GFCC
Global Federation of Competitiveness Councils

Leveraging Extreme Innovation

A report by the GFCC University and Research Leadership Forum

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The Global Federation of Competitiveness Councils (GFCC) is an international network of leaders, non-profit organizations, government agencies, universities and companies working collaboratively to build sustained prosperity through innovation. The GFCC develops initiatives and tools to better understand and navigate the complex competitiveness landscape, and disseminates best practices.

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We dedicate this report
to Stephen Hawking and
Sir John Sulston.

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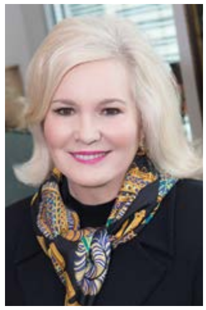
Throughout history, humans have sought to push back the frontiers of knowledge and advance the technologies that support human existence. This quest for progress continues at an accelerating pace today. Around the world, universities are deeply involved in big, bold, and transformational science and technology initiatives, from massive research infrastructure in physics and astronomy, to large multiparty research programs on the cutting edge of neuroscience and quantum technology, even to challenge competitions in space exploration driven by modern day mavericks who aim to disrupt incremental innovation with breakthrough progress.

These extreme innovation endeavors can accelerate scientific discovery and technological advancements, and enable developments that otherwise would not be possible. As a result, they can boost a host country's competitiveness, attract global talent, benefit industry, and drive the creation of spin-off companies and the commercialization of new products.

Universities are central players in these extreme innovation initiatives, as concept developers, leaders, managers, research performers, and members of teams competing in challenges. To explore these roles, the Global Federation of Competitiveness Councils' University and Research Leadership Forum established the Task Force on Leveraging Extreme Innovation to undertake a review of extreme innovation projects, and the roles universities have played in them. We are pleased to present the Task Force's report, Leveraging Extreme Innovation, which characterizes these initiatives, and identifies how universities can strengthen their capacity to lead and engage in extreme innovation projects. We are grateful for the work of the Task Force co-chairs and members who guided this effort.

The GFCC is dedicated to sharing knowledge and best practices on innovation, economic development, growth and prosperity. Amplifying this mission, the Forum was formed to identify, analyze, and disseminate best practices in universities and research institutions that can scale up globally. With the release of this report, we have strived to help fulfill the GFCC mission by offering insights we hope will be useful to universities in increasing returns on their research, serving the learning needs of their students, supporting the efforts of companies and start-ups to grow and compete, and increasing their contribution to local, regional, and national economies and their global competitiveness.



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A Letter from the Task Force Chairs

> "Research universities provide the scientific, technical, and professional foundations for those who will go on to found and lead the new industries made possible by innovative research."[1]

Robert Berdahl
Research Universities: Their Value to Society Extends Well Beyond Research

Extreme innovation projects drive discovery and human progress, result in new business models to meet social needs, mold the future of work, and sow the seeds for future economic growth and job creation.[2] From the Apollo moon landing, to the Graphene Flagship and Large Hadron Collider, universities have played an essential role in the design and execution of extreme innovation projects.

Ready to tackle the next big challenge, universities bring an array of facilities, and a transdisciplinary and collaborative approach across faculty and students to support these groundbreaking projects. They perform crucial foundational research, and teach and inspire the next generation of society's innovators. In developed countries, universities benefit from a high degree of freedom in developing curricula, resulting in novel courses tied closely to global challenges and private sector needs.

But research alone is insufficient to promote economic growth; instead, science and new technology must be translated into new processes, services and products. Innovation is an incredibly complex system impacted by culture, resources and knowledge assets. Universities are primed for stimulating innovation as they can provide an entrepreneurial mindset. Many universities have established startup incubators to encourage entrepreneurship and foster creative thinking, a crucial activity for stimulating innovation. These are just a few of the factors that make universities ideal partners for extreme innovation projects.

Universities are uniquely positioned to develop and advance innovative projects, which led us to initiate a task force to research the drivers and success factors of extreme innovation in an effort to encourage university participation in ongoing and future projects. The goal of the task force was to evaluate extreme innovation projects, both past and present, to provide evidence-based recommendations for how universities can be successful in this arena and encourage an innovation ecosystem in their own environment.

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1 http://www.chronicle.com/article/Reassessing-the-Value-of/47038.

2 https://www.rand.org/randeurope/research/projects/social-innovation.html.

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Foreword

Held in London in November 2016, the inaugural meeting of the GFCC University and Research Leadership Forum included a session on extreme technology and shared infrastructure. This session ultimately led to the creation of the Extreme Innovation task force and inspired this report.

Major discussion points in London were that innovation, science and technology are key drivers for economic competitiveness, and extreme science and technology projects exemplify this concept. They push the boundaries of human knowledge and technical capabilities, generate a variety of spinouts, and can be important sources of competitiveness for nations, cities, regions, companies and universities. Universities play an essential role in the design, deployment and operation of advanced research facilities, most of them funded by government, which play a key role in these extreme innovation projects.

However, the landscape for extreme innovation projects is changing, with implications for the role of universities. A new breed of extreme projects and expanding private sector participation in groundbreaking technology initiatives create new opportunities for universities, and require new thinking and entrepreneurial approaches. This report explores these changes and lessons learned from past and current projects with the goal of providing context and understanding with regard to the role of universities.

The report is organized into five sections.

- Section one introduces the work, reviews the types of projects analyzed and lists them.
- Section two outlines the landscape for extreme science and technology projects and takes into consideration some of the different perspectives that define it.
- Section three presents information on each of the projects reviewed and insights that emerged from their cross-analysis.
- Section four addresses key differences between public and private extreme science and technology initiatives in terms of funding, governance and management.
- Section five reviews the roles universities can play in extreme science and technology projects, and offers comments on how universities could be better positioned to take advantage of existing opportunities and carve out new opportunities.

1. Introduction

Humans are explorers. Since we left the savannahs, we have been exploring distant and extreme geographies on this planet, the seas, space, our own bodies and the mind. Ambition and, above all, curiosity have driven humanity for generations to seek new discoveries.

Our desire to know, understand and conquer new places reflects our eagerness to understand nature and the universe, and extend into new knowledge domains. Research and exploration share a natural nexus and a common necessity for increasingly sophisticated tools.

Over history, examples of the connections among exploration, technological achievements and science are not in short supply. From the astrolabe, the ALMA[3] and HMS Beagle to the Deep Sea Challenger,[4] microscope and Large Hadron Collider,[5] we have built objects that allow us to know the micro and the macro, perform complex tasks, visit new places and answer critical questions.

Exploration, the advancement of human knowledge and the pursuit of solutions for big human problems can assume the form of initiatives that span across nations and mobilize massive distributed resources. In many situations, globally distributed resources are combined with unique facilities and tools to solve complex problems. The conceptualization, development and construction of extreme tools create business opportunities for industry and generate new groundbreaking technological solutions.

Universities are often central players in the science and technology enterprise, and involved in extreme projects through a variety of roles and capacities. Nevertheless, the landscape is evolving and universities have new opportunities to explore. Taking that into account, and building upon the examples highlighted and the insights obtained during the 2016 London meeting, the GFCC University and Research Leadership Forum established a task force to review extreme innovation projects and develop recommendations for universities. These recommendations also have relevance to government and private sector groups currently involved or considering participation in extreme innovation projects, or supporting them. The task force analyzed a variety of big, transformational science and technology projects, with the aim of answering three fundamental questions:

- What are the key aspects of extreme science and technology projects with respect to conception, funding and governance?
- How can universities better position themselves to initiate, participate or lead such projects?
- What are some of the emerging opportunities for universities to take part in extreme projects?

Seventeen projects were reviewed (case studies included in section 3). In addition to desk research, the task force team engaged directly with project leaders to learn about projects' conceptualization, design, implementation, governance and future perspectives. The task force also collected perspectives from governments and private sector organizations on the importance and future prospects for big, bold, transformational projects.

The projects analyzed are not representative of the full spectrum of big, bold and transformational science and technology projects; many others could have been

3 http://www.almaobservatory.org/en/home/.

4 http://www.deepseachallenge.com/the-sub/.

5 https://home.cern/topics/large-hadron-collider.

included. Nevertheless, they illustrate the variety of projects in the "extreme innovation" sector, including public/private/philanthropic-funded initiatives.

To choose specific projects for review, the task force identified key characteristics of extreme projects, including novelty, scale (number of people involved and size of investment), complexity, outcome and risk. In addition, the task force reviewed projects that involved:

- Design and implementation of unique, large-scale and technically challenging facilities and equipment at the bleeding edge of technology;
- Advancing the frontiers of human knowledge and mobilizing significant resources to solve global grand challenges or complex technical problems; and
- Large, internationally distributed teams and substantial investments in science and technology development.

The projects reviewed are complex in terms of governance, organization and management, and require funding ranging from tens of millions to billions of U.S. dollars. While the smaller projects are typically innovative in their concepts and models, the large ones tend to involve the creation of big science facilities.

The projects analyzed in this report can be categorized as:

- Big science projects
- Big research endeavors
- Extreme/big technology initiatives

Big Science Projects

These involve the design and construction of massive research infrastructures–big science tools–that are used by scientists from different nations. Such tools are planned, designed and built over years or decades, with large government funding.

- Atacama Large Millimeter Array (ALMA)
- Five-hundred Meter Aperture Spherical Radio Telescope (FAST)
- International Thermonuclear Experimental Reactor (ITER)
- Large Hadron Collider (LHC)
- National Ignition Facility (NIF)
- Psyche Mission
- Square Kilometre Array (SKA)

Big Research Endeavors

These are massive research endeavors that mobilize resources (i.e., capabilities, researchers, infrastructure) in several locations and countries to meet project goals. Final outcomes include new technologies (i.e., methods, materials, artifacts) and knowledge.

- Human Genome Project
- EU Human Brain Project
- EU Graphene Flagship
- EU Quantum Flagship

Extreme/Big Technology Initiatives

These are big, bold and extremely ambitious technology development initiatives initiated and led by public or private sector organizations. They follow a variety of models, including government or private sector backed initiatives, centrally-managed projects, awards and competitions that mobilize resources distributed across the globe.

- Ansari Suborbital Spaceflight XPrize
- Apollo Moon-landing Project
- ASU BioXFEL
- Breakthrough Starshot
- DARPA Autonomous Vehicle Challenge
- Google Lunar XPrize

2. The Global Landscape for Extreme Science and Technology Projects

2.1 Why Is It Important to Have Big, Bold, Transformational Projects?

A half a century ago, the United States accomplished one of the most ambitious, audacious feats of science and engineering in human history—"to land a man on the moon and return him safely to the Earth." This extraordinary achievement extended the limits of humanity's scientific and technological capabilities. It also reshaped our imaginations and our very sense of self. We are no longer earthbound—we are a spacefaring species.

The Apollo program that led to the moon landing is perhaps the most recognizable example of extreme innovation. It involved the largest commitment of resources ever made by any nation in peacetime:

- A total of US$19.4 billion by the program's completion,[6] or about US$140 billion in today's dollars
- At its peak, it employed 400,000 Americans
- Support of more than 20,000 industrial firms and universities[7]

The moon landing positioned the United States as a global technology superpower. Through Apollo, NASA kick-started the fledgling microelectronics industry, upon which all of today's computers and cell phones depend. In addition, discoveries made throughout the Apollo program spun off numerous technologies and rapidly advanced many of the items we depend on today.[8]

At American universities, NASA provided numerous opportunities to advance space science, from scholarships and expedited doctoral degree programs, to summer training and research opportunities for faculty. Through these programs, many aerospace and space science departments were established throughout the United States. In addition, many universities signed Memoranda of Understanding with NASA that allowed for construction of laboratories large enough to conduct research for space missions.

Extreme innovation projects have high technical and reputation risk, but they also have high rewards. The results—to education, research, commerce and culture—ripple far beyond the original objectives. They are inspirational. One important outcome of the Apollo Project was coining the "moonshot" concept; that is, the notion that extreme goals can be achieved and big problems solved via long-term, ambitious, forward-looking projects at the frontiers of technology, and inspire generations of innovators and entrepreneurs. It is a global reference point for transformational ideas and projects in industry, and many of the most successful high-tech entrepreneurs cite Apollo as their inspiration. For example, today, Alphabet's X (formerly Google X) portrays itself as the "Moonshot Factory."

Broad impacts, like those identified in the Apollo project, are also associated with other projects described in this report. For example, technology spinouts from CERN's particle physics projects have benefited medical technology, aerospace, safety, the environment, industry 4.0 and big data applications.

Extreme projects have been the object of attention of governments, national strategies and plans, corporations, universities and,

6 https://history.nasa.gov/SP-4029/Apollo_18-16_Apollo_Program_Budget_Appropriations.htm.

7 NASA Langley Research Center's Contribution to the Apollo Program, https://www.nasa.gov/centers/langley/news/factsheets/Apollo.html.

8 NASA https://www.nasa.gov/sites/default/files/80660main_ApolloFS.pdf.

X: A Moonshot Factory

X believes that audacious thinking and radical new technology create the foundation for a unique moonshot factory. Its inventors, engineers, designers and makers take on high-risk ideas and research with the focus and speed of a startup. The goal is to advance and de-risk early stage ideas and technologies, and create the foundation for large, sustainable businesses. X's "product" is not an item for sale. Rather, it creates new ventures that generate value for Alphabet.

X's overarching goal is to create moonshot technologies, as demonstrated by its current projects: Loon (providing Internet access to rural and remote areas via a network of balloons traveling on the edge of space), Wing (building delivery drones), and Makani (creating kites that harness energy efficiently from the wind). Previous endeavors at X included the development of self-driving cars (spun-off in 2016 as Waymo); the revolutionary AI advancements of Google Brain; and the Life Sciences project (spun-off in 2015 as Verily), created to leverage health data collection to improve decision-making and interventions in healthcare.

As the world has no shortage of problems in need of solutions, X believes the moonshot approach could be followed by other organizations in pursuit of extreme innovation, including universities.

more recently, private sector foundations and philanthropic organizations. Big science projects fit squarely in this context; they have not just mobilized attention and resources at a national level, but are international by nature and their implementation has birthed well recognized and respected international organizations.

Extreme innovation is not about thinking outside the box. It is about boldly dismantling the box and developing new paradigms that borrow from existing knowledge and achievements, creating something that previously did not exist–new tools, new artifacts and new organizational solutions.

2.2 Extreme Tools and Infrastructure are Important National Assets

A country's extreme science and technology infrastructure is an important source of competitiveness. These instruments, equipment and facilities typically require large investments beyond the financial capabilities of single institutions or the incentive structures of industry (they are often funded by government). But, they enable research activities that otherwise may not be possible, including scientific discovery at the frontiers of knowledge and technology development at the leading edge. As platforms for cooperative projects and focal points for research effort, they may accelerate research outcomes through agglomeration of research activities, compared with the fragmented efforts of single investigators acting alone. Due to their special nature, they open important opportunities for industry involvement and serve as magnets for global talent.

The Sirius: A Unique Science Facility Based in Latin America

The Brazilian Synchrotron Light Laboratory (LNLS)–one of four National Laboratories of the nonprofit Brazilian Center for Research in Energy and Materials (CNPEM)—designed, built and operates the UVX, the only synchrotron light source in Latin America. UVX is a 2nd generation machine, inaugurated in 1997 and built over more than a decade with technology developed in Brazil. It operates as an open-access facility.

In 2012, LNLS took on the challenge to design and build the US$500 million Sirius, a new Synchrotron Light Source funded by the Brazilian Government, which will be the largest and most complex scientific facility ever built in Brazil. When it opens in 2019, this 4th generation machine will be the brightest of their energy class in the world. It will create new opportunities for research in material science, structural biology, nanoscience, physics, earth and environmental science, cultural heritage and other areas. Industries critical to Brazil—such as energy (solar, fuel cells and batteries), agriculture and food, oil and gas, environment and health—are expected to use the facility.

The Sirius project has enabled Brazilian businesses to acquire new technological capabilities and boost competitiveness. Currently, there is growing effort to engage academic and industrial partners to identify leading edge scientific and technological problems, and develop experiments that will tap Sirius' capabilities.

Countries around the globe are highlighting science and technology in national priorities and strategies, including investments in developing research capabilities and their enabling infrastructure. Big science projects and extreme infrastructure are often an integral part of these national strategies. Examples can be found in country specific road maps, surveys and reviews such as:

- Research Council UK (RCUK) 2010 Roadmap (currently being revised)[9]
- MRC Roadmap 2016[10]
- European Strategy Forum on Research Infrastructures (ESFRI) Roadmap 2016[11]
- Japan Aerospace Exploration Agency (JAXA)[12]
- Australian Government 2016 National Research Infrastructure Roadmap[13]
- South African Research Infrastructure Roadmap 1st Edition[14]

9 http://www.rcuk.ac.uk/documents/research/rcuklargefacilitiesroadmap2010-pdf/.

10 https://www.mrc.ac.uk/publications/browse/delivery-plan-2015-16/.

11 http://www.esfri.eu/esfri_roadmap2016/roadmap-2016.php.

12 http://global.jaxa.jp/activity/int/index.html.

13 https://docs.education.gov.au/system/files/doc/other/ed16-0269_national_research_infrastructure_roadmap_report_internals_acc.pdf.

14 http://www.hsrc.ac.za/uploads/pageContent/7451/SARIR_2016.pdf.

