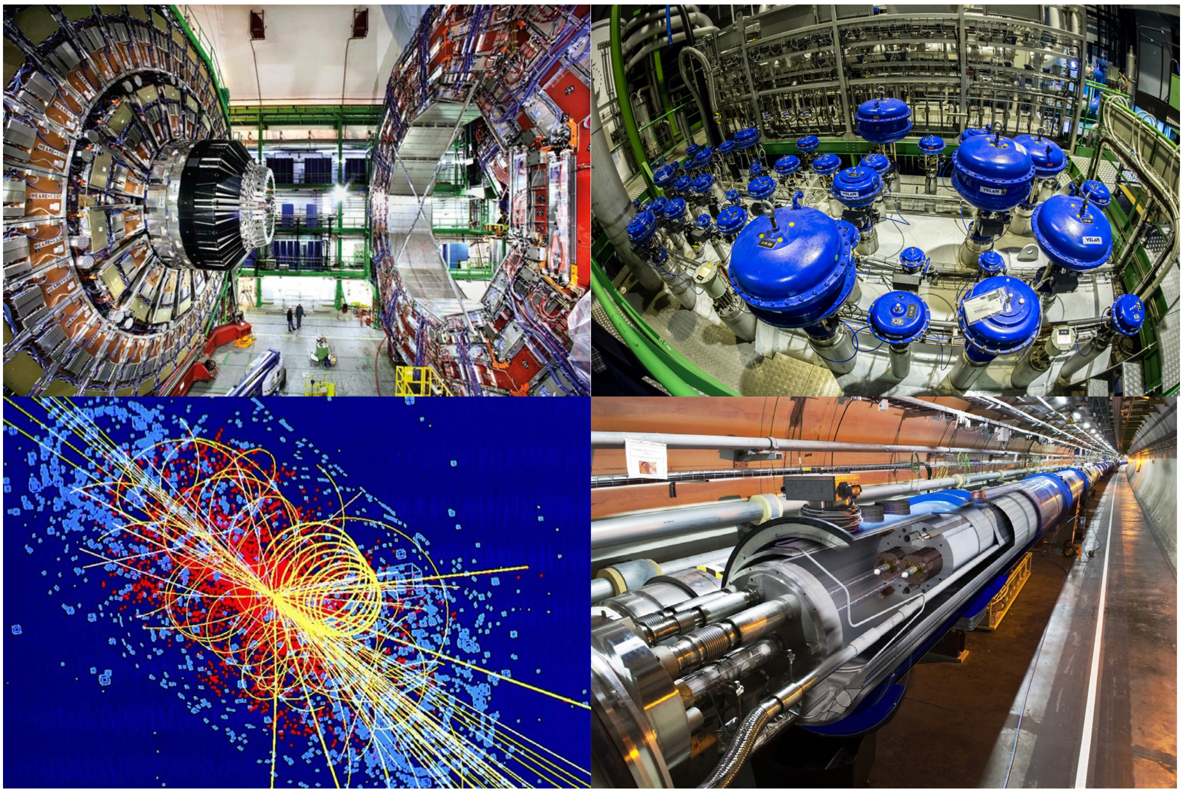
Evaluation of the Benefits that the UK has derived from CERN



Main Report

August 2020

Executive Summary

CERN addresses fundamental questions of the Universe at a facility of unprecedented scale. It is the world's largest particle physics laboratory, making available complex, purpose-built particle accelerators and detectors, as well as computing technology, for its global research community (more than 13,000 researchers, from 75+ countries and 100+ nationalities) that spans various fields (particle-, nuclear-, astro- and accelerator physics, computing, engineering and beyond). As an international organisation, it brings together the community to develop and build state-of-the-art instruments and experiments, continually pushing the boundaries of facilities technology and engineering, computation and analytics.

