdisciplinary, cross-sectoral serendipitous engagement, and research. Spaces such as studios, workshops, galleries, cafes, and laboratories, encourage structured serendipity facilitating unlikely interaction.

The Design Factory Global Network, mentioned in Chapter 6, is one example of a change agent that uses networks and nodes made up of cross-sectoral, international universities and research organisations to structure serendipity and innovation across disciplinary silos (Björklund et al., 2019). Other forums include the European Commission's 'Science with and for Society' (SWAFS, 2020) full cycle innovation programmes structured for diverse societal actors; researchers, citizens, policymakers, businesses, and non-governmental organisations.[9]

ATTRACT[10] mission shifts gears to accelerate the conversion of opportunities gleaned from Big Science's lengthy timescales and advances structured serendipity to systematise serendipity for ground-breaking applications (Wareham et al., 2022).

With the help of Big Science initiatives, such as the CERN experiments, ATTRACT aims to create the next generation of scientific tools that will enable the emergence of new businesses (see Figure 10.1).

Despite their differences, both arts and science share a common goal in the above-mentioned programmes to combine the contributions that artists, designers, engineers, and scientists can make to the challenges of our time:

[6] https://mitpress.mit.edu/books/series/leonardo.
[7] http://userwww.sfsu.edu/infoarts/links/wilson.artlinks.org.html.
[8] https://en.unesco.org/creativity/policy-monitoring-platform/european-digital-art-science.
[9] https://horizon-swafs2020.b2match.io/.
[10] https://attract-eu.com/about-attract-phase-2/.

Both value the careful observation of their environments to gather information through the senses.
Both value creativity.
Both propose to introduce change, innovation, or improvement over what already exists.
Both use abstract models to understand the world.
Both aspire to creative works that have universal relevance.

(Wilson, 2002: 18)

Forums like residencies in scientific organisations, museum outreach programmes, academic institutions, and cultural organisations that have been boosted by digital social networks have allowed experts and non-experts alike to interact across the fields of art, design, science, and technology in order to use the research done by others and look into alternative contributions to their own research. The forums, such as the Australian Network for Art and Technology[11] for art sciences research have potentially influenced the idiosyncrasies of science production experiences. Increasing interest 'among scientists in interdisciplinary projects at the interface between art and culture'[12] may see the inclusion of aesthetic approaches to resolving a problem or at the very least offer multiple avenues for communication. Such is the case in the fight against plasticised fish and the unacceptable status of the 'plastisphere'. The exhibition and book, *Mare Plasticum* (Streit-Bianchi et al., 2020) reaffirm scientific purpose as an art intervention drawing on marine biologists, ecotoxicologists, oceanographers, mathematicians/modellers, chemists, and physicists

Figure 10.1 ATTRACT programmes connect industry and research organisations
Source: ATTRACT

[11] https://www.anat.org.au/about/.
[12] https://en.unesco.org/creativity/policy-monitoring-platform/european-digital-art-science.

motivated by the urgency to act. Aesthetic and experiential approaches to science that are more than or extend beyond the purpose or utility of the science as transferable to other or unintended outcomes are less likely to emerge from a single discipline.

Reflecting on the design science research lens, what can we learn from science's integrated approach to the analytical, logical, theoretical, and synthetic aspects—as well as the practical value and conversion in the real world and the aesthetic—from a design science research perspective? What can we learn about the subjective experience of science? Which includes pleasure and flow (Baskerville et al. 2018)?

A snapshot of exemplars reaffirms the arduous journey from fundamental science towards unexpected permutations as a result of historic forums including:

- www.jodi.org, 1995 (Joan Heemskirk and Dirk Paesmans), responding to the aesthetics of the then World Wide Web (WWW), revealed abstract, non-functional designs commenting on slippages in truth and misinformation represented by a non-user design. Jodi.org, like many other information arts and design contributions built a digital language, disrupting print and providing new paradigms for omnipresent visualisation in today's common work tasks such as maps, 3D digital worlds, the use of gamification and database aesthetics;
- *Software engineer network collectives*: a hive model approach to open software use, also generated new interface visualisation semantics and interaction born from social networking, code sharing, and publishing. This community of practice democratises open-source development for rapid ideation, project development, and distinct repertoires of practice and language. Functions also have new graphic semiotics and hybrid languages, such as *fork, pull, request, and re-use*, which describe in very general terms a process where you can copy, extract, re-use, redevelop, add on to another string of code and improve, live test, and generate something new;
- *A tradition of citizen science*: through digital networks improved accessibility as volunteer computing clouds, volunteer thinking; projects like Seti@home (extra-terrestrial life search), Einstein@home (gravitational wave detection), Folding@home (protein folding), and ClimatePrediction.net (large-scale modelling of Earth's climate), (Bonney et al., 2014).