- U.S. Astronomy and Astrophysics Decadal Survey 2010 overview[15]
- U.S. Earth Science and Applications from Space Decadal Survey 2007[16]
- U.S. Nuclear Physics Decadal Review 2010[17]

While big science and its tools are innovative and exciting, they require significant monetary investment. As such, the projects outlined in the roadmaps above require a broader impact case that forms part of the business case for funding them. Big science projects and facilities are expected to simultaneously achieve their scientific objectives, contribute to meeting national needs or Global Grand Challenges (Health, Energy, Environment, Education, Food and Manufacturing), and develop public outreach initiatives.

Initiatives related to research infrastructure are not exclusive to advanced economies; they include emerging economies such as South Africa and Brazil. The former has launched a Research Infrastructure Roadmap and is engaged in projects such as the SKA. The latter has reviewed its

Quality Research Facilities are Key for Australia's Future Competitiveness

The Australian Government is the primary funder of National Research Infrastructure (NRI), in expectation of a wide variety of outcomes:

- Sustained research excellence
- Delivery of benefits to solve nationally and internationally-significant problems
- Sustained international prestige
- Increased collaboration
- Support of Australia's soft diplomacy
- Sustained development of a highly-skilled workforce

Other direct benefits may include economic or industry growth, especially if outcomes are product-focused, as well as the creation of new technologies and methodologies.

The 2016 NRI Roadmap identifies indirect improvements from research infrastructure to food security, health, longevity and wellbeing. The 2015 Australian Research Infrastructure Review considers investment in NRI "… as the patient capital required to secure Australia's future in research and innovation."

Australia gains access to global research infrastructure through a range of mechanisms, such as offering reciprocal access to Australian facilities, making direct investments and entering partnerships with international facilities. For example, Australia is an associate member in the European Molecular Biology Laboratory, a recent partner in the European Southern Observatory, and an established partner in the Square Kilometre Array project. Australia also benefits from global infrastructure training of students and researchers, contributing to the global stock of knowledge.

15 http://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_064932.pdf.

16 https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Earth_DS.pdf.

17 https://www.nap.edu/read/13438/chapter/1#xiii.

infrastructure and, in spite of all the challenges it faces, is investing in a cutting-edge synchrotron light source.[18]

Due to their high cost, the vast majority of big science projects and facilities are funded by governments through public funds, directly or indirectly, for example, participation and financial contributions to an international organization such as CERN or ITER. Therefore, fiscal oversight activities are important to ensure that funds are being spent wisely and on the highest priority projects.

2.3 The Expansion of Human Knowledge Requires New and Advanced Global Tools

Over centuries, humanity's constant search for understanding our universe has driven the development of science projects, both small and large. Typically, the grandest of these projects are those seeking knowledge of the cosmos, and examples from the past include Stonehenge (United Kingdom), the Temple of El Karnak (Egypt), Chaco Canyon (New Mexico), Geocheng (China) and Jantar Mantar (India).

In nearly all science disciplines, there has been a time when a significant effort has been required to make a real step change in knowledge. This realization and need have driven the development of large, complex instruments and the coming together of large communities of scientists to answer key scientific questions.

The physics community exemplifies this reality. Decades ago, this community realized that establishing and operating the infrastructure necessary for significant advancements in the field of physics would be too difficult and costly for one country to bear independently. This recognition led to the creation of treaty organizations and international facilities such as the European Organization for Nuclear Research (CERN) and European Southern Observatory (ESO). Science has evolved into an international endeavor and big science tools follow the same track.

The 1954 CERN convention sets out CERN's original program objectives and three initial programs, including "the programme carried out at its Laboratory at Geneva including a proton-synchrotron for energies above ten giga electronvolts (1010 eV) and a synchro-cyclotron for energies of six hundred million electronvolts (6 x 108eV)." The Proton Synchrotron (PS) — with a circumference of 628 meters — first accelerated protons on November 24, 1959 and operated up to 25 GeV. This achievement demonstrated the success of CERN. The Large Hadron Collider (LHC), featured in this report, is an outcome of CERN's evolution and, in more general terms, the evolution of a variety of fields in physics.

As science advances over time, new tools are required for pushing back the frontiers of knowledge with continued discovery. And, new extreme technology projects often drive the development of new advanced tools. However, new generations of tools often require new engineering solutions, materials and systems. For example, science and technology development in computing is particularly important now for many fields, as scientific research becomes ever more data intensive and computational, as the examples of CERN, ALMA and SKA illustrate. Over time, the existing research infrastructure of international organizations can evolve with the addition of new big science tools as they emerge.

18 http://www.ipea.gov.br/agencia/images/stories/PDFs/livros/livros/livro_sistemas_setoriais.pdf

While new big science facilities may face considerable technical and funding risks, they do not have commercial risks. In principle, if implementation is successful, demand is guaranteed as they emerge from necessities of the scientific communities involved. Budget risks are related to potential cost escalation in big projects, maintaining long-term political support for significant government expenditures in the face of competing needs and interests, and to a countries' science policy for big science facilities; however, typically, science policy evolves over long time periods (compared to change in the commercial world), reducing the financial risk.

2.4 Research Is a Global Enterprise

Collaboration is the norm in science, at the local and global scale. As human knowledge expands, science specializes and global connectivity increases, research projects are becoming increasingly complex and large. Many of today's top research endeavors involve large teams and significant resources. For example, in 2015, a paper published in *Physical Review Letters* featured the most precise estimate yet of the mass of the Higgs boson, based on a series of experiments done at CERN's LHC. The paper had more than 5,000 authors,[19] reflecting both a trend for hyperauthorship[20] found in different scientific domains, and the increasing scale and complexity of research projects. Adding all of the authors without any order showed that this advancement was the result of a community effort.

While many large-scale research endeavors use big science facilities, they also can assume other configurations. Advancements in computation, telecommunications and global connectivity increasingly allow for projects to operate at a global scale. As scientists and funders continually identify new grand challenges, these will be met with innovative, grander experiments and with a broader, integrated set of collaborators.

The Human Genome Project, and EU Flagship Future and Emerging Technologies (FET)[21] projects featured in this report represent examples of big research endeavors that mobilize resources across nations. They are some of the largest endeavors of this type. The Bill and Melinda Gates Malaria Strategy,[22] for which the Gates Foundation has committed more than US$2 billion so far, is similar. The U.S. Materials Genome Initiative[23] and the U.S. Brain Initiative[24] mobilize resources on a national scale.

As many nations around the world build their scientific and technical capabilities, the evolution of global science will continue, and new tools and forms of global collaboration and work will emerge. More massive, internationally distributed and resource-intensive projects are likely to be launched in the years and decades to come.

19 https://www.nature.com/news/physics-paper-sets-record-with-more-than-5-000-authors-1.17567.
20 http://archive.sciencewatch.com/newsletter/2012/201207/multiauthor_papers/.
21 http://ec.europa.eu/programmes/horizon2020/en/h2020-section/fet-flagships.
22 https://www.gatesfoundation.org/What-We-Do/Global-Health/Malaria#Our Strategy.
23 https://www.mgi.gov/about.
24 https://www.braininitiative.nih.gov/.

2.5 Philanthropy Is Increasingly Involved With Big Research and Tech Projects

Industry has a long history of mega projects at the frontiers of technology in areas such as energy, construction, shipbuilding and aerospace. While industry projects and commercial endeavors are not the focus of this report, it is important to note the expanding role of private sector sources in funding science and technology.

Today, governments are the main funders of science, and also the main investors in big/extreme/transformational tools and projects. But was this always the case?

Fundamental knowledge in areas such as electricity, electromagnetism, the structure of matter, quantum mechanics and others can be traced to Cambridge University's Cavendish Laboratory.[25] Established in 1847, the lab was for several decades one of the most advanced facilities in the world and the place where giants in the history of physics such as Maxwell, Thomson, Rutherford, and others made fundamental discoveries, and created and tested groundbreaking theories that laid the foundations for modern physics and chemistry. The Cavendish Lab was established with private funding and endowed by William Cavendish.

In the United States, Ernest Lawrence, the renowned Nobel laureate scientist who invented the cyclotron and is dubbed the "father of big science," had his first machine in Berkeley funded mainly by private sources.[26] Lawrence went on to build successive generations of synchrotrons, supported by capital from philanthropy. In 1940, the Rockefeller Foundation pledged US$1.4 million for a new machine, the largest single magnet synchrotron ever built. Adjusted for inflation, the Rockefeller Foundation's pledge would be equivalent to US$24.7 million today. However, this investment of US$1.4 million, adjusted relative to the size of the economy, would be equivalent to more than US$264 million in 2017.

In "The Long Space Age," Alexander MacDonald analyzes the history of American space exploration. For him, it is a history in "…which personal initiative and private funding is the dominant trend and government funding is a recent one." MacDonald identifies three key periods for space exploration in U.S. history. It is only in the third period, from 1950 to the present, that activity is driven mostly by government.

Observatories have been built and leveraged to develop our understanding of the skies for millennia. With the invention of the telescope, observatories developed new capabilities and became the undisputed tools for astronomical observation and exploration. MacDonald reveals that, from 1820 to 1940, 40 astronomical observatories were built in the United States. The investment made in those facilities, adjusted relative to the size of the economy, would be equivalent to US$9.8 billion in 2015, with investments as large as US$1.5 billion for the Licks Observatory. Ultimately, about 96 percent of the resources for those 40 projects were provided by private sources.

There is now an invigorated presence of the private sector in space exploration. Companies

25 https://www.phy.cam.ac.uk/history.

26 https://history.aip.org/exhibits/lawrence/radlab.htm.

such as SpaceX[27] and BlueOrigin[28] are good examples, as are philanthropy-backed initiatives such as the Ansari Suborbital Space Flight, Google Lunar XPrize and the Breakthrough Starshot Initiative, all of which are covered in this report.

MacDonald believes the future of space exploration in the United States should not be about the displacement of government, but rather a "…product of networks of public and private actors." Complementarity, collaboration and hybridization appear to be emerging attributes in space science, technology and exploration. Some potential implications of this new reality are explored in section three of this report.

William Broad made a similar observation in an article published in the New York Times in 2014.[29] Broad wrote that there is a "profound change taking place in the way science is paid for and practiced in America." Changes include more private sector funds for science and an emergent approach in which government follows private sector-initiated projects, such as the Brain Initiative. In Cambridge, Massachusetts (US) alone, rich benefactors have invested almost US$2.2 billion in the creation of nonprofit research institutes, some of them linked to institutions such as MIT and Harvard University.

Rich philanthropists are not likely to overtake government in funding science, but they are reshaping the field. They are doing so across the whole spectrum of science and technology projects and initiatives, including big, bold and transformational projects. As noted in the following sections, this change comes with new opportunities, demands and rules of engagement for universities.

27 http://www.spacex.com/.

28 https://www.blueorigin.com/.

29 https://www.nytimes.com/2014/03/16/science/billionaires-with-big-ideas-are-privatizing-american-science.html.

3. Extreme Projects Push the Boundaries of Science, Technology and Business

The 17 projects reviewed in this report, conceptualized and implemented over a 60-year time frame, involve more than 80 countries, leverage a variety of models and different dynamics, and include some multi-billion-dollar endeavors. In 2018's money, the total capital expenditure for their implementation exceeded US$200 billion, with the Apollo Moon-landing Mission taking the lion share.

Most of the projects were/are based in or initiated by the United States and Europe. Some are part of or are themselves international organizations. One of the projects, the Five Hundred Meter Aperture Spherical Telescope

(FAST), was built by China, a sign of the country's emergence as a science and technology powerhouse. China is designing and implementing a series of extreme science and technology projects that include a Mars Probe,[30] a Space Station,[31] a new Super Collider,[32,33] (twice the size of CERN's LHC), and a Deepsea Submersible.[34]

Public sector sources fund most of the projects reviewed, but new models and initiatives backed by philanthropy are emerging. (The differences between public and private sector funded and managed projects are analyzed in section 4.) The projects cover a spectrum of different knowledge or application domains such as fundamental physics, astronomy, space, bioscience and others.

Fundamental physics	Astronomy	Space technologies	Biosciences	Specific technologies	Multi-sector technologies
LHC	ALMA	Suborbital flight XPrize	Human Genome	Autonomous Vehicle	EU Graphene
NIF	FAST	Apollo Moon-landing Mission	EU Brain	ITER	EU Quantum
	SKA	Breakthrough Starshot	ASU BioXFEL		
		Lunar XPrize			
		Psyche Mission			

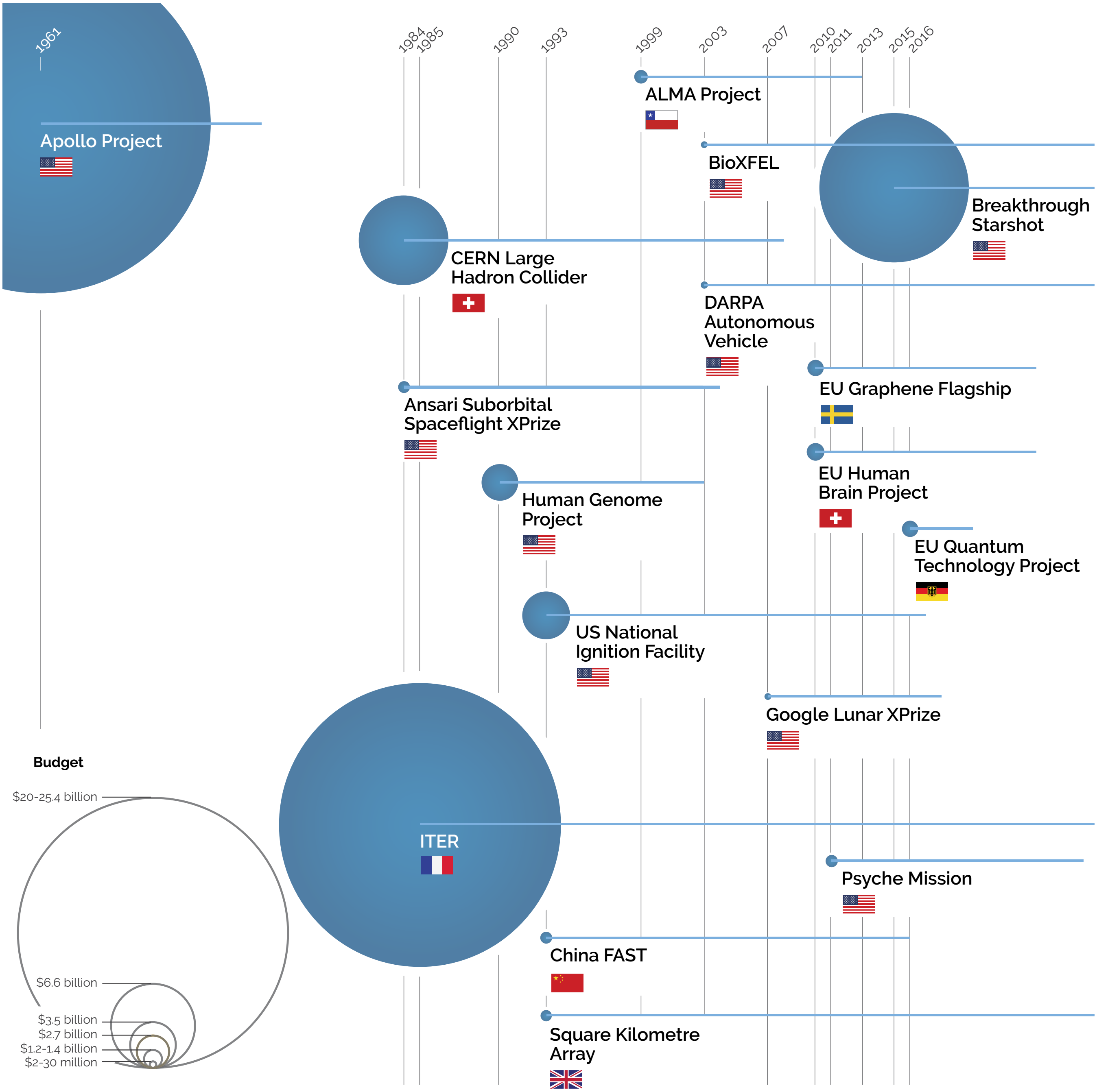
30 http://english.cas.cn/newsroom/china_research/201709/t20170921_183338.shtml.

31 http://english.cas.cn/newsroom/china_research/201709/t20170918_183253.shtml.

32 http://english.cas.cn/newsroom/news/201501/t20150127_135741.shtml.

33 http://english.cas.cn/newsroom/news/201610/t20161019_168829.shtml.