The UK is one of CERN's founding members and has been centrally involved throughout its history. Through a subscription –managed by the Science and Technology Facilities Council (STFC), on behalf of the UK – it currently contributes £144m per year to the CERN budget (16% of Member State subscriptions, 2019). This covers the building, operation and maintenance of the infrastructure, plus the governance and administration of CERN. The construction, maintenance, upgrade and operation of the experimental programme and the computing infrastructure is then additionally supported through funding from agencies of participating countries (for the UK, mainly by STFC). Over the past decade, the UK's total investment in CERN through subscriptions and funding has averaged £152m per year.

STFC commissioned Technopolis to undertake an evaluation that would capture, demonstrate and measure the range of scientific, economic and social impacts emerging from the UK's investment in and co-development of CERN, both from direct UK involvement and use, as well as wider influences of CERN on the UK. The study drew on multiple sources of evidence, including desk research, surveys, interviews, case studies and bibliometrics, to explore the various impacts of CERN on the UK across four main areas.

Benefits and Impacts relating to World-Class Research

CERN research makes important advances in particle physics, including a series of landmark discoveries such as the Higgs boson - the last missing piece of the Standard Model of particle physics, hypothesised more than 40 years earlier. Other major breakthroughs made at CERN include the discovery of weak neutral currents (1970s) and electroweak (W and Z) gauge bosons (1980s), measurement of the number of lepton generations (1990s), observation of CP violation in charm quarks (2019) and the (to-date) null result showing the lack of supersymmetry. These advances support further scientific progress and offer the potential for very significant wider societal impacts in the longer term. UK scientists also build on this research to support their further progress and achievements. In the past 10 years alone, over 20,000 UK scientific papers have cited CERN articles, and this includes many of the UK's most influential physics papers (25% of these UK papers are among the 10% most cited in their field globally).

Pooled investments by Member States have enabled facilities that would be beyond the reach of any country alone. CERN therefore provides access and opportunities at world leading facilities, at a fraction of the overall costs. This includes access to unique technologies and capabilities, international collaborations and networks, frontier science and experiments, the latest theories and developments, new methods, training and learning opportunities. The UK science and engineering community is taking up such opportunities on a significant scale, with e.g. over 1,000 researchers from 30 UK organisations currently using CERN (third highest amongst Member States).

CERN opportunities support the strength of the UK research community, helping to sustain the UK as a world leading research nation. UK personnel have been involved in all of the major experiments and discoveries at CERN, with many UK researchers holding key positions. CERN-based publications have also significantly pulled the UK's citation metrics upwards, demonstrating the high-quality research enabled. In addition, CERN contributes to the UK's international presence, visibility and reputation, which plays out through the attraction of funding, talent and other forms of recognition for the UK.

Benefits and Impacts relating to World-Class Innovation

CERN's scientific breakthroughs have required major advances in technologies, which have then found wider application, across research and industry. In several notable cases (e.g. the World Wide Web, detectors for PET scanners, touchscreens, GRID computing), CERN has provided the platform for a major new technology that has come into general use and had a transformative effect, bringing economic and societal benefits to the UK and the rest of the world. Other examples of innovations emerging from CERN include the HTTP protocol, next-generation (hadron beam) radiotherapy, radiation-hardened robotics for nuclear decommissioning, fibre optic sensors to help manage water shortages and various software tools and advances in machine learning, pattern recognition and big data analyses (amongst many others). Forthcoming upgrades to the facility will require further technological innovation, which in time will no doubt also find wider uptake and application beyond CERN and particle physics.

CERN membership also gives UK companies access to a steady stream of contract opportunities, with ~500 UK firms having sold goods and services to CERN in the past decade, bringing in an additional £183.3m in revenue and supporting employment (all figures in 2018 prices, unless stated). In addition, at least £33.4m was awarded to UK firms for CERN experiments (organised by collaborating countries) and by the CERN Pension Fund. These contracts have been won by a wide range of UK firms, from small precision engineering companies, through to global technology firms and pension fund managers.