The above examples underscore the sentiment of working for a better world, which is increasingly found at the intersections of disciplines (Malina, 2008). He names a future generation of creative individuals, thinkers, and builders, 'new Leonardo's' at the intersections and disciplinary boundaries. Malina's report on four decades of contributions at the intersection of art and science saw the emergence of new Leonardo's, individuals and teams responsible for a new cultural fabric who both develop meaningful art, drive new agendas in science and disrupt technological innovation to address hard problems (Malina, 1997; Malina, 2008).

These creative individuals include the new Leonardo's who are pursuing basic science for both fundamental research and the rising demand for influencing major, intricate, and urgent social innovation challenges. Today, there may be a new generation of Leonardo's who will seek inspiration by crossing disciplinary boundaries, investigating alternative methodologies, engaging with and developing novel aesthetics, and perhaps even influencing their discipline. New Leonardo's may at the boundaries or outside specific disciplines create new or hybrid disciplinary fields, inventions, and experiments to respond to their world and future. New levels of access on professional, social, and disciplinary fronts afford new Leonardo's access to technical, scientific, digital, aesthetic, and cultural differences. The convergence of disciplines, 'Alt.Art-Sci' by a 'networked' community of practice conversant with big data, distributed networks, and digital culture, is motivated out of purpose as hackers, makers, and people's science movements are motivated by communities of interest (Malina, 2011). The acceleration of social development is influenced by the digital, technical, and network world, where social media redefines new words in the dictionary, disrupting, and influencing applications of creativity, the experiential, and narratives for art and science (Rosa, 2010).

New Leonardo's look through new lenses and open up to new tools and new research methods. The new Leonardo's, the contributors to basic science, may similarly draw on other sources of inspiration or disciplinary expertise. CERN's research data analysis platform was created as a result of leveraging code and data recycling, as led by the REANA project (Beck et al., 2020: 20).

Futuristics suggest that in the transition from traditional Big Science to modern Big Science, it is essential to focus on innovation for global challenges, economic growth, and sustainability in addition to science (Hallonsten, 2016).

Part of this mandate is to instigate breakthrough innovation in society, which necessitates the investigation into socio-cultural models, resulting in art, design, and science synergies. Art- science synergies have shifted beyond the socialisation of science for breakthrough innovation through design-driven innovation research (Verganti, 2008). Design methodologies are incorporated invariably into science experiments consciously or unconsciously as part of Big Science construction process. This concept trickles down to the values of technology applications in society through the focus on 'how signs, languages, and symbolic elements are shaped and diffuse society' (Verganti, 2008: 442).

As Big Science innovation projects explore the meaning and value of technological applications for society, design methodologies integrated into science experiments with 'how signs, languages and symbolic elements are shaped and diffused in society' (Verganti, 2008: 442) in cultural production.

There are many questions that need answers or solutions. What peculiarities might have emerged as a result of science synergies involving Big Science, deep technology[13] and enmeshed sciences as well as information, communication, and/or computational communication technologies?

As Big Science includes theory, laboratory experiments, Gedanken or thought experiments, and computer experiments (Mitchell, 2009; Li Vigni, 2021), how have

[13] https://www.ansto.gov.au/work-with-us/nandin.

interactive, experiential, and visual modes of science evolved in both fundamental and applied forms? What possible influences, for example, of computer modelling and simulation have influenced information design and vice versa? For example, in order to codify and widely share and distribute data, New Leonardos, who are digital natives, have integrated interaction, visualisation, simulation, and gamification as a kind of communication aesthetic (Reas and Maeda, 2004).

What can we learn about the techniques and art of Big Science, which influences disciplines at the boundaries through aesthetic approaches and methods?

New Leonardo's are well understood for contributing to artistic responses to science, however, they may equally be found in scientific responses to art and design. What can we learn from the New Leonardo's, the researchers, scientists, and advocates known as moonshots whose teams are for the mission itself purely to seek and solve the mission? Moonshot missions, synonymous with the challenges of the moon landing, are likened to ambitious, radical, exploratory and ground-breaking projects or missions. What aspects of the craft, specifically the theory, the lab, the mind, and computer experiments, have an impact on the internal and external collaborations of moonshot missions?