34 http://english.cas.cn/newsroom/news/201710/t20171009_183704.shtml



Flags denote the country of the project headquarters or origin

Extreme Projects Comparison Table

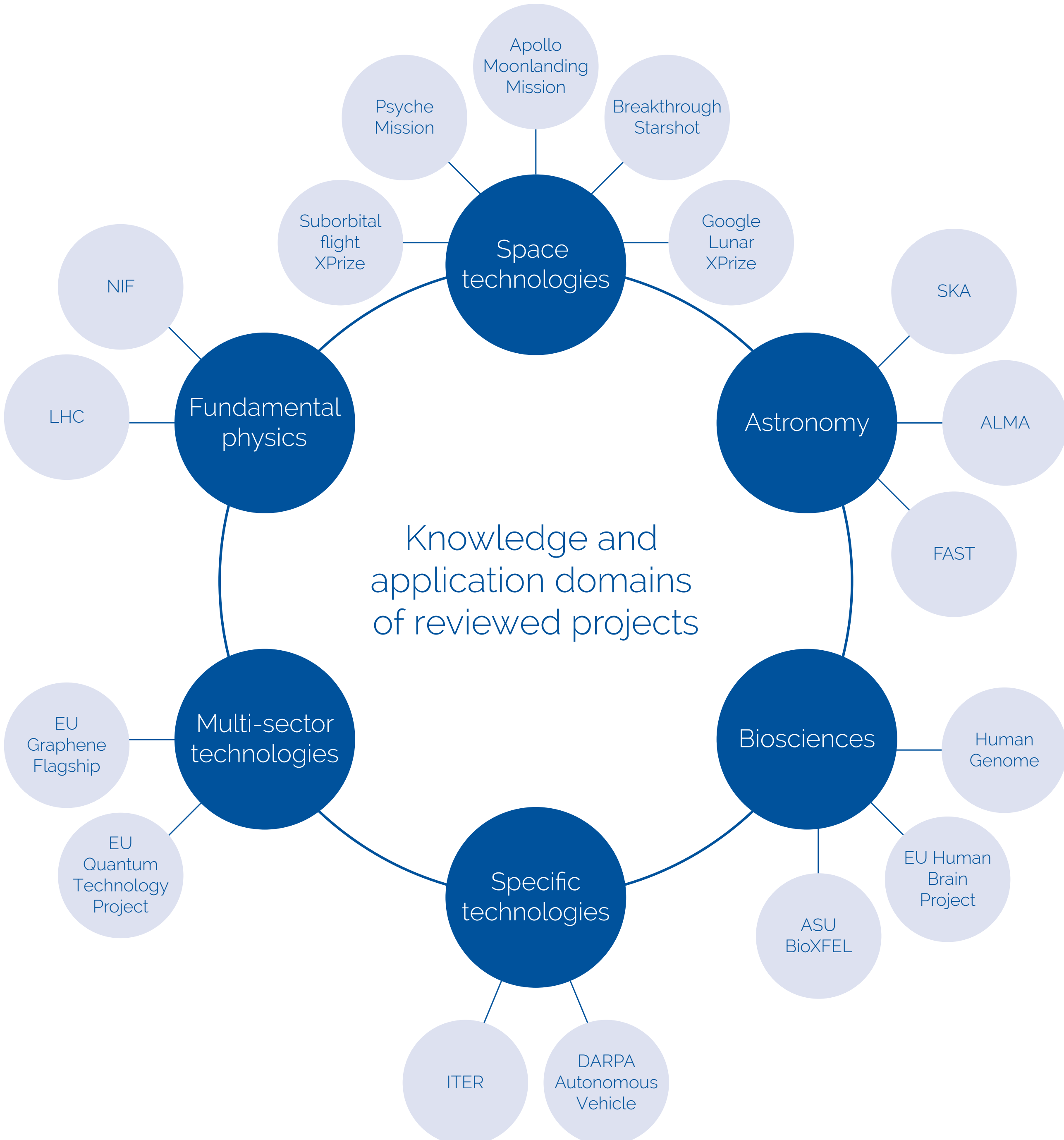
Project Name	ALMA	Apollo Project	Biodesign Center for Applied Structural Discovery	Breakthrough Starshot	CERN Large Hadron Collider	DARPA Autonomous Vehicle	EU Graphene Flagship	EU Human Brain Project
Duration	1999–2013	1961–1975	2003–	2015–	1984–2008	2003–2007	2010–2024	2010–2024
Big Facility	yes	yes	no	once finished: yes	yes	no	no	no
Development Stage	operation	finished	operation	implementation	operation	finished	research	research
In Operation?	yes	no	yes	yes	yes	no	yes	yes
Budget[3] $USD £EUR	$1.4 B	$25.4 B	$151.5 M	phase 1: $100 M, phase 2: $1 B (tentative), phase 3: $10 B (tentative phase 3)	$6.6 B	$2 M prize investment	£1 B	£1 B
Funding (public/private)	public	public	public	public and private	public	public and private	public and private	public and private
Main Funder	Variety of national astronomy organizations and institutes[2]	NASA	State Research Infrastructure Funding	Yuri Milner for phase 1, 2nd phase to be determined, government for possible 3rd phase (tentative)	CERN members	DARPA + private sponsors for the teams	European Commission	European Commission
Project Type (big science project /big research endeavor/extreme tech initiative/ university-led initiative)	big science project	extreme tech initiative	big research endeavor	extreme tech initiative	big science project	extreme tech initiative	big research endeavor	big research endeavor
University Affiliation (started by a university/ universities involved in the process)	involved in the process	involved in the process	started by university	involved in the process	involved in the process	involved in the process	started by a university/ involved in the process	started by a university/ involved in the process
Number of Universities Involved	n.a.	10	1	10+	>100	>15	101	118
Objective (defined artifact/ knowledge)	knowledge	defined artifact & knowledge	knowledge	defined artifact & knowledge	defined artifact & knowledge	defined artifact	knowledge	knowledge

1 European Organisation for Astronomical Research in the Southern Hemisphere (ESO), EU; National Science Foundation (NSF), US; National Institute of Natural Sciences (JINS), Japan; Chile.

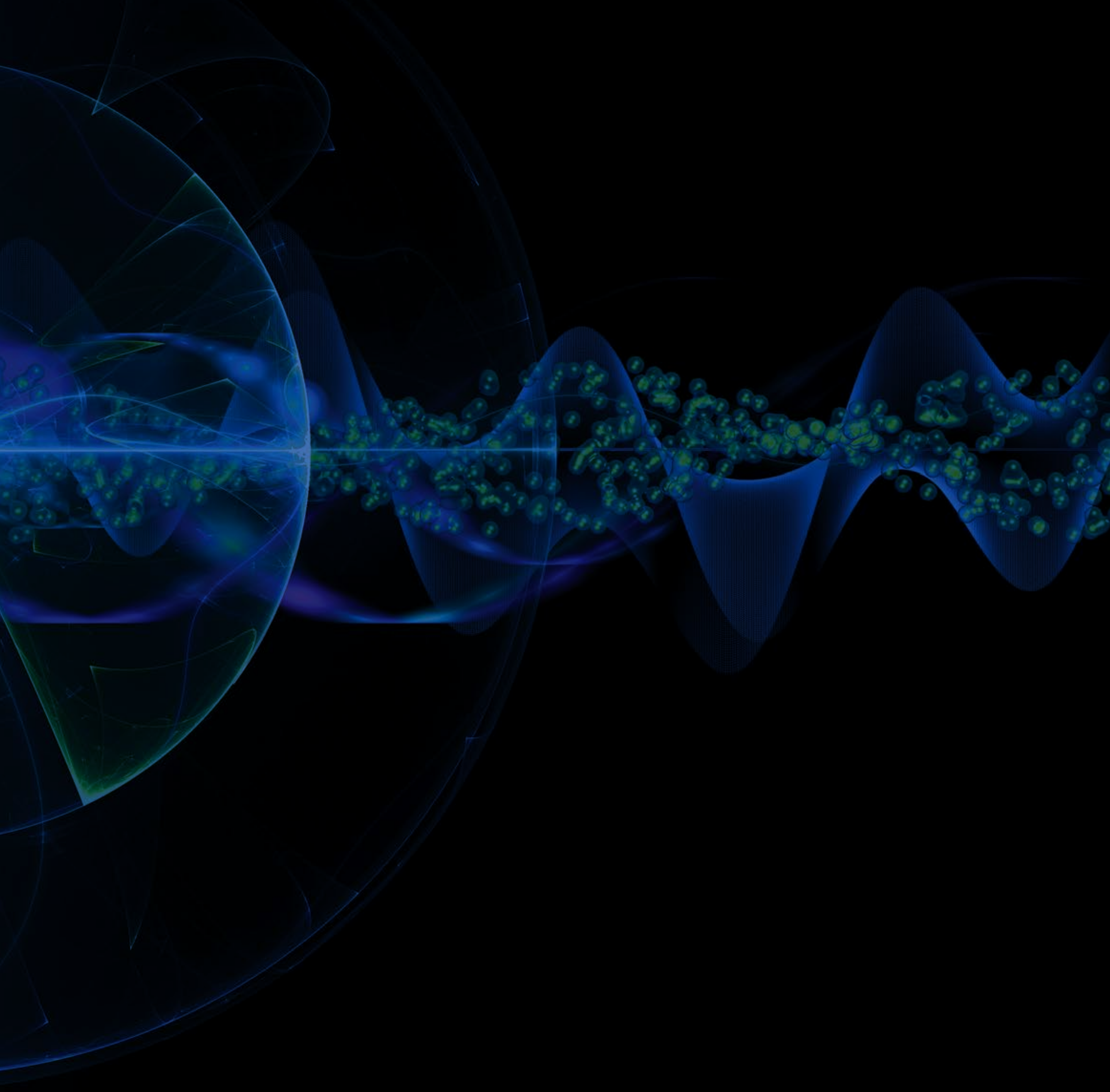
2 These organizations include: European Organisation for Astronomical Research in the Southern Hemisphere (ESO), EU; National Science Foundation (NSF), US; National Research Council (NRC), Canada; National Science Council (NSC), Taiwan; Korea Astromony and Space Science Institute (KASI), Korea; National Institute of Natural Sciences (JINS), Japan.

EU Quantum Technology Project	China FAST	Ansari Suborbital Spaceflight XPrize	Google Lunar XPrize	Human Genome Project	ITER	US National Ignition Facility	Psyche Mission	Square Kilometre Array
2016–2020	1993–2016	1995–2004	2007–2018	1990–2003	1985–	1993–2009	2011–2027	1993–
no	yes	no	no	yes	yes	yes	no	yes
preparation	operation	finished	finished	finished	implementation	operation	design	design
starting in 2019	yes	no	yes	no	no	yes	yes	no
£1 B	$173.75 M	$10 M + $100 M	$30 M (+ teams' investments)	$2.7 B	£17 B	~$3.5 B	$900 M	$1 B
public and private	public	private	private	public	public	public	public	public
European Commission	Chinese Academy of Sciences	XPrize Foundation (w/ Ansari family) + private sponsors for the teams	XPrize Foundation (w/ Google) + private sponsors for the teams	National research agencies, NIH, DoE	ITER members	DoE + Lawrence Livermore National Laboratory	NASA	SKA member countries
big research endeavor	big science project	extreme tech initiative	extreme tech initiative	big research endeavor	big science project	big science project	university-led initiative	big science project
started by a university/ involved in the process	started by a university/ involved in the process	no involvement	no involvement	started by a university/ involved in the process	involved in the process	involved in the process	involved in the process	started by a university/ involved in the process
12	~20	n.a.	n.a.	20	100's (per member)	8	2	~100
knowledge	defined artifact & knowledge	defined artifact & knowledge	defined artifact & knowledge	knowledge	defined artifact & knowledge	defined artifact & knowledge	defined artifact & knowledge	defined artifact

3 In this table, to ensure cross-comparability, we are only looking at the initial budget for each project and not the budget to keep the big facilities in operation.


Knowledge and application domains of reviewed projects
Space technologies
Apollo Moonlanding Mission
Psyche Mission
Breakthrough Starshot
Suborbital flight XPrize
Google Lunar XPrize
Astronomy
SKA
ALMA
FAST
Biosciences
Human Genome
EU Human Brain Project
ASU BioXFEL
Specific technologies
ITER
DARPA Autonomous Vehicle
Multi-sector technologies
EU Graphene Flagship
EU Quantum Technology Project
Fundamental physics
NIF
LHC

3.1 Case Studies: A Deep Dive Into 17 Extreme Science and Technology Projects



ALMA

The most expensive ground-based telescope in operation in the world

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

At a cost of about US$1.4 billion, the 66-antenna ALMA array (and its associated facilities and equipment) is the most expensive ground-based telescope in operation in the world. The array became operational in 2013. ALMA is the result of a partnership operating under a series of nonbinding agreements among astronomical organizations in Canada, Europe, Korea, Japan, the United States and the Government of Chile.

ALMA's scientific objectives are to produce detailed images of the formation stars and planets, born in molecular clouds near our Solar System and to observe galaxies in their formative stages at the edge of the Universe, as they were roughly ten billion years ago. ALMA will provide a window on celestial origins that encompasses both space and time, providing astronomers with a wealth of new scientific opportunities.

Three partners led the effort to design and implement ALMA. The European South Observatory (ESO), the North America consortium (Canada, United States) and the National Radio Astronomy Observatory (NRAO) each provided 37.5 percent of the budget. East Asia's participation has been managed by the National Astronomical Observatory of Japan (NAOJ) on behalf of Japan, Taiwan and South Korea; it provided 25 percent of the budget.[35] ALMA partners agreed on the types of equipment each would provide and had local offices in charge of sourcing the goods.

35 Global Collaboration, Atacama Large Millimeter/submillimeter Array, http://www.almaobservatory.org/en/about-alma-at-first-glance/global-collaboration/.

"We needed encoders to go on the telescope to position the antenna's unprecedented accuracy in the sky. Those encoders in the U.S. were built by a small company in Arkansas. Because of the size of their contract, they were able to improve their equipment and tooling so that they could compete with similar companies in Germany. That would not have happened without the contract from ALMA."

Al Wooten
North American Program Scientist
North American ALMA Support Center

Economic Impact

Each of the 50 antennas in ALMA's main array costs an estimated US$10-$15 million.[36] Different consortia participated in the bid, and companies in North America, Europe and Asia developed new capabilities though the project. In the United States, the ALMA project was responsible for the "…largest single procurement ever funded by the National Science Foundation," according to Associated Universities Inc., the research management organization that operates NRAO.[37]

ESO built 25 12-meter antennas with the AEM Consortium (Alcatel Alenia Space France, Alcatel Alenia Space Italy, European Industrial Engineering S.r.L., and MT Aerospace). The North American partners built 25 12-meter antennas with SATCOM Technologies, while the 4 12-meter and 12 7-meter antennas provided by NAOJ were built by Mitsubishi Electric Corporation. The two 130-ton transporters were commissioned by ESO, and designed and built by Scheuerle in Germany.[38]

Small companies got involved with the project, developing new technical capabilities that allow them to be more competitive in the marketplace. Computational and Big Data technology advances were also pursued during the development of ALMA.

University Involvement

Universities and research organizations are critical ALMA users. They were involved in ALMA's design and construction via their connections to the leading astronomical organizations in their regions. Participation was at the individual and laboratory (or department) level.

Universities and research laboratories engaged in the development and manufacturing of critical and special purpose equipment such as the receivers and the correlator. Those involved in the design and manufacturing of receivers included Chalmers University, IRAM,[39] the Rutherford Appleton Labs,[40] NRAO and others. The University of Bordeaux[41] was involved with the Correlator project.

36 http://www.nature.com/news/2011/110202/full/470014a.html.

37 http://www.aui.edu/our-story/.

38 http://www.almaobservatory.org/en/about-alma-at-first-glance/how-alma-works/technologies/transporters/ and https://www.scheuerle.com/products/special-transporters/antenna-transporter.html.

39 http://www.iram-institute.org/EN/content-page-43-5-43-0-0-0.html.

40 https://www.stfc.ac.uk/research/astronomy-and-space-science/front-end-integration-centre-alma/.

41 https://www.eso.org/public/news/eso1253/.

FAST

The largest single-dish telescope ever built and a key technology achievement for China

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

The FAST is currently the largest radio telescope in the world and one of China's first mega science projects. Its initial concept was developed in 1993, construction commenced in 2011 and the telescope became operational in 2016.

The FAST has a single management team headquartered at the Guizhou Radio Astronomy Observatory. At a cost of about US$180 million, the Chinese Government via the China Academy of Sciences (CAS), the Beijing Astronomical Observatory (BAO), and provincial and central governments funded FAST.[42] A 20-person management team works with industry and university teams (20 partners) in designing and implementing FAST. Currently, about 70 people are work on the FAST project.

The radio telescope has similar scientific objectives to the SKA, including strong-field tests of gravity using pulsars and black holes, and advancing knowledge about galaxy evolution, cosmology and dark energy, the origin and evolution of cosmic magnetism, the Cosmic Dawn and the cradle of life: are we alone?

42 World's Largest Radio Telescope Begins Operation, *Xinhua*, September 25, 2016.

Economic Impact

FAST's implementation was in the context of China's national development. It has had a broad impact in both the technology sector and across the local region where the telescope is located. Technology developments include:

- New way to build moveable dishes
- New cable design applied for other things such as elevators and ships
- Integrated optical mechanic technologies, bending optical fibers that can be applied for communications
- Measurement high accuracy laser system for China, developed in partnership with German and U.S. team
- Broader regional impacts include:
- Big Data Science center in Guizhou Province built and operating
- Guizhou Province now has three centers for astronomy education, where previously there were none
- Massive increase in public radio astronomy education in Guizhou Province and across China
- Massive increase in tourism to about 500,000 visitors per year from across China and internationally
- To accommodate visitors, the site includes a new local hotel and conference center

FAST is expected to extend its impact as new astronomy education centers are planned and new opportunities for Chinese participation in astronomy research are created. FAST was approved as a pathfinder for SKA and is in conversations with philanthropy-backed initiatives such as the Breakthrough Initiatives.

University Involvement

Universities developed the concept, participated in the design, supported the construction and took part in the telescope tests. They are also the telescope's main users. University doctoral students have been involved in the project at all stages and there are currently 500 students involved in analyzing data from the observatory.

FAST not only opened up new research opportunities, it has been instrumental in creating connections among universities in China.

ITER: Large, Unique and Challenging

The last experimental step to prove the feasibility of nuclear fusion as a source of green energy

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

ITER's mission is to demonstrate the feasibility of fusion power, with a specific aim to produce ten times more thermal energy from fusion reactions than that supplied by auxiliary heating. The ITER nuclear fusion tokamak reactor is expected to have its first ignition in 2025 and be fully operational around 2035. Several developments in technology will be needed for the tokamak reactor and its supporting systems.[43]

With a history that dates back to 1985, ITER was formally established as an international organization via an agreement signed in 2006 by China, the European Union, India, Japan, Korea, Russia and the United States. ITER Organization's functions include encouraging the use of ITER facilities by institutions and personnel from member countries involved in fusion research.