These UK suppliers also realise wider benefits, beyond the value of the contracts themselves, for instance through the development of innovative technologies or access to new market opportunities. CERN contracts also bestow a degree of prestige on suppliers that is not easily replicated elsewhere, which aids new sales. Half of UK suppliers reported that past CERN contracts had resulted in an increase in other sales income, and we estimate that a further £1bn in turnover and £110m in profit has been supported amongst UK suppliers in the past decade, on top of the direct income received through contracts.

Benefits and Impacts relating to World-Class Skills

There is significant uptake of CERN training opportunities in the UK. In the past decade, around 1,000 individuals have participated across the various formal schemes that CERN offers, receiving (free) training worth more than £4.9m. Even more acquire skills and knowledge 'on the job', including each year around 1,000 researchers, 300 CERN staff, 40 fellows and hundreds of individuals at UK suppliers. Through these interactions, the UK workforce gains knowledge and skills across a variety of areas (technical, scientific, digital, problem solving) through an experience that is considered near-unique. Young UK researchers who have engaged with CERN are estimated to earn 12% more across their careers as a result (with an extra £489m in additional wages realised in the past ten years alone).

The knowledge and skills gained via CERN are also deployed more widely in the UK economy. Students, researchers and staff move to various roles (analysts, scientists, engineers, developers, management) across a variety of sectors (IT and software, engineering, manufacturing, financial services, health) in the public, private and third sectors. Their capabilities are in great demand, with shortages of STEM skills in general costing UK firms £1.5bn a year in recruitment, temporary staff and additional training.

CERN, researchers and the media also disseminate and reach out to the wider UK public. Each year (on average) from the UK: 12,000 school students and other members of the public visit CERN in person; 220,000 visit CERN's website; and 40,000 interact with its social media. There are also 2,000 mentions of CERN in the UK media each year, plus TV/Radio broadcasts. CERN helps to increase the UK public's appreciation of science, awakening interest in CERN, the science that it supports and the benefits of this work. This helps promote scientific literacy and in the development of a culture valuing science. The results of a separate study (Florio, 2018, Scientific Research at CERN as a Public Good) suggest that the UK public would be willing to pay (through taxation) around £1.2bn for CERN over a decade – nearly equivalent to the UK's total investment in CERN through subscriptions and funding over the period.

CERN also undertakes activities specifically aimed at engaging, enthusing and educating young people. The UK has the most teachers attending the CERN National Teacher Programme (over 1,000 in the past decade), who go on to teach an estimated 175,000 school students with context from CERN within 3 months of the visit. As mentioned above, thousands of UK pupils also visit CERN each year, increasing the likelihood and capability of young people pursuing STEM subjects at A-level and university.

Benefits and Impacts relating to Science Diplomacy

The UK is actively involved at all levels of CERN governance, providing UK ministries, funding agencies, and the wider UK science base with an important platform for international engagement, leadership and agenda-setting. CERN also provides a platform for the UK to engage more widely in global initiatives and international networks. CERN is highly visible and well regarded internationally, which spills over to favourable perceptions of its members and greater engagement (in science, technology and beyond).

CERN has been instrumental in science diplomacy, with a constitutionally-defined policy of openness and a commitment to provide a neutral space for global collaboration, the importance of which was recognised when CERN was granted observer status at the UN General Assembly. CERN also actively seeks to establish links with and promote research by countries across the globe, facilitating cooperation among the scientists and policy makers of many countries that are experiencing strained relations at the political level. For example, the SESAME synchrotron light source showcases the critical role that CERN has played in fostering cooperation across political, religious and cultural divides.

CERN has also nurtured the global physics community through the development of young researchers (particularly in less well-endowed scientific communities) and via collaborations. UK scientists have been at the centre of this outreach work that has resulted in many countries – from Argentina to South Africa – engaging with CERN experiments and investing in their own national researchers and facilities, with improved local capabilities and wider international research collaborations resulting.