Today's generation of new Leonardo's contributes to cultural diversity and draw on multiple digital network touchpoints for information. It is at the intersections of different disciplines where co-innovation is more likely such as the Manhattan Project, the Human Genome Project (HGP) and Large Hadron Collider (LHC) experiments at CERN (Beck et al., 2020). Arts at CERN programme, invites multiple disciplinary contributions in the world's largest laboratory of particle physics to explore 'notions of creativity, human ingenuity and curiosity'.[14]

Exploration of basic science through a diverse disciplinary lens of art, design, science, and technology, has demystified the discourse of basic science (Latour, 1987), socialising institutional co-operation and increasing mutual respect for interaction across disciplines. However, the new Leonardo's, working in basic science, are drivers and producers of a highly specialised discipline, grappling with the building blocks of the universe, engaged in a language of head splitting theories that are challenging to learn let alone comprehend for the layperson. They may yet benefit from art and science forums offering artefacts, methods, and narratives, reinforcing the value and practice of experimental or novel methods and resulting aesthetics. The age of accelerations, digital convergence, artificial intelligence, and social networks has seen new image schemes, (Johnson, 2008) and aesthetics derived from the visualisation of complex large amounts of data; thus, building systems of symbols and narratives. Artists, software engineers, information designers, and scientists build software and form networks to find 'unusual relationships between events and images' (Wilson, 2002: 19). The artefacts born out of computational science include information design, computational aesthetics, and design thinking approaches to human–computer interaction providing an arsenal for new

[14] https://arts.cern/.

Leonardo's to experience methods that include ambiguity, serendipity, and accident (Maeda, 2019).

Could the interdisciplinary dialogue and experimentation forums envision by Leonardo and now exemplified by places like IdeaSquare and CERN (see Chapters 6 and 14) foster young Leonardos, mitigating Negroponte's risk of a big idea famine (Negroponte, 2018)? Big Science questions require 'long time horizons and high risk' (Negroponte, 2018), and ongoing benefits from art, design, and science forums in the pursuit of basic science are part of a cultural discourse.

The new Leonardo's are more likely to be enriched, 'by standing on each other's shoulders' (Negroponte, 2018) and shoulders from diverse disciplines to create a culture that explores questions about the universe we live in and how to apply this knowledge.

Normative actions in science can likely gain new insights if they stand on the shoulders of idiosyncratic arts. Answering the call in the first volume of Leonardo is to 'ask not what the sciences can do for the arts, ask what the arts can do for the sciences' (Malina, 2008). Today, as the importance of the problem context rather than the discipline grows, debates about disciplinary heterogeneity continue. Clues towards transdisciplinary thinking for emerging and disciplinary subspecialties 'may emerge in response to paradigmatic shifts, scientific spill-overs, increases in available data or the development of new types of data' (OECD, 2020: 29).

Finally, the difficulty in communicating meaning through the experience of Big Science is diffusion, which will facilitate through rich dialogue explored in art, design, and science forums, regardless of disciplinary differences. When discussing the difficulties of building the new collider, Tara Shears, a physicist at the University of Liverpool, writes that 'we do know that the only way to find answers is by experiment and the only place to find them is where we haven't been able to look yet'. This statement highlights the tensions that exist in any discipline between facts, context, and the connections that make information meaningful (Castelvecchi and Gibney, 2020).

Scientific and cultural endeavour calls for new Leonardo's from all walks of life to invest in the pursuit of understanding science and ourselves. Many fields and interactions between art, science, and design have shown the value of viewing things via an aesthetic, subjective, abstract, and emotive lens.

10.4 Valuing Science and the Need for a New Paradigm

One outstanding characteristic of fundamental research is the substantial time lag between discoveries and their materialisation into tangible and pragmatic benefits for society (Stefik and Stefik, 2004; Lehman and Stanley, 2015). Let us briefly illustrate the case with Schrödinger's equation below (Fleisch, 2020). It is not the aim to enter into physics or mathematical considerations of Schrödinger's equation here, but we cannot resist the temptation of writing it down in its modern form.

Thus, if you are not a technically trained reader, please consider the strange signs below in the same way as an abstract painting:

$$H\psi = E\psi$$

(H=double derivative. E= energy of e- Ψ= wave function representing e-)

It's interesting that all of the supposedly quantum particles' locations are controlled by this 'intellectual' thing, which is mysterious but elegantly symmetric. One of them is the electron, which is the ultimate 'actor' behind the operation of all the electronics devices we use today, such as your laptop and smartphone. It was proposed in 1925 by the Austrian-Irish physicist Erwin Schrödinger. The first working device fully based on his equation was the point-contact transistor invented in 1947 by the American physicists John Bardeen and Walter Brattain while working under the American physicist William Shockley at Bell Labs. Nevertheless, the realisation of the first integrated circuit did not come until 1958, thanks to many different contributions from scientists of diverse disciplines, especially Jack Kilby while working at Texas Instruments and Robert Noyce who co-founded Fairchild Semiconductor and Intel Corporation. Nonetheless, the personal computer did not become a mass-market consumer electronic device until 1977, when the first microcomputers were released (Orton, 2004).