Member countries contribute in-kind and cash for ITER. Cash contributions fund the ITER Organization. In-kind contributions include components, equipment, materials, buildings, and other goods and services. Seven national agencies (or offices) were established to manage the contributions of each member, and procure the goods and services. Member contributions represent "almost 90% the value of the equipment/construction."[44]

> "At ITER, we need close interactions with universities and national laboratories. Because this facility is for the use of universities, scientists and researchers, we want to be associated with various universities worldwide as well as with national labs."
>
> **Bernard Bigot**
> Director General
> ITER Organization

Project governance, and communications and coordination across teams carrying out different parts of the project's technical work are particularly critical in a complex project like this, and a 2013 ITER management assessment documented a number of serious management and organizational shortcomings.[45] In response, a new Director General was appointed in 2015. He ordered a full project review, centralized authority, tightened project management,

43 https://www.iter.org/mach/supporting.

44 Interview with Director General.

45 https://assets.documentcloud.org/documents/1031934/2013-iter-management-assessment.pdf.

and stressed the integration of all teams and agencies as one single organization.

Although final results still have to be proven in practice, the changes introduced by the new administration were well received in a follow-up 2016 assessment.[46] This case suggests that leadership and governance play a pivotal role in the success of big and complex science and technology projects. It also highlights the importance of combining soft and hard skills in project leadership; while hard skills confer technical and scientific authority, soft skills are essential for managing interfaces and the political aspects of a complex endeavor.

Economic Impact

ITER is expected to launch a new era of sustainable energy. Mastering fusion energy would cause a paradigm shift in civilization by creating a large-scale, sustainable and carbon-free form of energy based on widely available resources.

The ITER Organization and the national agencies are developing the supply chain and talent pool required for the reactor implementation, operation and decommissioning, and the potential startup of a nuclear fusion industry. In doing that, they are developing capabilities in industry that will be needed to manufacture and supply parts and services for future nuclear fusion power plants, building competitive advantage.

A variety of new technologies are being developed in areas such as: magnet systems, cryostats and cooling systems for the plasma chamber; robotics; vacuum systems; sensors and automation; cryogenics; materials; nuclear fuels; nuclear protection and insulation. Access to intellectual property (IP) will not be limited to companies from member countries, but they will have more favorable conditions. ITER's implementation significantly benefits the region around it. More than €6 billion in contracts were awarded to European companies, half in France, and three-quarters of this fraction went to companies in the region.47 Currently, more than 3,200 people work at the French site. ITER spends more than €300 million in salaries and local services. The Regional Government is investing almost €470 million in infrastructure.

University Involvement

Universities have been involved with ITER through a variety of channels at the member countries and directly. The ITER Organization has many agreements with universities for scientific and technological cooperation in the fusion field. Also, the ITER Organization or domestic agencies can award grants to universities to fund R&D tasks in support of project needs.

ITER is the focal point for the International Tokamak Physics Activity (ITPA) network, established in 2001.48 In 2016, the Inter-Scientists Fellow Network was launched to catalyze engagement with universities and national labs.49

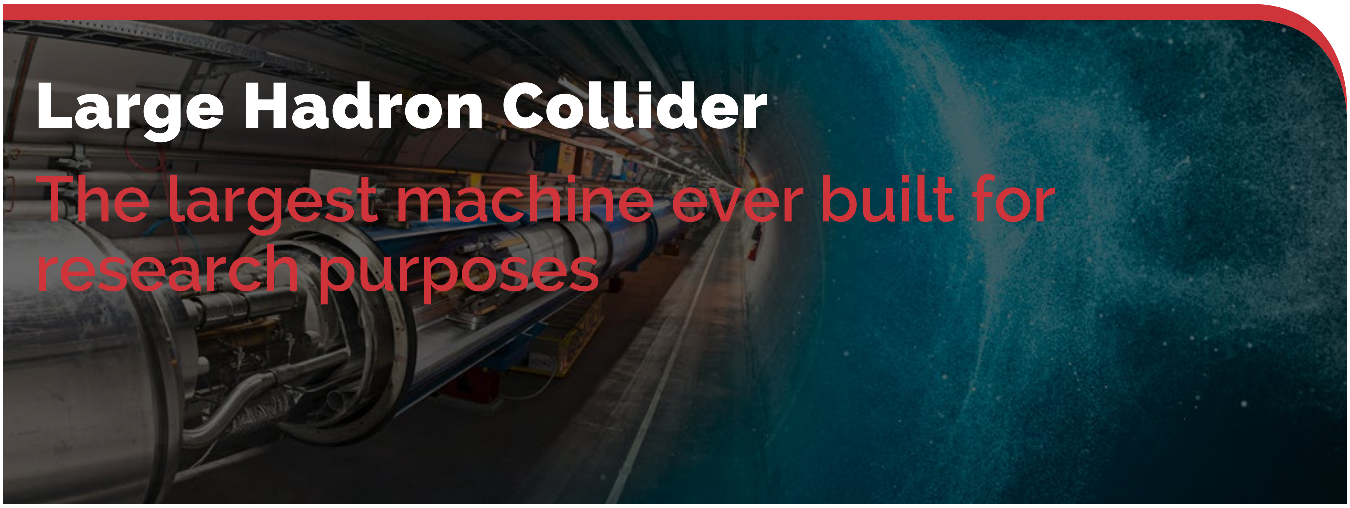
Engagement with universities also has an important education component — educating and training the people who will work on the project and, potentially, in industry in the future. ITER looks for collaborations in which universities can develop new curricula and degree programs centered on project advancements.

46 http://www.sciencemag.org/news/2016/04/updated-panel-backs-iter-fusion-project-s-new-schedule-balks-cost.

47 https://www.investinprovence.com/en/news/iter-marks-10-years-of-thermonuclear-fusion-provence.

48 https://www.iter.org/org/team/fst/itpa.

49 https://www.iter.org/newsline/-/2343.



Large Hadron Collider

The largest machine ever built for research purposes

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

CERN hosts the Large Hadron Collider (LHC), the largest machine ever built for research purposes. In 1984, CERN hosted a workshop in which the concept for the LHC was originally presented. The construction was approved in 1994 and the LHC became operational in 2008.50

The LHC was designed and implemented to answer fundamental questions in Physics such as:

- What gives matter its mass?
- What is the nature of dark matter?
- What are the differences between matter and antimatter?
- How has matter evolved since the beginning of the universe?

The first question was answered with the discovery of the Higgs boson, the source of all mass. This discovery earned a Nobel Prize for François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles," which was confirmed during experiments at the LHC.

CERN invested in the construction of the accelerator, and provided about 20 percent of the implementation of the detectors. The total cost of all detectors was about CHF1.5 billion.[51] CERN's investment was funded by member states, via its budget and member contributions.[52]

CERN is a treaty organization with a sophisticated, centralized and well-developed governance scheme, which also allows for intensive participation of the scientific community. CERN's model allows for interplay between top-down and bottom-up approaches to project planning, development and construction, and highlights the importance of functional governance solutions for big science projects.

The importance of technology development was recognized upfront in LHC's implementation: "the success of the LHC is directly linked to the ability of CERN's scientists, in close collaboration with industry, to push the limits of known technology way beyond today's frontiers."[53]

50 http://press.cern/press-releases/1994/12/cern-council-gives-go-ahead-large-hadron-collider.

51 https://press.cern/backgrounders/facts-figures.

52 https://home.cern/about/member-states.

53 https://press.cern/press-releases/1994/06/lhc-technological-challenge.

Economic Impact

Member countries provide funding to CERN and, in accordance with the Convention, members are provided with contracts by a juste retour process, proportional to their funding contribution. The member countries involved in the design of LHC have benefited from construction contracts, with several companies taking part in design and manufacturing of parts. The procurement for coil winding and the assembly of the dipole cold masses led to the largest LHC contract, won by companies in France, Germany and Italy.[54]

The experiments had their own architectures and were mainly funded by research agencies in the countries involved.[55] Universities, national laboratories and companies in those countries worked in design and construction of components.

The economic impact of spin outs from the LHC and its experiments is still being measured, but there are already visible results. ATLAS, the largest of LHC's detectors, rendered technology spin-offs with applications in medical devices, medical imaging, ultrasound gas analysis, neurosciences, data storage and manufacturing.[56] Among other things, the Medipix chips developed for the LHC are being commercialized by a number of partners for applications within medical imaging, education, space dosimetry and material analysis.[57] These application cases are part of a broader benefits framework adopted by CERN in the late 1980s, when the Industry and Technology Liaison Office (today "Knowledge Transfer"[58]) was established.

University Involvement

Universities are deeply involved in CERN and the LHC. The original proposals for the ATLAS[59] and ALICE,[60] for instance, mapped the interests of several universities in participating in all stages from the development to the operation of the different detectors subsystems. The same applies to the other experiments.

To carry out their research projects, universities have benefited from grants provided by funding agencies in the countries participating in these projects, and have being involved in the design and implementation of the LHC. They took part in developing the technologies, building and installing equipment for the experiments. Some equipment was built at university facilities across the globe and transported to CERN under special logistical arrangements.[61]

Universities are involved in LHC's operation and researchers from around the globe are LHC's main users and benefactors of its data.

54 "The Impacts of Large Research Infrastructures on Economic Innovation and on Society: Case Studies at CERN". OECD. Paris : 2014. Available at: https://www.oecd.org/sti/sci-tech/CERN-case-studies.pdf..

55 For instance, Canada: http://www.atlas-canada.ca/canconlhc.html.

56 https://atlas.cern/discover/technology-transfer.

57 http://medipix.web.cern.ch/.

58 http://kt.cern/.

59 https://cds.cern.ch/record/291061/files/cm-p00043027.pdf.

60 http://cds.cern.ch/record/290825/files/SC00000003.pdf.

61 http://lhcb-public.web.cern.ch/lhcb-public/en/Installation/International-en.html.

U.S. National Ignition Facility

The largest and most powerful laser ever built

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: The image depicts the National Ignition Facility's Preamplifier Support Structure. This image is the property of the Lawrence Livermore National Laboratory and is not for replication or distribution.

The U.S. Department of Energy's National Ignition Facility is the largest and most energetic laser facility ever built. Planning for the NIF began in the early 1990s, construction began in 1997 and the facility became operational in March 2009. Later that year, the first laser target experiments and, in 2010, the first integrated ignition experiments were performed.

The NIF is the world's preeminent facility for conducting inertial confinement fusion (ICF) and laser fusion energy research, and for studying matter at extreme densities, pressures and temperatures. NIF's 192 intense laser beams are capable of focusing more than 1.8 million joules of ultraviolet laser energy and 500 trillion watts of power in billionth-of-a-second pulses on a BB-size target. The chief goal of NIF is to use its laser energy to create pressures and temperatures so intense that the nuclei of hydrogen atoms within a target fuse—a process that mimics on a small scale what occurs constantly within the Sun. A successful fusion reaction within an NIF target will release many times more energy than the energy required to initiate the reaction. The NIF currently conducts more than 400 ICF, high energy density and discovery science experiments a year.

NIF's construction cost of US$3.5 billion[62] was significantly higher than the year 2000 budget estimate for the project of US$2.1 billion, and its original 1995 baseline budget of US$1.07 billion.[63] Ongoing expenditures are used to operate and maintain the facility.

62 https://lasers.llnl.gov/content/assets/docs/news/pk_faqs.pdf.

63 https://www.gao.gov/assets/240/230520.pdf.

Economic Impact

Fields affected by the NIF include nuclear weapon physics, inertial fusion energy science and technology, and fundamental science research. The NIF not only supports national security but also energy security missions by laying the groundwork for research and development in using fusion as a clean energy source. This may offer virtually unlimited safe and environmentally sustainable energy, and will provide the research basis for an energy production revolution.

NIF's implementation required technology development in various areas, including glass (materials), advanced optical control devices, energy amplifiers, computer-controlled advanced mirrors, a high-speed process to grow crystals, advanced control and automation solutions, and precision materials fabrication.[64] More than 3,000 industry partners contributed to building NIF and its tens of thousands of components.[65] The solutions developed are not just applicable to NIF, but have applications across industries and could even revolutionize frontier areas such as 3D printing.[66]

University Involvement

Universities advised on the design and implementation of NIF. They also play a role in developing diagnostics protocols and technology, in partnership with NIF's team.

NIF serves as a user facility for U.S. universities and research organizations, and is transitioning to become an international user facility for experiments related to the understanding of the universe.[67]

64 https://lasers.llnl.gov/about/how-nif-works/seven-wonders/target-fabrication.

65 https://lasers.llnl.gov/about/nif-partners.

66 https://www.llnl.gov/news/nif-technology-could-revolutionize-3d-printing.

67 https://lasers.llnl.gov/about/nif-partners.

Square Kilometre Array

Designed to create the world's largest radio telescope using an innovative design concept

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: Artist's impression of the full Square Kilometre Array at night featuring all four elements. The low frequency aperture array antennas (bottom right), and precursor ASKAP dishes (background right) will be located in Western Australia. The SKA-mid (front left) dishes and precursor MeerKAT dishes (background left) will be located in South Africa, with some remote stations in other African partner countries.

The SKA will be the largest radio telescope and scientific instrument in the world once complete. The initial concept was developed in 1993, and the current design effort was initiated in 2011. Construction is expected to commence in 2018 and operation in 2023. This is only the first phase; a second phase of design and construction is expected to follow that will enlarge the SKA to its full size. The first phase project is funded by its 10 international members, and the cost-capped budget for the instrument is €674 million. The second phase is expected to cost between US$4 billion and US$5 billion.

The SKA has a central project office, headquartered at Jodrell Bank in the United Kingdom. This project office manages the global commercial and university teams working on the design of the telescope.

The SKA will be used to answer fundamental questions of science and about the laws of nature, such as: how did the Universe, and the stars and galaxies contained in it, form and evolve? Was Einstein's theory of relativity correct? What is the nature of "dark matter" and "dark energy"? What is the origin of cosmic magnetism? Is there life somewhere else in the Universe? But, perhaps, the most significant discoveries to be made by the SKA are those we cannot predict.

"We are not designing new computers. We are broadening the scope of what the high-performance computing (HPC) industry does. We are influencing the leading players in the industry to deliver data-intensive computing, which is a different style of computing than is used to deliver these HPC systems."

Prof. Phil Diamond
Director General
Square Kilometre Array (SKA)

Economic Impact

The technologies and systems needed for the SKA will require engineers to work at the forefront of design and innovation, such as high-performance computing, big data, fast networking, and new manufacturing and construction techniques. The most important spin-off, however, will be the creation of new knowledge and knowledge workers, young scientists and engineers with skills and expertise in a wide range of innovative fields in a large number of countries around the world.

Beyond the science, broader benefits of the SKA are expected to include: use of sustainable energy sources, development of energy-efficient processing, new data processing techniques on the cloud, new data communication strategies and technologies to distribute large packets of data quickly around the world, development of human capacities and capabilities, inspiring future generations that will work on and with the SKA, and enhancement of global and transcultural collaboration in the advancement of knowledge for the benefit of mankind.

Computation will be a critical area for technology development, since SKA will generate data at a rate more than 10 times today's global Internet traffic.[68] The SKA organization is directly engaging with leading global technology companies such as Amazon, Google, IBM, Microsoft and others to determine how to manage this amount of data. The SKA will also impact the development of critical infrastructure and scientific capabilities in host countries. For example, new supercomputer centers serving the SKA will be created in Cape Town, South Africa and Perth, Australia.

The South African partners have been investing in developing skills through their dedicated Human Capacity Development Program. About 700 people have already received scholarships and the project is causing a surge of interest in mathematics, engineering and astrophysics at local universities.

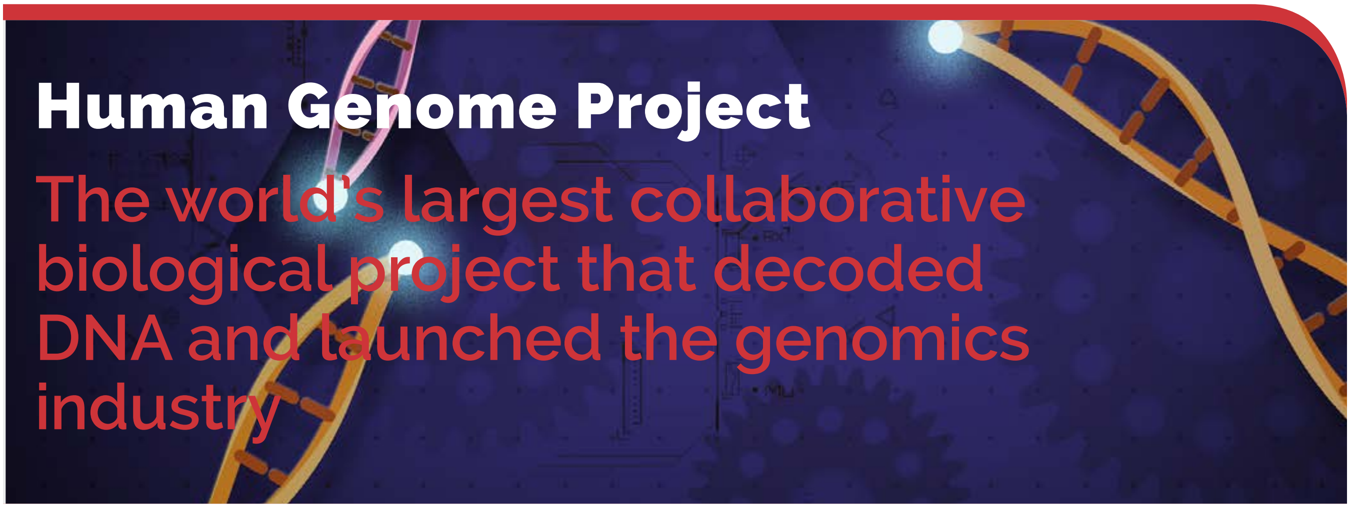
University Involvement

SKA emerged from the scientific community. University researchers developed the concept, raised resources from a variety of funding agencies and the EU, and built momentum for the project from the ground. Universities took part in bids to host the SKA offices and the SKA Organization, which were both won by the United Kingdom.