Introduction

The Evaluation and this Report

This report presents the main findings from an evaluation of the benefits that the UK has derived from CERN, which was undertaken by Technopolis on behalf of the UK's Science and Technology Facilities Council (STFC). A fuller presentation of results is available in an accompanying Evidence Document.

The aim of the study was to capture, demonstrate and measure the range of scientific, economic and social impacts emerging from the UK's investment in and co-development of CERN, considering both direct UK involvement and use, as well as wider influences of CERN, particularly over the last decade. It drew on pre-existing documentation and data, a programme of 64 stakeholder interviews, the results of surveys completed by 262 UK scientists & engineers and 65 UK-based CERN suppliers, and a separate bibliometric analysis. A series of 29 illustrative case studies were also developed, based on interviews and further research, which cover major achievements and benefits flowing from CERN.

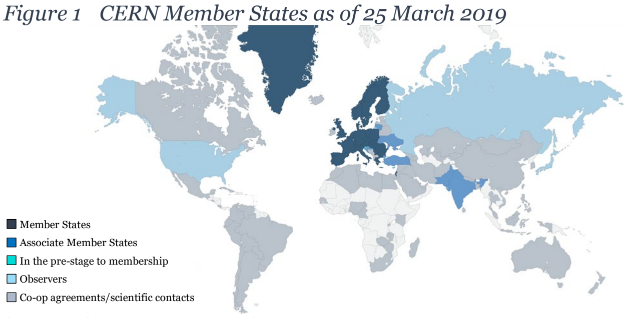
The study was also asked to propose a monitoring and evaluation framework, building on the approach and tools developed, as well as any lessons learnt, in order to support the assessment of benefits and impacts in future. Based on the experiences of conducting the current evaluation, suggestions have also been made for ways in which the current monitoring and evaluation system could be strengthened, with recommendations put forward for a range of additional data collection exercises and targeted studies.

The European Organisation for Nuclear Research (CERN)

CERN is an international research organisation that operates the world's largest physics laboratory. The focus of its research programme is particle physics, which investigates the smallest detectable particles and the fundamental interactions that explain their behaviour. However, the physics programme is also much broader, ranging from nuclear and high-energy physics to studies of antimatter and cosmic rays.

CERN was one of Europe's first joint ventures, with 12 founding members, including the UK. Today, it has 23 member states, plus various associates and observers, each of which contributes to the capital and operating costs of CERN.

Figure 1 CERN Member States as of 25 March 2019



Source: CERN Document Server

CERN's budget (derived from national subscriptions, based on GDP) covers the building, operation and maintenance of the research infrastructure (such as the Large Hadron Collider), as well as the governance and administration of CERN. The construction, maintenance, upgrade and operation of the experiments (the experimental programme) and the computing infrastructure is then mainly supported by the funding agencies of participating countries (e.g. by STFC for the UK).

Currently, the laboratory employs around 2,500 people directly, who are involved in the operation of the facilities, the construction of new accelerators, and in supporting data preparation, analysis and interpretation. More than 13,000 researchers from over 75 countries (and 100+ nationalities) also conduct research at CERN (as well as at their home institutes). This includes mainly particle physicists, but also large numbers of nuclear physicists, astrophysicists, engineers and others.

UK involvement in CERN

The UK has been centrally involved in CERN throughout its history and is the second highest contributor to its budget (16% of member state contributions, or c. £144m in 2019). Through this subscription (coordinated and managed by the STFC), the UK secures a number of opportunities. These include:

- Access for UK physicists/engineers to key research infrastructure and collaboration networks
- The opportunity for UK companies to bid for contracts for building, maintenance and operations
- Education, training and work opportunities for schools, students, researchers and professionals