As a result, there has been a 52-year gap between Schrödinger's audacious leap of creativity and imagination and the first market-ready electronic devices. Today, the electronics industry segments itself into various sectors. Just as an example, in 2018, into semiconductors generated annual sales of over $480 billion in 2018.[15] The largest sector, e-commerce, spawned over $30 trillion in 2017.[16]

Certainly not bad for a fundamental physics equation!

The incredible journey from Schrödinger's equation to the first microcomputers and beyond, teaches several lessons. Here, we highlight two of them. The first is that the pathway from Fundamental Science discoveries through abstract thinking towards tangible and concrete market innovations is highly non-linear and serendipitous. The second is that it is necessary, in view of this non-linearity, to have a long-term economic perspective mind frame. Unfortunately, the traditional economic mind-set, tools, and paradigms are not always suitable in this respect. Therefore, as this chapter title suggests, there is a need for new paradigms in the realm of science, and more in particular, Big Science valuation. One of the, arguably, most illustrative examples is the so-called discount rates.[17]

We use here a context for discount rates as the one considered in Discounted Cash Flow analysis (DCF). DCF models are powerful, however even the most sophisticated DCF calculations have shortcomings as they are purely mechanical and the

[15] Semiconductor Industry Association. 5 February 2018. https://www.semiconductors.org/.
[16] United Nations Conference on Trade and Development. 29 March 2019. https://unctad.org/en/Pages/Home.aspx.
[17] Economics of Big Science was extensively discussed, please refer to https://cds.cern.ch/record/2744400?ln=en; for discount rates in various engineering economics books and http://sciencebusiness.net/sites/default/files/archive/eventsarchive/OpenScience/BigScience.pdf.

quantitative valuation tool is subject to the axiom 'garbage in, garbage out'. Big Science projects are extremely complex, large, and have various components that work as a system, which has many variables and uncertainties and often runs for decades. Therefore, it is difficult to accurately predict future cash flows and costs associated with such projects. However, DCF is a widely used valuation method, based on the concept of 'time value of money'[18] for some R&D projects. DCF is an economic analysis tool for estimating the value of an investment based on its expected future cash flows. It helps assessing the viability of a project or an investment by calculating the present value of expected future cash flows using a discount rate.

It would be beyond the purpose of this section to enter into a full analysis of DCF. Therefore, the intention is to illustrate, with a somehow detailed example in the DFC context and especially for the not-so-familiar reader, the unsuitability of classical economic tools for long-term thinking. The concept of discount rates serves the purpose since, as it is worth noticing, acknowledged economic experts have expressed concerns since early on. For example, Hardin states that:

> The economic theory of discounting is a completely rational theory. For short periods of time, it gives answers that seem intuitively right. For longer periods, we are not so sure.
>
> (Hardin, 1981)

For getting our heads around discount rates, it is useful considering two economic concepts that we will illustrate below with examples as explained in *Revealed Time Preferences* and *Opportunity Costs* (Drupp et al., 2018) as explained in future value. The future value of a sum of money today is calculated by multiplying the amount of cash by a function of the expected rate of return over the expected time period. Future value works in the opposite way, discounting future cash flows to their present value.

Another important concept is the opportunity cost. In the economics language, how much an investment pays in the future relative to other potential uses of the same invested money is known as its opportunity cost.

The joined consideration of the *Revealed Time Preference* and the *Opportunity Costs* establishes in economic terms the discount of the value of future benefits. An intuitive way of thinking about by imagining yourself as an investor. Any returns you will receive in the future recede each year by some percentage with respect to their value today. The longer they materialise in the future, the more they decline with respect to their value today.

The discount rate is the percentage that a return (or benefit) declines in value each year into the future. Let us illustrate the inadequacy of discount rate reasoning when long-term thinking is required. In practical terms, discounting means that a gain or loss in 50 years, for example, would be valued, using a relatively low discount rate at 4%, at only 14% of its value now. Transposed to problems faced by the world,

[18] For a detailed discussion on these topics relevant to Big Science projects see Florio (2019).

imagine an environmental related damage cost of $1 billion in one hundred years from now. The use of discounting, again at 4%, means that such a loss would appear as $140 million in any economic appraisal including a traditional cost-benefit analysis related to the mitigation measures and related investments today enabling future environmental preservation (Pearce et al., 2003).