Universities are directly involved in designing the SKA; 600 scientists and engineers from around the globe take part in the effort. For example, the University of Cambridge is leading the design of the High Performance Computer and the "Science Data Processor" that will deliver the data products from the SKA. Research organizations, universities and companies in Canada, Europe and South Africa are designing and manufacturing the receivers to be connected to the prototype dishes.

University-based scientists will take part in construction, testing and operation of the SKA. They will be the telescope main users and have voice in the continued development of the SKA telescope.

68 https://www.skatelescope.org/frequently-asked-questions/.



Human Genome Project

The world's largest collaborative biological project that decoded DNA and launched the genomics industry

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: Image is the property of National Human Genome Research Institute and is not for replication or distribution.

The Human Genome Project (HGP) was the world's largest collaborative biological project, bringing together scientists from more than18 countries to sequence all 3.2 billion base pairs in the human genome, the complete set of DNA in the human body. The project was launched in the United States in 1990 when the U.S. Department of Energy (DOE) and the National Institutes of Health (NIH) published a joint research plan, setting out specific goals for the first five years of what was then projected to be a 15-year research effort. Shortly thereafter, to expedite completion of this monumental task, the International Human Genome Sequencing Consortium was established, and almost all of the actual genome sequencing was conducted by its numerous member universities and research centers throughout the United States, the United Kingdom, France, Germany, Japan and China.[69] Direct funding was provided by various government bodies involved and, in its final stage, there was some coordination with private sector.

There was competition from the private sector, which accelerated the quest to sequence the human genome. With private funding, the Celera Corporation, founded by Dr. Craig Venter, used a different technique, and a combination of its own data and data produced by the Consortium (freely available online), and achieved a draft genome sequence before the Consortium. In June 2000, Celera and the Consortium jointly announced that both had completed a working draft of the genome. By 2003, the Human Genome's Project's goals had been met or surpassed, under budget and two and a half years ahead of schedule.[70]

The United States spent about US$ 2.7 billion for scientific activities carried out under the HGP umbrella. But this amount does not reflect the additional funds for an overlapping set of activities pursued by other countries that participated in the HGP.[71]

The Human Genome Project was a great example of important, world-leading science delivered by public and private sector researchers from across the globe. Mapping the genome was a groundbreaking scientific achievement and has had a profound impact.

69 https://www.genome.gov/11006939/ihg-sequencing-centers/.

70 International Consortium Completes Human Genome Project. https://web.ornl.gov/sci/techresources/Human_Genome/project/press4_2003.shtml.

71 https://www.genome.gov/27565109/the-cost-of-sequencing-a-human-genome/.

Economic Impact

The Human Genome Project demonstrated that technology advancement can substantially decrease costs and open new opportunities for research and discovery; if the project was started when it was finished, it would cost almost 60 times less.[72] The project was the main force driving the advancement of DNA sequencing technology; since 2001, performance advanced exponentially and sequencing cost decreased 10,000 times, unleashing the development of new businesses and industries.[73]

The economic impacts for the U.S. economy were massive. A 2013 Battelle report suggests that each $1 invested by the U.S. government in HGP-related genomics activities until 2012 generated $65 for society.[74] If this study was focused on the period of the project which finished in 2003, it is possible that $178 was being generated by each $1 invested.

The Human Genome Project led to the creation of a new worldwide research and industry ecosystem, with the global whole genome sequencing market valued at €4.6 billion in 2015 and expected to reach €19 billion by 2020.[75] CB Insights predicts that the number of human genomes sequenced will increase 200 percent annually (CAGR) between 2015 and 2025,[76] driving the demand for DNA-related data storage and processing, and new initiatives that leverage the technology still are emerging.[77]

University Involvement

Universities were decisive in the development of DNA sequencing technologies. The initial developments that led to such technologies were all made at university laboratories, mainly in the United States and the United Kingdom.

As members of the International Human Genome Sequencing Consortium, universities and research organizations took part directly in the Human Genome Project, including hundreds of scientists at 20 sequencing centers in China, France, Germany, Great Britain, Japan and the United States.[78]

72 https://www.genome.gov/27565109/the-cost-of-sequencing-a-human-genome/.

73 https://www.genome.gov/27541954/dna-sequencing-costs-data/.

74 http://web.ornl.gov/sci/techresources/Human_Genome/publicat/2013BattelleReportImpact-of-Genomics-on-the-US-Economy.pdf.

75 https://labiotech.eu/genome-sequencing-review-projects/.

76 "Genomics: The Next Phase of Personalized Medicine". CB Insights: New York, 2017.

77 https://www.weforum.org/press/2018/01/new-partnership-aims-to-sequence-genomes-of-all-life-on-earth-unlock-nature-s-value-tackle-bio-piracy-and-habitat-loss/.

78 https://www.genome.gov/11006939/ihg-sequencing-centers/.

EU Graphene Flagship Project

The largest research collaboration ever undertaken in the EU

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: Official images courtesy of the European Union Graphene Flagship Project.

The EU Graphene Flagship Project (EU GP) was initiated in October 2013 together with the EU Human Brain Project as part of the Future and Emerging Technologies Flagship program (FET). It was originally proposed and is coordinated by Chalmers University of Technology.

Graphene gained relevance in 2004 when researchers isolated a single atomic layer of carbon, an achievement earning a Nobel Prize in Physics. Graphene offers the advantage of being a material much stronger than steel, and it is an excellent electricity conductor, flexible and relatively cheap to produce in comparison with other materials. The Graphene Project focuses on the application of graphene in composites and coatings, sensors, energy generation and storage, biomedical technology, electronics, and photonics and optoelectronics.

The process that led to the Graphene Project's implementation began in 2010 with an EU open consultation. A call for preparatory actions followed in the same year, and 21 project proposals were received and 6 pilot projects were selected for further development. A follow-up call to select two topics from within the six pilots was opened in 2012.

Project proponents were required to develop their proposals, pitch their concept, build partnerships for the proposals and continuously develop them. As of November 2017, the Graphene Flagship consortium had more than150 academic and industrial research group partners in 23 countries, and more than 60 associated members.[79] Thirteen hundred individuals were working on the project, equivalent to about 450 fulltime staff.

Its scale, competitive nature and complexity highlight the **importance of leadership and soft skills in the context of big research endeavors.** The Graphene Project's governance structure includes an Executive Board, a General Assembly representing the project's partner institutions, an expert advisory council, and various boards and forums to

79 One-third come from industry, about one-half from academia and about one-sixth are research institutes and other organizations

"In Europe we have companies that are very good, for instance, in producing materials, making components or integrating them in systems, but we don't have any company that has the entire value chain under its structure. That's a little different in Asia, where you find companies like Samsung, for instance, that cover internally the entire value chain and can make the decision to do something like this. In Europe, it requires collaboration."

Prof. Jari Kinaret
Director
EU Graphene Flagship Project

facilitate communications and cooperation.[80] The project is implemented through six divisions, four of which are research and innovation related.[81]

Overall, 50 percent of funding for the Graphene Project comes from the European Commission and the rest from other European Commission agencies, member state organizations and partner institutions.

Economic Impact

To date, the Graphene Flagship has published about 1,500 scientific articles, applied for 40 patents, launched some 20 products and created a handful of spin-off companies. The launched products are mostly different types of materials and some specific composite applications such as a motorcycle helmet; ongoing projects include a solar cell farm in Crete and parts of the Airbus 350 airplane. Partners have demonstrated several prototypes (e.g., the world's fastest chip-integrable photodetector, or a magnetic field sensor that outperforms competing technologies by a factor of 100), but challenges remain for large-scale production. Since the project has only been running for 40 percent of its planned duration, the full scope of its economic impact is still to be seen.

The project is partnering with industry. Industry's share of the group of project's partners is growing, from an initial 25 percent to an expected 40 percent during 2018. Most of the companies that have spun off from project partners are in the production of graphene and composites using graphene.

More generally, graphene can be applied in a variety of products and industries. Due to its specific properties, graphene is particularly attractive to industries such as aerospace, automotive, solar and cellular (e.g., coatings, electric conductors, batteries for electric cars). Graphene is deemed as a material of the future and, according to BBC research, its market in 2020 could worth US$700 million.[82]

University Involvement

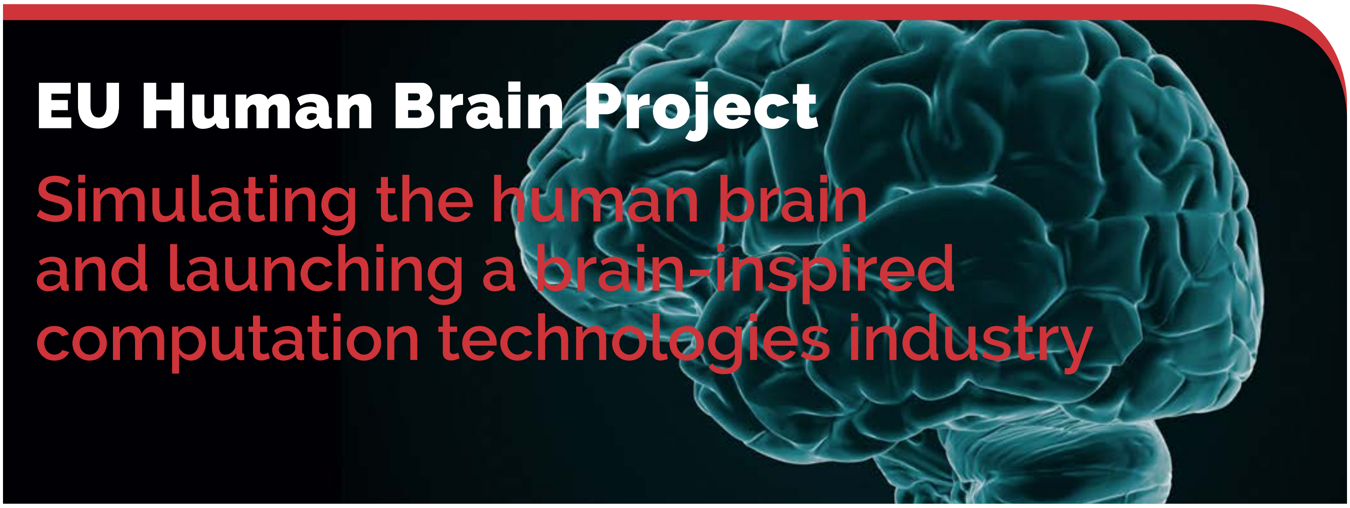
Universities are involved in the Graphene Flagship as consortium members, and act as a primary avenue through which research takes place. To date, there are about 80 European universities involved. They are signatories of the Framework Partnership Agreement with the European Commission and beneficiaries in the core projects governed by Specific Grant Agreements with the EC.

Researchers at universities that are not partners in the consortium, and hence do not participate in the core projects, can become Associated Members and participate in those flagship activities that do not require confidentiality. Associated Members do not share EC financing but are supported by other sources, typically funded by themselves or by national programs. The EU Graphene Flagship is a case where universities are directly responsible for conceptualizing and implementing a large-scale project.

80 http://graphene-flagship.eu/project/governance/Pages/Core1Governance.aspx.

81 http://graphene-flagship.eu/project/divisions/Pages/divisions.aspx.

82 https://innovateuk.blog.gov.uk/2017/07/20/what-is-graphene-and-what-is-its-potential-economic-impact/.



EU Human Brain Project

Simulating the human brain and launching a brain-inspired computation technologies industry

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

EU Flagship Projects are designed to establish the EU region as a key player in a specific field of research and are aimed at making the region more competitive in the long term, either in relation to research or spin-off technologies. The EU Human Brain Project (EU HBP) was launched in 2013 in an effort to better understand the human brain and accelerate research in multiple disciplines related to neuroscience, computing and brain-related medicine. Key interests and research topics include:

- Better the understanding of human brain organization and neuroinformatics
- Brain simulations that allow for the study of diseases with in-silico experiments
- Neuromorphic computing as a basis for robotics and neuro-based controlling
- Better the understanding of cognitive and theoretical neuroscience (e.g., learning, perception, sleep and consciousness)

The Ecole Polytechnique Federale de Lausanne (EPFL) coordinates the EU HBP.. The HBP core is funded directly by the European Commission. It also includes Partnering Projects funded by national organizations, including government agencies, philanthropy, and businesses. The total budget is estimated at about €1 billion, including €500 million from the European Commission, €500 million from national partners and €19 million provided by various sources for the core ramp-up phase.

The HBP is organized in twelve subprojects, including six related to the digital platforms that form the heart of the research infrastructure: Neuroinformatics, Brain Simulation, High Performance Analytics and Computing, Medical Informatics, Neuromorphic Computing and Neurorobotics.[83] It also includes partnering projects (projects that already have their own funding and are aligned with the HBP research roadmap), and six co-design projects (transdisciplinary initiatives that cut across the subprojects and interface with the partnering projects).[84]

83 https://www.humanbrainproject.eu/en/about/project-structure/subprojects/.

84 https://www.humanbrainproject.eu/en/about/project-structure/codesign-projects/.

Economic Impact

The EU HBP has developed hardware and software for the six platforms: Neuroinformatics, Brain Simulation, High Performance Analytics and Computing, Medical Informatics, Neuromorphic Computing and Neurorobotics. These platforms are made available for the scientific community and interested parties, under different types of agreement and levels of access.

The Brain Simulation Platform and the Neurorobotics Platform allow for neuroscientific simulations of the human brain. These simulators will not only be useful to neuroscientists for a better understanding of the human brain by analyzing underlying data, but also for researchers and developers interested in neuro-inspired controllers for advanced robotics.

Also, the Project led to the design and construction of two large-scale neuromorphic machines that operate at a much higher speed than conventional supercomputer simulations. Neuromorphic chips are being used in vision and speech systems, motion control and adaptive robotic controllers in the development of advanced robotics and AI. The HBP team has also developed a series of new neuromorphic chips, announced during the 2018 Neuro Inspired Computational Elements Conference.

With the EU being one of the prominent regions for research and development in artificial intelligence, HBP has an indirect impact on the industry by making their results and data accessible. Given the European Commission's investments in robotics and advanced manufacturing, this has a direct impact on Europe's competitiveness in the industry.85

University Involvement

Universities are involved in the project as consortium members and act as a primary avenue through which research takes place. Seventy-five universities are signatories of the Framework Partnership Agreement with the European Commission and beneficiaries in the core projects governed by Specific Grant Agreements with the EC.

Researchers at universities that are not partners in the consortium, and hence do not participate in the core projects, can become Associated Members and participate in those flagship activities that do not require confidentiality. Associated Members do not share EC financing but are supported by other sources, typically funded by themselves or by national programs. In total, the Project directly employs some 500 scientists at more than 100 universities, teaching hospitals and research centers across Europe.

The EU HBP is a case where universities are directly responsible for conceptualizing and implementing a large scale project.

85 In November 2017, the European Commission released a statement acknowledging the global competition with countries such as the United States and China that are increasing their R&D expenditures in the AI field. (https://ec.europa.eu/commission/commissioners/2014-2019/ansip/blog/making-most-robotics-and-artificial-intelligence-europe_en).

EU Quantum Technology Flagship Project

Kick-starting a quantum technology industrial ecosystem and economy

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: Official images courtesy of the European Union Quantum Technology Flagship Project.

In April 2016, the European Commission announced the EU Quantum Technology Flagship Project (EU QTFP) in the context of the European Cloud Initiative. The EU QTFP is a program co-funded by the European Commission and the EU Member States. Like the two other Flagship Programs, the total investment will be approximately €1 billion, half funded by the EC.

The flagship is still in the preparatory phase. In spring 2018, the flagship will announce a first call for proposals with deadlines in the summer and fall of 2018. Proposals will be evaluated and project funding will start in January 2019. This initiative is set to drive research into this disruptive technology within the program, and also establish and support long-term cooperation in Europe between academia, industry and businesses.

The main goal of the flagship initiative is to foster European leadership in science and research, to build a competitive European industry in quantum technology and elevate Europe's position as a relevant cluster for this particular field. It builds technological and industrial capabilities on top of Europe's existing research capabilities in the field.[86]

University Involvement

Universities are expected to be involved in the project as consortium members and act as the primary avenue through which research takes place. Researchers at universities that are not partners in the consortium are expected to participate in flagship activities as Associated Members, following the example of other Flagships.

86 http://ec.europa.eu/newsroom/document.cfm?doc_id=46979.