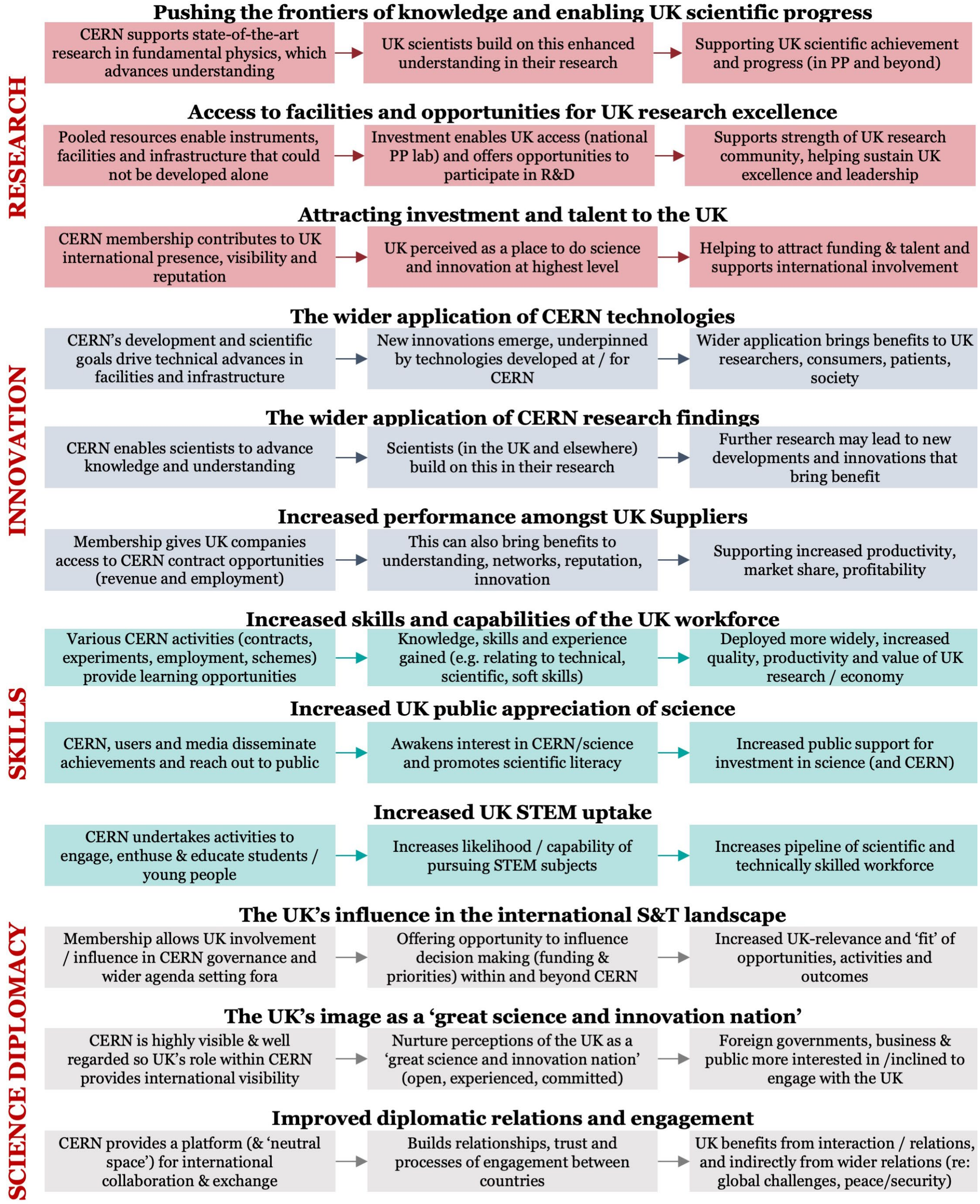
It is important to note that CERN is *not* a user facility in the way that many other research infrastructures are. The UK is a partner in the co-development of the CERN facility and its programmes of work. CERN is also the UK's national laboratory for particle physics. The UK has played a key role in its strategy and development, while UK personnel have been involved in all the major experiments and discoveries.

As such, when this evaluation refers to *CERN's* activities and achievements, these are really the results of cross-country collaborative efforts and endeavours, including UK support and involvement.