As we mentioned before, one of the main characteristics of fundamental research is its non-linearity and serendipity with respect to predicting what its future benefits will be worth in economic terms, how much those will be and when in the future they will materialise in the form of new innovations. Applying the strict logic of traditional economic concepts such as discount rates will lead us to the conclusion that fundamental research is worth very little as an investment today. Nevertheless, as we have exemplified with the case of Schrödinger's equations, the long-term benefits can be staggering. Therefore, a dilemma appears right in front of us.

A recent study conducted by Florio (2019), suggests cost-benefit analysis is more suitable and offers a systematic analysis of the benefits in terms of the social agents involved. The benefits to scientists, students, and postdoctoral researchers as well as the effect on firms of knowledge spill overs and the benefits to users of information technology and science-based innovation can be considered in such an analysis to show the benefits of funding fundamental knowledge creation. Perhaps the solution to this dilemma of valuing Basic Research starts by reconsidering the vision of what Big Science (and especially fundamental science) carries towards all of us, as humankind. Many academics offer intriguing starting points that might serve as the foundation for such an integrative vision.

First is considering scientific research, scientific knowledge, and technology as global public goods, to be cultivated for the benefit of humanity and accessible to all (Bishop, 2015). In this sense, science is placed on with equal footing as other socioeconomic rights such as education and healthcare. It considers science and technology beyond their purely utilitarian value, emphasising their intrinsic value as a means of expressing our human nature, and personality, and facilitating international understanding. The essence of this approach is that scientific and technological knowledge should be accessible to all, as a human right.

Second is considering knowledge in general and (fundamental) science in particular, as a shared resource within a 'commons' context (Hess and Ostrom, 2007). Such a context is defined as a complex knowledge-sharing ecosystem formed by diverse groups subject into social dilemmas. Therefore, knowledge, in its intangible form of ideas, thoughts, or wisdom, would fall in the category of a public inclusive good. For example, one person's use of knowledge (such as Einstein's theory of relativity) does not subtract from another person's capacity for using it as well. New governance modes and models are necessary for organising efficiently and openly the production, access, use, and preservation of knowledge. This is key, especially with the current and upcoming digital technologies and paradigms such as the internet and the World Wide Web (WWW).

Third is considering science as an Option Generator (Boisot et al., 2011). In this sense, the value of science is viewed as consisting of two parts, broadening the scope of purely conventional economic paradigms. The first part does consider science's net present value in relation to an identifiable and definable stream of future benefits. The second one is the option part, which fundamentally broadens the traditional economic paradigms by reflecting potential future opportunities that scientific knowledge might create at a later date that are not yet known or clearly defined. The 'vagueness' overcomes, at least partially, the above-described rigid paradigm of discount rates. For example, omitting the option value carried by fundamental science will seriously distort its appraisal process.[19] This distortion will detrimentally favour what is investable in the short-term (e.g. favourable with respect to a certain discount rate standard) over what is potentially achievable and capable of transforming established paradigms and markets in the short term.

10.5 Conclusions

This chapter examines the multifaceted and entangled relationship between Big Science and society. Varied perspectives on the complexity, richness, and multifaceted nature of Big Science relationships require analysis using multiple lenses and flexible valuation frameworks. Therefore, the challenge is open to the collaboration of novel and flexible paradigm models that can capture both ontological and epistemological aspects of scientific activity. The ideologies of individual actors and communities need to be factored in. A potential starting point could be to ask oneself why and how fundamental scientific activities pursued in Big Science embed human traits like curiosity and imagination? How is Big Science able to build collaborative communities? Who is willing to contribute to both collective and individual values and ambitions?

In times where there is an excessive focus on the practicality, productivity, and efficiency of science and technology, human beings leave little room for the type of curiosity and serendipity that lead to the discovery of transformational ideas and paradigms. Moreover, as the Covid-19 pandemic teaches us, the knowledge generated by Big Science is not a luxury but essential for tackling not only this global emergency but many others including climatic and planetary changes.

Perhaps, we may intermittently revisit Abraham Flexner's great essay *The Usefulness of Useless Knowledge* (Flexner, 2017), to remind ourselves about the dangerous tendency to forgo pure curiosity in favour of excessive pragmatism:

> We make ourselves no promises, but we cherish the hope that the unobstructed pursuit of useless knowledge will prove to have consequences in the future as in the past.

[19] This option value is intrinsically necessary precisely to consider the non-linear and serendipitous nature of the process taking a Fundamental Science discovery to generate market value.