Economic Impact

The Quantum Flagship call for proposals is focused on four quantum technology application domains:[87]

Communication: "Development of state-of-the art network devices, applications and systems (memories, quantum repeaters, network equipment, high throughput miniaturised quantum random number generators, etc.) for quantum communication mesh-networks. […]"

Computation: "The development of open quantum computer experimental systems and platforms[5], integrating the key building blocks such as quantum processors (>10qubits) with limited qubit overhead, control electronics, software stack, algorithms, applications, etc. […]"

Simulation: "Proposals should aim at delivering operational demonstrators, based on existing physical platforms that have shown a clear perspective to achieve more than 50 interacting quantum units and / or full local control. They should work towards demonstrating a certified quantum advantage for solving difficult scientific or industrial problems (e.g. material design, logistics, scheduling, machine learning, optimisation, artificial intelligence, drug discovery, etc.). […]"

Sensing and Metrology: "Quantum sensors for specific application areas such as imaging, healthcare, geo-sciences, outdoor and indoor navigation, time or frequency, magnetic or electrical measurements, etc. … as well as novel measurement standards, making use of the advances in controlling the fundamental quantum properties […]"

Fundamental Science: "Research and development of basic theories and components, addressing a foundational challenge of relevance for the development of quantum technologies in at least one of the four areas a.-d. described above, to improve the performance of the components or subsystems targeted in those areas. […]"

87 http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/fetflag-03-2018.html.

Ansari XPRIZE Suborbital Spaceflight

Catalyzing a private sector wave of business investments in space technologies

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

To encourage development of commercially viable space travel, the Ansari Suborbital Spaceflight XPRIZE challenged teams from around the world to build a reliable, reusable, privately financed spaceship capable of carrying three people to 100 kilometers above Earth's surface. The competition was launched in May 1996 and the US$10 million prize awarded in October 2004. The XPRIZE was inspired by the 1919 Orteig Prize, which offered US$25,000 in a challenge to aviators to fly nonstop from New York to Paris and was won by Charles Lindberg flying the Spirit of St. Louis.

A total of 25 teams from 7 nations competed in the challenge.[88] And, for their flight to an altitude of 112 kilometers in the SpaceShipOne craft, the XPRIZE was awarded to the "Tier One Team" from Mojave Aerospace Ventures, a company led by aerospace engineer Burt Rutan and funded by Microsoft founder Paul Allen.

The Ansari Suborbital Spaceflight XPRIZE was the first of a series of challenges and marked the beginning of the XPRIZE Foundation. More importantly, it turbocharged the role of prizes as catalysts for new ventures and technology development in the 21st Century, inspiring a variety of similar initiatives.

University Involvement

Although some university students and professors were involved in the teams, no universities competed in the Ansari Suborbital Spaceflight XPRIZE as teams.

88 https://ansari.xprize.org/teams.

Economic Impact

The competition catalyzed US$100 million for R&D in suborbital space flight by the different teams, funded by investors and sponsors from around the globe. The project resulted in new technologies and commercialization opportunities, and was instrumental in launching the more than US$2 billion private sector space industry.[89]

Richard Branson entered into an agreement with Mojave Ventures, and the technology developed for the SpaceShipOne laid foundation for the startup of Virgin Group's space ventures, initially with through Virgin Galactic,[90] but today including The Space Company and Virgin Orbit.

Beyond the space industry, the original XPRIZE was instrumental in accelerating the adoption of prizes and competitions as tools to spur innovation,[91] inspiring and/or informing initiatives in philanthropy and government. For example, the White House launched a toolkit[92] for U.S. Federal agencies, which provides guidance on running challenges and prizes, and these agencies sponsor numerous challenge competitions described at www.challenge.gov.

XPRIZE

XPRIZE grounds itself on the belief that the democratization of science and technology through crowdsourcing can create a critical mass of experimentation aimed at solving the world's most pressing social and scientific problems. By building a structure of gamified incentives, XPRIZE's model replaces the big firm or state actor with the small team as the driver for innovation, empowering citizens directly.

"Not just three or four teams, governments or industries can do these breakthroughs, but we can have hundreds if not thousands of small teams and individuals that can now experiment," said Marcus Shingles, XPRIZE's CEO.

By organizing competitions, XPRIZE aims to use an incentive-based methodology to direct grassroots entrepreneurial efforts to devise solutions to problems and challenges that, despite their potential to benefit communities, may lack sufficient profitability. Central to this mission is drawing on a diverse range of contributors, from engineers to sociologists, to address scientific issues through a multidimensional approach. A current initiative aimed at innovation in housing, for instance, involves biotechnologists, engineers and anthropologists working side-by-side as a competitive team.

As XPRIZE expands its scope, it hopes to work with universities to involve students in the process of crowdsourced innovation. XPRIZE helps design courses that teach students the fundamental concepts of crowdsourcing and modern innovation. In combination, these courses offer an avenue for students to participate in XPRIZE competitions on small teams. Young people can then incorporate themselves into the network of grassroots entrepreneurship that XPRIZE intends to foster.

At its core, XPRIZE believes in using competition to harness the emergent "crowd economy," democratizing research and experimentation. This process begins locally, with XPRIZE engaging with small teams and schools, and ends with the advancement of scientific knowledge at a societal level. As new technology continues to empower and connect concerned citizens, XPRIZE aims to decentralize innovation and birth the entrepreneurial explosion needed to address the world's emerging concerns.

89 https://ansari.xprize.org/teams.

90 https://www.engadget.com/2016/02/19/virgin-galactic-unveils-the-new-spaceship-two/.

91 https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/using-prizes-to-spur-innovation.

92 https://obamawhitehouse.archives.gov/blog/2016/12/15/incentivizing-innovation-new-toolkit-federal-agencies.

Apollo Moon-landing Mission

Start of the "moonshot" concept, culminating with the extraordinary feat of taking humanity to the moon

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

The Apollo project was the vision of U.S. President John F. Kennedy in response to geopolitical tensions in the 1960s, and is perhaps one of the most recognizable examples of extreme innovation projects. Its goal was straightforward–put a man on the moon–but the execution was difficult and constrained by both time and budget.

The project was managed by the National Aeronautics and Space Administration (NASA), but consisted of several units and offices. To ensure effectiveness and efficiency, a management council was formed with representation from each unit. The project was a success; in 1969, the Apollo Lunar Module landed safely on the moon and returned safely to Earth, while meeting temporal and monetary constraints. At its peak, the Apollo Project accounted for 2.2 percent of the U.S. Federal budget.

Economic Impact

Technology: It rapidly accelerated the pace of technology development and gave rise to numerous technologies including: non-flammable fabrics, breathing systems for firefighters, wireless control of pacemakers, storage tanks for liquid methane fuel, cordless power tools and vacuum cleaners, cooling suits, implantable heart defibrillators, solar panels, improved kidney dialysis and improved athletic shoes.

Human Impact: Sent a striking message to encourage mankind's drive to explore, while also sending the message that the United States was an undisputed military and technological superpower.

Legal: Invention disclosure policy was debated with regard to rights over all new technologies, which gave way to new patent laws.

Economic: At its peak, employed more than 400,000 Americans and funded more than 20,000 firms and universities, directly or indirectly.

University Involvement

NASA set up university scholarship and doctoral programs to attract students to the space sciences. It also set up summer training courses for faculty, who could do research at a NASA laboratory or space center, and ideally return to their universities ready to establish research in the space sciences. It is through these programs that many aerospace and space science departments were established at universities throughout the United States.

Many universities signed Memoranda of Understanding with NASA for the construction of laboratories to conduct research for space related projects. Twenty-seven labs were established. Roughly two-thirds of NASA's university investments went into what were called "Project Research Programs": that is, grants or contracts given to individual faculty members. One-third of the funding was through the "Sustained Universities Program" in which the money went to institutions as opposed to individual researchers. A third category, "Apollo Guidance," is listed separately in NASA documents; because of its unique nature, it was carried out primarily by MIT.

Breakthrough Starshot

A multi-billion private sector-initiated initiative that aims to change the economics of space exploration

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Breakthrough Starshot is part of Breakthrough Initiatives, a program founded in 2015 by Yuri and Julia Millner to "seek scientific evidence of life beyond Earth, and encourage public debate from a planetary perspective." Starshot was announced on April 12, 2015 in New York City, as a US$100 million initial effort to begin work on a multi-decade program to send a gram-scale robotic nanocraft probe to the nearest star system, Alpha Centauri 4.3 light-years away, pushed by an Earth-based laser beam. A board composed of Professor Stephen Hawking, Facebook's Mark Zuckerberg and Yuri Milner has governed Starshot. Dr. Simon Pete Worden, former director of NASA's AMES Research Center and GFCC Distinguished Fellow, is the Executive Director.

The program will include three main phases: (i) research and engineering (US$100 million), (ii) building a prototype system (US$1 billion), and (iii) mission implementation (approximately US$10 billion). A public-private partnership is expected to complete the final stage of the mission. The initial two phases will take 20-30 years (including 5-7 years of research and engineering); the interstellar flight is expected to last about 20 years and will be followed by approximately 4.3 years of data transmission back to Earth.

> "We are interested in more general interdisciplinary university collaborations and have begun discussions with several universities along these lines. Key to these collaborations will be to include both Breakthrough Initiative resources as well as university contributions".
>
> **Dr. Pete Worden**
> Executive Director
> Breakthrough Starshot

Economic Impact

Breakthrough Starshot will create new-to-the world technology solutions and, potentially, new industries. If successful, it will also change the economics of space exploration.

Massive technology developments will be needed. For example, the aimed velocity is three orders of magnitude faster than what can be done today. The three major engineering and technical challenges are to (i) design, build and implement an affordable laser system of 1km diameter, 1,000 times more powerful than what exists today, (ii) build a material that can withstand the power produced by the laser and not tear apart, and (iii) develop an inter-stellar communication solution. According to the project team, up to 20 other areas require almost as significant advancements. Achieving even part of these goals will open up vast new opportunities in research and industry.

Areas of technology that will be advanced include: lasers, materials (i.e., composites, structures), electronics (i.e., printed electronics, organic electronics, flexible electronics), optics and extreme condition optical components, control systems, energy production and storage (i.e., batteries, capacitors, etc.), asteroid detection, image capture (cameras) and processing, propulsion, flight control, autonomous AI computing, and compact, long-distance laser communication systems.

University Involvement

Universities are involved with Breakthrough Starshot through participation in the Advisory Committee, and direct engagement with research and development calls. Starshot is connecting resources and capabilities distributed in universities across the world.

The initial set of Starshot calls for proposals address the so-called "photon engine," the laser system that will push the starcrafts. Starshot will run three phases of R&D and demonstration for the engine over a five year period; as many as 19 awards are expected to be granted to research and technology developers.[93] Other requests for proposals for a variety of systems and subsystems will follow. These will create new opportunities for university engagement.

In other Breakthrough Initiatives, universities take part mostly via individual arrangements or research groups funded by the Initiatives. Broader models for engagement are being sought for the Breakthrough Starshot and will require a new type of integrated response from universities.

For the moment, universities provide technical support and advice to Breakthrough Starshot. Other models of engagement can be expected to emerge as the project evolves.

93 http://breakthroughinitiatives.org/i/docs/170919_bidders_briefing_zoom_room_final.pdf.

DARPA Grand Challenges: Autonomous Vehicles

Pioneer tech competition that jump-started the autonomous vehicle industry

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

In 2000, the United States Congress set the goal of making one-third of U.S. military operational ground combat vehicles autonomous by 2015.[94] And, in 2002, Congress authorized U.S. Department of Defense agencies to award cash prizes for outstanding scientific and technological achievement in support of its missions.[95] Based on this goal and authorization, the Defense Advanced Research Projects Agency (DARPA) offered US$1 million in prize money for developing an autonomous vehicle that could navigate a course.

The initial DARPA Grand Challenge, which ran in 2004 and 2005, was created to spur the development of technologies needed to create the first fully autonomous ground vehicles capable of completing a substantial off-road course within a limited time. Its 2004 edition was the first long distance competition for driverless cars in the world.

None of the 15 vehicles that competed in the 2004 final race completed the 142-mile route in the Mojave Desert–all vehicles failed. The vehicle that traveled the farthest distance completed only 7.5 miles. No prize was awarded. Following the event, DARPA announced that the prize money had been increased to US$2 million for the next event, which was claimed on October 9, 2005. The 2005 event involved 23 finalists and 5 of them completed the course. The Stanford University team won the 2005 competition, a success that was mostly attributed to the pioneering use of AI machine-learning techniques.

Following the 2005 success, DARPA extended the challenge to autonomous operation in a mock urban environment. The first, second and third places in the 2007 Urban Challenge received US$2 million, US$1 million and US$500,000, respectively. The 2007 Urban Challenge involved 11 finalist teams and 6 completed the course, with the Carnegie Mellon University team as the big winner.

94 Public Law 106-398, National Defense Authorization, Fiscal Year 2001, October 30, 2000.

95 Public Law 107-314, Bob Stump National Defense Authorization Act for Fiscal Year 2003, December 2, 2002.

Economic Impact

The potential spinout from the challenge was important to DARPA, which wanted to foster the development of autonomous vehicle technology to support the armed forces. Companies such as Oshkosh Defense and TORC Robotics, which competed in the challenges, went on to develop solutions for the military.[96]

The commercial civilian potential has also been exploited, and can be seen in the development of autonomous vehicles from Google, Uber and a number of car manufacturers. In fact, the DARPA Autonomous Vehicles Grand Challenge had a fundamental impact in launching a global community of technologists, and jumpstarting an autonomous vehicle industry with massive economic potential.

Sebastian Thurn, the professor who led the 2005 Stanford team was recruited by Google and, there, founded GoogleX and led Google's famous self-driving car project, which spun-off as Waymo. Thurn's team building approach for Google's self-driving car project was straightforward: he recruited people from the best teams that competed in the 2005 and 2007 challenges, mainly from Stanford and Carnegie Mellon.[97]

Technologies such as LIDAR[98] were tremendously improved as an outcome of the challenge and companies such as Velodyne, a manufacturer of LIDAR devices that participated in the challenge, had a major push. Above all, machine learning and deep learning techniques became the standard in the industry.

In 2040, more than 90 percent of all vehicles sold worldwide are expected to be highly or fully autonomous.[99] A study released by Intel in 2017 suggests that autonomous vehicles will create a US$7 trillion annual mobility economy by 2050.[100]

University Involvement

Universities were deeply involved in the competitions. Teams from Carnegie Mellon, University of California-Berkeley, Stanford, Virginia Tech, Caltech, University of Florida, Cornell, University of California-Los Angeles, MIT, Princeton, University of Utah and others competed. The Stanford and Carnegie Mellon teams won the 2005 and 2007 challenges.

The DARPA Autonomous and Urban challenges provide great examples of universities leading competing teams. Participation in the challenges allowed universities to engage with industry, develop and promote their capabilities and created unique opportunities for research and education.

96 https://www.darpa.mil/news-events/2014-03-13.

97 https://www.wired.com/video/how-a-bunch-of-geeks-and-dreamers-jump-started-the-self-driving-car/.

98 https://www.wired.com/story/lidar-self-driving-cars-luminar-video/.

99 http://loupventures.com/auto-outlook-2040-the-rise-of-fully-autonomous-vehicles/.

100 https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/05/passenger-economy.pdf.

Google Lunar XPRIZE

The largest technology competition ever to foster private sector lunar and space exploration

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

The XPRIZE Foundation, with sponsorship by Google, chose the Moon as the center of this particular challenge. The goal is to inspire engineers, entrepreneurs and innovators from across the globe to develop low-cost methods of robotic space exploration. The moon was chosen as it provides opportunity for expanding exploration in the solar system including human habitation.[101]

A total of US$30 million is to be awarded, including a grand prize of US$20 million for first place, the largest incentive ever offered in a technology competition. To win the prize, a privately-funded team must successfully place a spacecraft on the Moon's surface, travel 500 meters, and transmit high-definition video and images back to Earth.

Initially, 32 teams registered by December 31, 2010, with 16 teams having participated in all activities, but only 5 teams satisfying the rule requiring a verified launch contract by December 31, 2016. Teams came from Brazil, Canada, Chile, Germany, Hungary, India, Israel, Italy, Japan, Malaysia and the United States, in addition to a variety of "international teams."[102]

The teams met various project milestones and the competition rendered other results. Nevertheless, in January 2018, the XPRIZE Foundation announced that, after reviewing the projects, the Prize would go unclaimed.[103] The competition was originally launched with a deadline set for 2012, which was later postponed on several occasions, with the last launch attempt deadline set for March 31, 2018. However, US$6 million were awarded to teams that met specific milestones. This case highlights the potential for this model, but also how difficult it is for big, complex privately financed challenges to fly.

101 https://lunar.xprize.org/about/why-the-moon.

102 https://lunar.xprize.org/teams/.

103 https://lunar.xprize.org/news/blog/important-update-google-lunar-xprize.

Economic Impact

In total, it is estimated that the teams raised US$300 million in capital from sponsors and investors. The project enabled private sector initiatives from different countries to be launched, technologies to be developed and a new global community of space technology entrepreneurs to be formed. It also catalyzed developments in regulation. Moon Express received the first-ever approval granted from the U.S. Federal Aviation Administration to send a private spacecraft to the Moon.

The project intended to develop a cost-effective and reliable pathway to the moon. An independent study calculates the market opportunities generated from the competition as close to US$2 billion.[104]

In the long run, the project outcomes could include access to materials such as raw metals, which could be extracted and leveraged on Earth, and even a new location for human habitation.

University Involvement

Among others, universities from Germany, Israel, Italy, Japan, Poland and the United States were involved with the competing teams and judging panel.[105] Different teams counted on the support of research organizations in their countries. There were also university professors that mentored members of the teams.