Main pathways to UK benefits and impact

CERN's strands of activity and engagement are multi-faceted, with a wide range of types of benefits and impact, flowing through a series of interrelated pathways. The study has defined and demonstrated 12 main areas of impact that flow to the UK, which are organised under the broad impact areas of **research, innovation, skills** and **science diplomacy**. The figure below summarises each of these impact pathways. These are then described in more detail in the remainder of this report.

Figure 2 CERN Impact Pathways



Source: Technopolis

Benefits and Impacts relating to World-Class Research

Researchers working at CERN make important discoveries

CERN has made critical contributions to advances in understanding over its history, including a series of landmark scientific discoveries. The full impacts from such advances in knowledge are typically on a long-term horizon and difficult to forecast and assess, but these may well be very significant, given their fundamental nature. In the meantime, the new understanding enabled by CERN is already benefiting wider research communities in the further progress of their scientific endeavour.

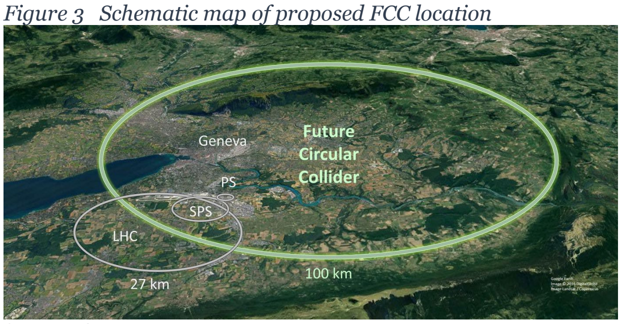
There are various studies and reports that attest to the critical contributions that CERN has made to advances in understanding over its history, whether speaking in general terms or more concretely itemising significant breakthroughs. Some of the most notable scientific advances enabled by CERN include verification of the Standard Model and confirmation of the Higgs boson (2012) – the significance of which was acknowledged through the award of the 2013 Nobel Prize in Physics – discovery of weak neutral currents (1970s) and electroweak (W and Z) gauge bosons (1980s), measurement of the number of lepton generations (1990s), observation of CP violation in charm quarks (2019) and the (to-date) null result showing the lack of supersymmetry.

"There is no question that the CERN laboratory has, during the past half-century, been one of the top institutions in its field. Even a cursory census of major discoveries illustrates this." (OECD Global Science Forum, 2014)

Impacts from such advances in fundamental physics are typically on a long-term horizon, however, and difficult to forecast and assess. For example, while Planck and Einstein's work on wave-particle dualism and photons (particles of light) formed the basis for lasers and for digital cameras (now a $2bn global market), these applications were realised with a time lag of many decades. As such, the full societal impact of the discoveries noted above is as yet unknown, but may well be very significant in the long-term, given the fundamental nature of the advances. In the meantime, the new understanding is already benefiting wider research communities in the further progress of scientific endeavour (see next section).

The significant advances undoubtedly represent major milestones in scientific understanding, but they are not the end of the story. For example, the Standard Model remains an incomplete theory, which in itself is insufficient to explain (or, in some cases, even to begin to address) several key problems in particle physics.

Figure 3 Schematic map of proposed FCC location



Source: CERN

For continued progress, conditions need to be created under which elementary particles interact at extremely high energies and in quantities sufficient to allow observation of extremely rare processes, possibly due to yet-to-be-discovered physics phenomena. The Large Hadron Collider (LHC) is therefore being upgraded to higher luminosities, while conceptual designs have been published for a higher-performance particle collider (the Future Circular Collider) to extend the research once the LHC reaches the end of its lifespan around 2035.

UK scientists build on CERN research, supporting further scientific progress

CERN research can reframe understanding and help underpin other advances, with UK scientists able to build on the new knowledge to achieve further scientific progress and push at the boundaries of research. In the past 10 years, over 20,000 *UK scientific papers* have cited CERN articles, and this includes many of the UK's most influential physics papers (25% fall among the 10% most cited globally in their field).