Examples of university involvement include: Pennsylvania State University sponsored the Penn State Lunar Lions, provided funding to the team, and members working on the project were students; Carnegie Melon University partnered with Team Astrobotic, which had students working on the project, which was led by Professor Red Whittaker, who was also behind CMU's participation in the DARPA challenges; the Israeli SpaceIL Team was led by a professor who heads the Center for Planetary Science at the Weizman Institute of Science; Tohoku University was part of the Hakuto Team, led by one of its professors.[106] The case provides an example of how universities can be involved with this model in different capacities.

TeamIndus

TeamIndus[107] competed in the Google Lunar XPRIZE. Founded by Rahul Narayan and a small initial group of innovators, TeamIndus has since grown to a team of 120 who share a goal for India to contribute to state-of-the-art technological development. Today's team combines the ambition of its young engineers with the expertise of its seasoned scientists from the Indian Space Research Organization (ISRO). With funding drawn from equity, grants and scholarships, TeamIndus represents a cohesive fusion of public, private and academic inputs towards a revolutionary objective.

At the core of TeamIndus' vision is the aim of lowering the cost of space projects in such a way that the barriers to human exploration exponentially collapse. Using the Google Lunar XPRIZE as a stepping stone, TeamIndus hopes to invest further in spacecraft architecture using the support of the ISRO. Achieving this goal calls for collaboration with a wide range of research and academic entities, such as the Indian Institute of Astrophysics and the University of Colorado.

Drawing comparisons to the information technology boom, TeamIndus believes that engaging with space holds the potential to unleash a critical mass of employment and technological innovation.

104 https://lunar.xprize.org/press-release/study-estimates-market-worth-19-billion-google-lunar-xprize-competitors-within.

105 https://lunar.xprize.org/about/judges.

106 https://www.tohoku.ac.jp/en/news/research/hakuto_google_lunar_xprize.html.

107 http://www.teamindus.in/.

Psyche Mission

The first space mission set to explore a metallic planet precursor, with student participation in all phases

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

Photo: This artist's-concept illustration depicts the spacecraft of NASA's Psyche mission near the mission's target, the metal asteroid Psyche.

Credit: NASA/JPL-Caltech/Arizona State University/Space Systems Loral/Peter Rubin.

The NASA Jet Propulsion Laboratory (JPL) has funded a project to journey to the orbiting Psyche asteroid. The Psyche asteroid is unique, as it appears to be the nickel-iron core of an early planet and may hold answers to many questions regarding the building blocks of our solar system.[108] Psyche will be the first metal world ever explored, as other worlds explored so far have had a surface of ice, rock or gas.

The project requires a solar-electric propulsion spacecraft with an imager, magnetometer and gamma-ray spectrometer that can gather data from the asteroid and communicate back to Earth. The launch date is 2022 with an arrival at Psyche in 2026. The goal of the project is to "understand the building blocks of planet formation and explore firsthand a wholly new and unexplored type of world."[109]

"A big impact for ASU is expected as the project lead. Winning and succeeding in this size of project takes the university to a new level in the eyes of peers, gives validation in the eyes of possible industry partners on other projects, and allows a new level of attention and access in Washington, DC."

Dr. Lindy Elkins-Tanton
Director
Arizona State University School of Earth and Space Exploration

108 https://www.jpl.nasa.gov/missions/psyche/.

109 https://asunow.asu.edu/20170104-discoveries-asu-lead-nasa-space-exploration-mission-1st-time.

"The project aims for significant international and national impact in the inspiration of people to take bolder steps in their own lives."

Dr. Lindy Elkins-Tanton
Director
Arizona State University School of Earth and Space Exploration

Psyche is part of NASA's Discovery Mission series, which have engaged university researchers as principal investigators. The mission concept was developed based on a paper co-authored by Dr. Lindy Elkins-Tanton, Director of Arizona State University's (ASU) School of Earth and Space Exploration. She was invited by NASA to lead the mission and is Psyche's principal investigator, responsible for the overall mission success.[110]

In its early stages, the project was funded by JPL, Space Systems Loral (SSL), ASU and other universities involved. NASA later provided US$3 million for a concept study, with equivalent funds invested by SSL, JPL and ASU. Currently, NASA funds the project, with some contributions from ASU and other players.

Economic Impact

A goal of Discovery Mission projects is to leverage low-cost, low-risk heritage technologies to achieve results. Major instruments are all going through improvements, but not complete redesigns. The biggest new technology involved is the Deep Space Optical Communications package, a sophisticated laser communication technology that will be capable of delivering information at rates at least 10 times faster than conventional systems of comparable mass and power. Psyche's main industry partner, SSL,[111] will have its first experience with a deep space mission, which is likely to lead to innovations for the company. A number of small companies are on contract for various aspects of technology and management, and will also be impacted.

The Psyche team is piloting and exporting advances in education, such as (1) Psyche-related projects for university senior-year capstone courses; (2), free online innovation-focused short courses based on Psyche's science, engineering and technology challenges and skills; (3) engaging undergraduates in communicating the excitement of the mission to the public through their artistic and creative talents; and (4) Psyche science communication undergraduates will develop and disseminate activities and demonstrations for use in formal and informal educational settings.

University Involvement

Universities participate through members on the science team, and instrument building and management. They receive subcontracts from the main NASA grant through ASU or JPL. Other university involvement comes through student collaborations. University participation was organized through research groups in the initial phase, but for support during the 2nd step proposal and thereafter, participation has been at the university level.

110 https://planetarymissions.nasa.gov/missions/psyche/management.

111 NEED

ASU BioXFEL (X-ray Free Electron Laser)

Making an extreme innovation tool accessible for broad biotech impact

Impact Dimensions

- Scientific discovery
- New technology
- Technical capabilities in industry
- Industry push
- Local economy
- Community
- Education
- Political
- National security

"Some of the most exciting science is happening in areas that require a team of scientific experts. BioXFEL research covers an amazing breadth of science, spanning physics, chemistry, biology and engineering. My vision for BCASD was to bring exceptional faculty in each of these areas to develop more powerful instruments and technologies that are extremely useful and productive at answering important questions in biology with a large impact on society."

Dr. Petra Fromme
Director
Biodesign Center for Applied Structural Discovery

The U.S. National Science Foundation (NSF) BioXFEL center has a goal of understanding how life works at the molecular level.[112] It leverages high intensity X-ray lasers to take snapshots of unprecedented clarity at the molecular level.

One specific funded program is housed within Arizona State University, with the goal of leveraging protein crystallography to develop methods for understanding structures of biomolecules using XFELs (X-ray free electron laser). ASU's Biodesign Center for Applied Structural Discovery (CASD) was established in 2014 to expand research capabilities in the field using an external XFEL instrument. In order to accomplish this goal, a large multidisciplinary team had to redesign nearly all methods and techniques.

ASU's Dr. Petra Fromme[113] and Dr. John Spence[114] originally envisioned the concept for a BioXFEL and its application at the university in 2004. (XFELs provide significantly more intense X-rays than synchrotron light X-ray sources. One application of BioXFEL research allows researchers to take snapshots of protein movements together with a series of drugs to understand how they interact.)

112 https://www.bioxfel.org/about/our-mission.
113 https://biodesign.asu.edu/petra-fromme.
114 https://physics.asu.edu/content/john-spence.

Since then, their teams met for 2 hours every Friday to develop the concept, but all early proposals to funding agencies were rejected as too risky. Once the world's first XFEL was built in 2009, it allowed them to test the ideas.

CASD is now building a new type of compact XFEL that could fit on a bench top and would cost about US$20 million to build, with funds provided by the President's Office. ASU plans to create a nonprofit company to disseminate technology, with the vision that, in the future, it could be installed in hospitals and medical clinics.

Economic Impact

Significant scientific results have been achieved, with more than 20 high impact publications published in Nature, Science, and Cell journals since 2011. Changes to drug relevance studies and structural biology were also produced.

The main impacts of BioXFEL research are in drug discovery and immunology. Molecular-level insights can result in more effective drugs and in better understanding of disease pathways including cancer. Impact in health is expected to be amplified through engagements with drug companies and the Mayo Clinic to evaluate drug targets, with potential additional funding sources. Developments are also expected in clean energy conversion technologies, through a better understanding of photosynthesis.

In addition to results in health and energy, CASD will have a massive impact in fostering the use of XFEL technology for biodiscovery and in health in general. The development of a compact XFEL at 1/50th the cost of a traditional synchrotron light source could revolutionize the field by democratizing the technology. If successful, the project will make XFELs available to many more scientists (and health service units) around the world and accelerate the rate at which we discover knowledge for helping solve critical global challenges.

University Involvement

Several universities are part of NSF's BioXFEL.[115] ASU's Center involves eight universities and several labs, and ASU's own Compact BioXFEL project involves other universities, such as MIT.

Overall, ASU's BioXFEL is a good example of a university-led initiative that can result in broader societal impact, with the potential democratization of an advanced technology with critical applications in health.

"The time and cost associated with using large XFELs restricts their access to perform the day to day research needed to accelerate and increase societal impact. For example, a drug researcher or company might want to see how their top 10 compounds work, which would help them design a superior drug that can be given in much lower doses and have far fewer side effects. This is not practical using large XFELs but would be possible with the lower cost compact XFELs we are developing. We think every major research institution, company or hospital could own one."

Dr. Petra Fromme
Director
Biodesign Center for Applied Structural Discovery

115 https://www.bioxfel.org/about/partner-institutions.

3.2 What Are the Key Takeaways From the 17 Cases?

Research credentials are key, but not enough. Leadership and entrepreneurial mindsets are needed.

In the majority of the case studies reviewed, universities were the originators of the initial concept for the projects, which, through strong leadership and entrepreneurial mindsets, were taken from an initial idea to completion. Those project leaders were required to raise funds, seek support and approval from their scientific communities, engage industry and, in some cases, engage governments. This required the individuals involved to have a strong vision for their science and resilience to ensure that projects would ultimately be delivered. Research excellence and world-class scientific capabilities are key qualifications for universities to lead or take part in extreme innovation initiatives. Nevertheless, projects are conceived, consortia formed and bids won mostly because of entrepreneurial mindsets and behaviors. As the cases reviewed reveal, such as EU Graphene, Psyche Mission, FAST and SKA, leadership is critical for the success of the projects.

Technology opens up new possibilities for university leadership in extreme projects.

Technology democratization is a key factor driving competitions, awards and prizes. It can also enable universities to experiment with new design concepts for big machines (e.g., ASU's Biodesign Institute) and explore new avenues of action and engagement with industry and society (e.g., DARPA Autonomous Vehicle Challenge). Universities are well positioned to harness the potential of technology as drivers for extreme innovation, impact in society and education transformation.

Extreme projects are increasingly global, even if started at a regional or national level.

There are two key reasons for this. First, the nature of knowledge and professional networks (communities) in science and technology are global. Second, due to the economic rationale of big projects, unique mega-global research infrastructures are "natural monopolies" with players from other countries seeking participation in the project (CERN, ALMA, SKA, FAST).

There is not "one model" for big, transformational science and technology projects.

Big, transformational projects come in a variety of models. They can be international organizations governed by international treaties; owned, managed and operated by government organizations; funded by philanthropy and run as decentralized initiatives; etc. Evolution in the landscape shows the re-emergence of prizes and awards as catalyzers of big and bold technology development initiatives, funded privately (e.g., XPrize) and/or with public funds (e.g., DARPA Autonomous Vehicle Challenge). There is also a trend towards big decentralized research initiatives as seen with the Human Genome Project, EU Flagships and the Malaria Strategy.

Governments do not have a monopoly on extreme projects.

Governments are the main funders of big science and technology projects. Nevertheless, private capital was instrumental in launching the "big science" era and, now again, increasingly relevant for bold, transformational science and technology projects (e.g., Breakthrough Starshot and XPrize, but also others such as Bill & Melinda Gate Foundation Malaria Strategy). Private funding for bold, big, transformational science and technology projects and initiatives is likely to expand in the years to come.

Private capital brings new rules of engagement to big science and technology projects.

This differs from the past when investments were channeled through foundations with loose connections to donors. This new wave of philanthropy has rich technology industry benefactors deeply involved with project design and implementation (e.g., Yuri Milner and Breakthrough Initiatives, the Gates and their Foundation). Another important difference is that project initiation is largely motivated by donors' personal interests and beliefs; it does not result solely from decisions made by staff at the foundation.

Industry engagement is still challenging for science projects.

It is important to engage with industry, but the timing can be difficult and the processes for engagement are not always in place. Big science projects have long development cycles that not always align with industry. In addition, intellectual property (IP) issues suggest that more effective models to engage industry up-front are still required. In general, project leaders state that they would have liked increased industry engagement in project design and implementation, and noted the importance of industry joining in early stages. Frameworks for that are not always in place and differences in the perspectives of government funders and project teams need to be aligned. Development of a framework is just as important when IP is created in the design phase of projects that have societal impact but also have technology spillovers into broader sectors. Some of the projects were implemented as part of organizations that have well-established frameworks for technology transfer (e.g., the LHC), others not (e.g., ALMA).

Extreme projects require sophisticated infrastructure, particularly digital and computation.

Even more than other human activities, science has been digitalized and is intense in data generation (e.g., SKA will generate six times more data than the Internet generates today)–big science means big data. The implementation and operation of big and advanced scientific facilities and tools requires high capacity data storage, processing and transmission. Big science and technology projects also require other types of complex infrastructure, which needs to be maintained and updated over time (e.g., LHC's annual operating cost is about US$1 billion).

4. Different Rules Apply for the Projects

Project origination, funding and university participation vary from project to project. Nevertheless, there is a thread of similarity among the projects reviewed.

University participation can occur at all levels of the project structures reviewed, but each category has a set route for university engagement. In general, universities find opportunities to lead and work on work packages in large research endeavors, at least in the European case. In other categories, such as prizes and private initiatives, it is possible to lead, but perceived barriers such as obtaining funding or assuring the private investor that they can deliver, may hinder a university's ability to assume a leadership role initially.

Philanthropy is particularly active in large research endeavors and extreme technology initiatives, but university engagement varies depending on if it's a prize (lower numbers of universities) versus direct research funding for a large project such as Starshot (higher numbers).

Finally, one of the findings in this report is about the growing role of private capital in extreme innovation projects (e.g, Starshot, SpaceX, Malaria Project). However, governments remain the main funders of these projects.

It must be noted that, for the particular case of university-led initiatives, projects typically originated at the university and participation, naturally, happens at the project management and work package levels.

Operational mechanisms and best practices for managing extreme projects do not vary substantially among categories, but the rules of engagement between privately and publicly-funded projects do. Below is a review on how

	Big science projects	Large research endeavors	Extreme tech initiatives
Origination	University Research organizations	University Research organizations Philanthropy	Government Philanthropy Research organizations Industry
Sweet spot for university participation	Work package	Project management Work packaged	Work package or team
Funding	Public	Public (+) Private	Public Private (+)

funding schemes work and the key differences between initiatives funded by public and private sources.

Public and private models are similar in management, but differ in terms of engagement and speed.

It is not uncommon for a university's or industry entity's central finance office to identify, approve, and execute project contracts, but also serve as the pass-through for funding flows from project funders. This approach is used in the funding by international organizations and EU projects. Most other projects use a hub and spoke approach, passing funding from the central project office to the university or commercial entity. Only the prize projects use a slightly different funding approach, which is described below.

Typically, the International Organization Model has two funding sources:

- Ongoing access to a large research platform or institution, such as CERN, ESO and SKA, requires a membership payment to cover the operational costs of the platform or institution and the overhead for its overall research activities. This funding typically comes directly from a government.
- For new projects carried out within the research platform or institution, funding is raised by members on a project-by-project basis, and may not require the participation of all members. This funding will be paid by members either directly to the platform or institution, and/or through country specific mechanisms directly to universities working on the project. In the U.K., for CERN, ESO or SKA projects, the Science and Technology Research Council manages this relationship and distributes funds either to the platform or institution or to U.K. universities.

This model has been developing over decades and there is now a robust governance process in place for identifying projects, assessing the business case, project approval, funding transfer, delivery and audit. The projects will be continually assessed as they progress through each stage prior to full operation.

Projects established without the need to create a treaty organization fall into a category of non-subscription, directly funded projects. Examples include EU Research Grant Projects. In this category, the appropriate research funding body will provide funds to the project management group or universities involved. Like the International Organization Model, this model also has a robust governance process in place for identifying projects, assessing the business case, approval, funding transfer, delivery and audit. The project will be continually assessed as it progresses through each stage prior to full operation. This ensures that public funding is spent appropriately.

Similar to those outlined above, the final model is the privately-funded Philanthropic Model, such as the Breakthrough Initiatives. A central funding body provides funding to a central project office, and a number of projects deliver the technical elements. The role of governance structures is less clear, though it is believed that these will be industry standard approaches. It is hoped that these will be transparent, so that it is clear how projects are progressing, that they are being managed appropriately and funding administered properly. This approach has greater flexibility than government-related funding models, and can be more readily adapted to the type of project being established. The extension of this model is Prize projects, which use similar approaches to funding; but, rather than providing grant funding, prize funds are offered. Government agencies may be authorized to use a prize model for particular challenges, as the DARPA example illustrates. Prize funding models do differ from all others in that they do not provide funding for research. Each team must provide their own funds to participate in the challenge competition. Prize organizers provide only a cash prize at the end of the challenge for up to four places (1st– 4th) depending on the particular scheme. This has the highest financial risk for any institution taking part. Prize organizers try to limit this risk by helping teams find sponsors for their activities.

Regardless of funding model, they all use similar, standard, management models to organize, govern and deliver projects to completion. The most crucial difference between public and privately-funded projects is probably related to the rules of engagement and governance.

For example, in rules of engagement, publicly funded opportunities are typically publicized and involve open calls for proposals, while privately-funded opportunities may not be publicized and involve direct engagement with donors.

In terms of governance, publicly funded projects are typically subject to a more rigid and transparent governance process than privately funded projects. However, for a typical project, regardless of the funding source, the following applies: there is a central project office that manages and coordinates activities on a day-to-day basis. The central office also provides assurance through appropriate reporting to the funding bodies (public or private). High level management and oversight could take the form of a Council or Board, with representatives from all of the funding bodies. Independent technical oversight and audit functions may also be created, depending on the scale of the project.

There are two key interfaces in large projects that are important to the success of the governance structure; the interface between the central office and the funding body, and the interface between the central office and the project teams delivering work packages. The former is important, as project risks and timelines should be estimated and communicated to funders, so they can support the project appropriately, but also be assured that funding is being used appropriately (important for funders own audit needs). The latter is important, because the project requires monitoring of work package performance to ensure work will be delivered on time, on budget and at an appropriate level

Table 1. Overview of Characteristics of Public and Private Funding for Extreme Projects

	PUBLIC	PRIVATE
Volume of resources	Billion(s)	Millions
Duration	Years to multiple decades	Years
Governance	Formal and structured Rules and processes: these are typically aligned to government standards, for example Prince2 project management method or equivalent The projects have to publish governance information and, as a general rule, public funding bodies need to publish their governance practices Independent audit is applied	Related to corporate standards for program/project management Can be informal/flexible Processes are generally held privately and not published It is not clear which type of audit practices are applied to the project, but these will be set by the funder
Rules of engagement	Clear and publicized Open calls	Not necessarily public Direct contact with donors May use open calls in project execution
Types of projects	Big infrastructure Big science endeavors Large research effort	Large research effort New technology development Exploration
Motivation	National priorities Scientific community objectives Global challenges	Personal interests of donors Desire for impact
Origination	Bottom-up + Top-down	Top-down

of quality, fulfilling the primary objectives of the business case. How this interface is integrated into the management model will define how much control the central office has over the external parties delivering the work package. It will also define the extent to which those work packages will fund the teams to deliver the project.

For both interfaces, the projects reviewed in this report take slightly different approaches with some having harder links at each interface. The scale of the project and budget is often reflected in the level of governance established to monitor and control the project.

Table 1 illustrates the most common characteristics associated with projects funded by public or private sources (no causal relationships implied).

Similarities across extreme projects, regardless of origination or funding sources, allow for the development of efficient and effective processes to ensure that focus can be on the project's technical rather than operational requirements, while ensuring fiscal responsibility and stewardship of funds in the interest of the funding organization and project goals. Similarities across projects also allow for the development of a set of concrete, evidence-based recommendations for further and future engagement by universities on big, bold, transformational projects.

	PUBLIC	PRIVATE
Challenges	Timeline: from concept to operation can take 10–20 years Connections with industry: given the length of time between concept and operation, industry can lose interest, waiting for an appropriate time point to engage with a project	Impact: may be designed for a specific objective which may not aid broader scientific communities May only benefit the private funder and be closed to other communities Specialized technologies may not have broad impact Connections with academia: need to establish new networks and create trust within the philanthropic/private community, as they are not used to working with these groups Documentation
Opportunities	Learning systematization: open data policies New organizational models Disruptive technologies: new technologies that may have a broad range of impact beyond the project, such as the World Wide Web from CERN Broad impact across multiple scientific areas, industry, engaging the public and skills/training development or capacity building	Scientific community awareness Capital availability New models for project delivery and working with universities New funding opportunities for universities Opportunities for different innovation models to extend the project (corporate/private led)
Trends	Global engagement to deliver projects: engaging talent from around the globe Broader national impact beyond the science Need for strong infrastructure to deliver the main project and its objectives (e.g., high performance computing and networks for CERN, ALMA, SKA, EU projects) Public engagement and diversity is important to these projects Open data policies	Scientific relevance Development of effective new funding mechanisms Covering a broad range of scientific disciplines Global networks of experts Commercially linked projects

5. Universities Already Play Several Roles, But Can Further Expand and Elevate Their Participation

In all the projects analyzed, universities are playing pivotal roles, but their responsibility and involvement varies. In this section, the types of roles are reviewed, opportunities identified and comments on how universities can better engage and leverage extreme projects are provided.

5.1 The Role of Universities in Big Science and Technology Projects

Universities can serve in both key and supporting roles, as leaders and implementers, and their role continues to evolve as the future of big projects changes. Examining the capacities in which universities participate in big science and technology projects helps in understanding how they can continue to engage on future projects.

Looking at the case studies, some well-defined roles being played by universities are evident.

Universities come up with innovative ideas

For many of the projects analyzed in this report, the original concept was conceived by academics. This is true in the case of the following projects: SKA, FAST, EU Human Brain Project, EU Graphene Flagship, EU Quantum Flagship and ALMA. In other cases, universities have led the generation of ideas and the development of the project concept, but within the boundaries of a call for proposals or participating teams from a funding body. Examples of these include CERN's LHC, Psyche Mission and the DARPA Autonomous Vehicle Challenge.

Universities participate directly in project implementation and even build devices

Universities have led and managed projects. In project execution, they have engaged in the design, development, construction, manufacturing and testing of critical research platforms, and special instruments and equipment used in these projects. They play a major role in performing the research work undertaken, and university students and professors have formed or participated on teams in prize competitions. They provide technical support, and serve as subject experts and advisors on projects. Often the academic teams bring in skilled project managers to support the successful delivery of their part of the project. In some cases, this has led to founding a spin out company to support construction of the project.

Universities are the main users and, in some cases, the operators of big science tools

In nearly all projects, particularly those that are government-funded, universities request access to the experiment and the data it is generating to further their own research activities. Big science tools such as the LHC, ALMA and SKA produce massive and truly unique sets of data. Universities and researchers are the key consumers of this data generated and, in turn, develop off-shoot research projects and research discoveries.

But…the role of universities is evolving

Individual universities are initiating projects, and working with industry and government partners to drive the delivery of these projects (e.g., Psyche Mission). Private funders offer a new avenue for funding, but private funders may have their own objectives and seek projects aligned with those objectives. Competitions provide a clear mechanism for commercial and academic research groups to work together, but do not provide funding to support research activities, which, in turn, transfers the risk to the teams. Universities can play a larger role in this type of endeavor, but will need to engage other funders or assume risk themselves; in both cases, they need to be entrepreneurial.

Part of such evolution should–or could–involve enhancing the capacity and the capabilities needed to perform the roles already outlined. Efforts should also include measures that would allow universities to better perform other responsibilities and roles that were not frequently identified in the case studies.

Universities could better explore the eight archetypical roles presented at right when they engage with extreme science and technology projects. These roles are not mutually exclusive and universities can serve in one or multiple roles on a per project basis.

The case studies suggest different opportunities for universities to engage with extreme science and technology initiatives, not just through big science, but also through innovative, distributed and low capital expenditure models. Universities can enlarge their responsibilities in work packages, expand engagement with industry, access new funding sources, experiment with new models, leverage projects for educational purposes and assume leadership in some situations. However, to do so, they will need to work on a series of enablers. A synthesis of these opportunities and their enablers is presented in Annex I, drawn from the overarching parameters presented in the following section.

Roles of Universities on Extreme Projects

1 Concept Developer
In a number of cases, the concept for the project was developed by a university group. This concept subsequently gained momentum within the scientific community, which led to the beginning of a construction project.

2 Technical Supporter
As projects are identified and grow, universities are required to join the project to apply technical expertise to the design, in order to further develop it.

3 Advisor or Oversight Role
In many projects, universities will have faculty members who are key experts and provide oversight and assurance reviews of the project for the central office and stakeholders.

4 Work Package Delivery
In some cases, universities have delivered completed items for projects, essentially acting as a commercial partner, delivering an item via contract.

5 System and Data Tester
Universities are often employed to test the system, prior to moving to full operation. The researchers' in-depth knowledge of the system that they have designed makes them effective testers and troubleshooters of the system, prior to full operation.

6 Experimental User
To extract output from these projects, skilled people are required to deliver the objective and collect and manipulate the data. Experts are required to deliver the project when operating — and more importantly to exploit the outputs of the data and project technical design — to deliver the broadest benefit possible.

7 Facility Operator
In some cases, universities operate and manage big science facilities built/owned by government organizations.

For instance: SLAC/Stanford and Argonne/Chicago.

8 Team Leader
Universities can assemble and manage teams that take part in technology challenges and awards.

5.2 What Could Universities Do to Better Engage With Extreme Projects and Leverage Existing Opportunities?

The task force did not cover the full landscape of big transformational science and technology projects in this report; that was not the intended goal. Instead, a variety of projects were reviewed with different characteristics to provide a good understanding of the opportunities for universities to engage, but also the capabilities they need to reinforce to maximize such opportunities. Universities have a unique set of assets and position within the scientific community. Understanding how they can leverage their assets and better position themselves to play a role in current and future extreme innovation projects will be key to ensuring future engagement.

First, universities should understand the structure of large innovative projects and ensure that they are equipped to participate. Transformational science and technology projects are on the rise, the number of initiatives is increasing and the investment expanding. The public sector is the main funder for such initiatives, but philanthropy has a growing participation. As a result, there is a proliferation of stakeholders. Participation in extreme projects can enable universities to involve researchers and students in cutting-edge initiatives and problems, engage with industry, develop unique capabilities, elevate their brand globally and tap into new pools of resources. Complex science and technology projects require capabilities across disciplines, and transdisciplinary universities are ideally equipped to play a role if well-structured management across multiple departments is well-established. (Integration was a central topic of discussion during the 2nd meeting of the GFCC University and Research Leadership Forum, held on November 30, 2017 in Kuala Lumpur.) To maximize opportunities, universities should know, understand and follow the developments in extreme science and technology projects globally. Structures, resources and processes for that should be present at the university level.

Second, universities must adopt an entrepreneurial mindset. The previous section reviewed different roles that universities can play in extreme science and technology projects. The analysis included in this report suggests that there are new opportunities for universities to engage and even lead projects. To maximize such opportunities, universities will need not just structures and processes, but creative mindsets. Universities can leverage their scientific and technological capabilities to launch extreme projects on their own as concept developers (e.g., ASU BioXFEL). They can also position themselves as project leads of government or philanthropy-backed initiatives (e.g., Graphene Flagship), or identify and build teams to compete for prizes and awards. In each of these cases, they will need to invest in themselves and take a risk. In short, universities have to be entrepreneurial to maximize participation in extreme projects. Tools to encourage such a mind shift include training, seed funds for project exploration and initiation, and strategic funds to support groundbreaking, innovative extreme technology initiatives.

Third, universities should invest in developing leaders. All cases reviewed highlighted the importance of leadership, for the projects and university participation. (This was also a main theme of discussion during the GFCC University and Research Leadership Forum 2017 meeting in Malaysia.) The importance of individuals who invest time in developing concepts, sell them to partners and peers, build coalitions, engage with stakeholders (in industry, government, philanthropy, education, media, etc.) and keep the ball rolling over the years cannot be exaggerated. Extreme science and technology initiatives have long project cycles. They require long term commitment, resilience and a variety of soft skills such as communications, negotiation, strategic thinking and team-building. They also demand social, cultural and political sensitivity, in addition to scientific and technical expertise. Universities depend on capable self-initiators to take part in extreme projects. They should intentionally and systematically develop and prepare such leaders. This can be done through a combination of leadership development programs, organizational solutions to free time and empower leaders to work with external stakeholders, and cross-training with well-established leaders.

Fourth, universities need to develop strong relationships with potential sponsors. An invigorated participation of philanthropy in the extreme science and technology landscape was noted in this report. And private capital brings new rules of engagement to the game, as the Breakthrough Starshot case illustrates. To tap into private sources of resources, universities need to understand the motivations of philanthropists, develop personal rapport with them and be ready to have donors actively involved in their initiatives. Information, analysis, outreach and relationship management are needed to grow this area within the university, and universities that invest in such activities will be better positioned to take part or even lead philanthropy-backed initiatives.

Fifth, universities can leverage their role in extreme innovation projects to benefit their educational programs. Extreme science and technology projects are long-term and demand expertise from various fields. They also create the opportunity for expertise development and integration in a real-world context. Universities can leverage the opportunities created by extreme science and technology projects by integrating them into their education and industry (i.e., innovation, economic development) portfolios. From an education perspective, students can be allowed to accrue academic credits through their participation in project activities. Universities can design curricula in relevant disciplines for long term projects in which they are involved, making it possible for students to engage in different project stages. From an industry perspective, universities can either serve as local hubs for technology companies in the local ecosystem to connect with big science and technology projects, as the ALMA case suggests. Or, universities can engage early on with industry to co-create solutions as part of the design and construction of these complex endeavors.

5.3 Final Thoughts

At this time, there are a growing number of opportunities to initiate and fund big, transformational science and technology projects. However, universities are not always positioned effectively or technically prepared to engage with the broad range of philanthropic, commercial and public funding bodies to deliver a pipeline of projects and seamless integrate them with their education, research and economic development portfolios.

This report shows that there is a strong foundation in place. Universities and research organizations are already striving to deliver projects through organizations such as CERN, but these projects can be limited to a few countries or delivery partners. There can be limited flexibility or potential for new partners to engage at any level.

This report also highlights the benefits that big, transformational science and technology projects can bring to local and national economies. They include a broad range of impacts, such as the development of new technologies and industry capabilities, innovation, education and training, commercial contracts, political partnerships and the growth of competitive advantage.

The case studies reviewed revealed that universities use various mechanisms to engage with extreme science and technology projects, and there are different roles to be played. The case studies also shed light and corroborated the importance of governance, leadership and integration across multiple university departments to provide consistent and timely responses to outside stakeholders. Above all, the case studies underline that universities need to be entrepreneurial and prepare leaders, if they want to elevate their participation in extreme science and technology initiatives, and take advantage of existing and emerging opportunities.

Global connectivity, technology advancements, and societal and economic transformations also create opportunities to experiment with and implement new modalities in extreme science and technology projects. Universities can play a leading role, solving big problems and challenges, partnering with government and industry, innovating, creating economic value and building prosperity in the communities in which they operate and worldwide.

To accomplish that, universities should purposefully seek to share best practices, open opportunities to network and partner on a global scale, and develop novel methods for funding and project delivery. However, new mindsets, strategies, structures, processes and capabilities are needed. The GFCC can serve as a platform for exchanging information on best practices, and for developing further guidance on university involvement in extreme science and technology projects. It can also provide a framework for universities to work with other innovation stakeholders–in industry, government, philanthropy, and international organizations–in piloting new models for extreme innovation. In this pursuit, the GFCC and its university members can make impact locally and globally by solving big problems and challenges, innovating, creating economic value and building prosperity.

APPENDIX A

Opportunities and Enablers

	Big science projects	Large research endeavors	Extreme tech initiatives
Opportunities	Expand responsibility in work packages Engage with industry at a deeper level	Take the lead in large scale research initiatives Access new private sources of funding	Leverage competitions and prizes in the context of education Partner with industry in competitions and awards Access new private sources of funding Engage in extreme technology initiatives in a more strategic and high-level position
Enablers	Leadership Research excellence Global networks Connections with funders Rapport with industry Administrative infrastructure	Leadership Research excellence Global networks Understanding rules of engagement Connections with funders Rapport with industry Seed funding for project exploration Administrative infrastructure	Leadership Research excellence Global networks Understanding rules of engagement Connections with funders Understanding new models Rapport with industry Administrative infrastructure

APPENDIX B

Glossary

AI Artificial intelligence

ALMA Atacama Large Millimeter Array

ASU Arizona State University

BAO Beijing Astronomical Observatory

CAGR Compound annual growth rate

CAS China Academy of Sciences

CASD Biodesign Center for Applied Structural Discovery

CERN European Organization for Nuclear Research

CMU Carnegie Mellon University

CNPEM Brazilian Center for Research in Energy and Materials

DARPA Defense Advanced Research Projects Agency

DOE U.S. Department of Energy

EPFL Ecole Polytechnique Federale de Lausanne

ESFRI European Strategy Forum on Research Infrastructures

ESO European Southern Observatory

EU European Union

EU GP EU Graphene Project

EU HBP EU Human Brain Project

EU QTFP Quantum Technology Flagship Project

FAST Five-hundred Meter Aperture Spherical Radio Telescope

FET EU Flagship Future and Emerging Technologies

GFCC Global Federation of Competitiveness Councils

HGP Human Genome Project

ICF Inertial confinement fusion

IP Intellectual property

IRAM Institute for Radio Astronomy in the Millimeter Range

ISRO Indian Space Research Organization

ITER International Thermonuclear Experimental Reactor

ITPA International Tokamak Physics Activity Network

JAXA Japan Aerospace Exploration Agency

JPL Jet Propulsion Laboratory

LHC Large Hadron Collider

LIDAR Light detection and ranging

LNLS Brazilian Synchrotron Light Laboratory

MIT Massachusetts Institute of Technology

MOU Memorandum of Understanding

MRC Medical Research Council (U.K.)

NAOJ National Astronomical Observatory of Japan

NASA National Aeronautics and Space Administration

NIF National Ignition Facility

NIH National Institutes of Health

NRAO National Radio Astronomy Observatory

NRI Australian National Research Infrastructure

NSF National Science Foundation (U.S.)

PS Proton Synchrotron

RCUK Research Council UK

SKA Square Kilometre Array

SSL Space Systems Loral

VLT Very Large Telescope

XFEL X-ray Free Electron Laser

APPENDIX C

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