Experiments at CERN produce massive volumes of data that can be analysed to test hypotheses and produce new insights, advancing our understanding of the basic properties, materials and forces of the Universe. These typically result in peer-reviewed publications and theses. The study has identified over 40,000 CERN papers (those based directly on CERN research) published in the past 20 years. This includes 6% of all nuclear and particle physics (NPP) papers globally, plus thousands of general and applied physics papers and hundreds in the fields of astronomy and astrophysics, nuclear medicine and medical imaging, fluids and plasmas, electrical and electronic engineering, and AI and image processing.

The data and papers produced through CERN (including by UK scientists) are available to the global scientific community (in physics and beyond), where CERN breakthroughs can reframe understanding and underpin other advances. UK scientists are thus able to build on this new understanding, enabling them to better address complex problems, ask the right questions and set up experiments that continue to push the boundaries. In this way, CERN supports further progress and achievement by UK science.

Over the past decade, more than 20,000 other scientific papers *with a UK author* have made reference through citation to one of the 40,000 CERN articles mentioned above. Unsurprisingly this is dominated by papers in the NPP field, but there were also hundreds of UK articles in e.g. astronomy, astrophysics and applied physics. We estimate that just the production of knowledge (i.e. the UK authorship and citation of CERN research papers) over the past 10 years can be valued at over £495m (2018 prices), before even considering the impact of the advances that this research may underpin.

Bibliometrics also shows that CERN research underpins many of the UK's most influential physics papers: a quarter (25%) of UK papers citing CERN research are amongst the 10% most highly cited publications in their field globally, while 4% of these UK papers fall within the top 1% internationally. By any measure, these are excellent figures for both CERN and the UK-based research groups involved.

Figure 4 Key indicators relating to CERN publications

40,740 (1996– 2017)	CERN papers	**20,275** (2009 - 2018)	UK papers citing CERN	**25% in top 10%**	Most cited in their field globally

Source: Science Metrix (Elsevier) analysis of Scopus

Our survey of UK of 262 scientists and engineers also provided testimony on the value, role and importance of CERN-generated knowledge. For example, 81% claimed that CERN had a large or critical impact on the speed of progress in their field or discipline, while nearly two-thirds (62%) said that CERN-generated knowledge had been critical to their ability to pursue particular research questions.

Pooled investment has enabled facilities that could not be developed alone

Pooled resources and expertise have enabled state-of-the-art instruments, facilities and infrastructure to be built at CERN, providing the UK with a national laboratory that could not have been developed alone. CERN therefore allows the UK to take advantage of world leading facilities and expertise, and to undertake world-class research, whilst sharing the cost of building and running the facility (the UK paid 16% of Member State subscriptions in 2019, down from 25% in 1960).

CERN is the world's leading laboratory for physics. The investments in next-generation accelerators and ever-more powerful detectors at CERN allow scientists to carry out experiments that were not possible previously and which explore fundamental concepts that have so far only been theorised.

Pooled resources and expertise (including UK investments and leadership) have enabled state-of-the-art instruments, facilities and infrastructure to be built, providing the UK with a national laboratory that could not have been developed by the UK alone. The increasing cost and complexity of successive generations of facilities has placed such investments beyond the reach of even the largest countries. The LHC alone cost £3bn to construct and costs several hundred million pounds a year to operate.

"The field of particle physics has reached a point where no single country alone can provide the necessary infrastructure and community for the field to flourish. CERN is about the only organisation left in the world that is able to provide the required expertise and facilities." (UK scientist)

CERN therefore allows the UK to take advantage of world leading facilities and expertise, and to undertake world-class research, whilst sharing the substantial cost of building and running the facility. The UK now pays 16% of the annual ~£1bn cost of the facility, down from 25% in 1960 when there were only 13 member states.

CERN provides UK scientists & engineers with unique access and opportunities

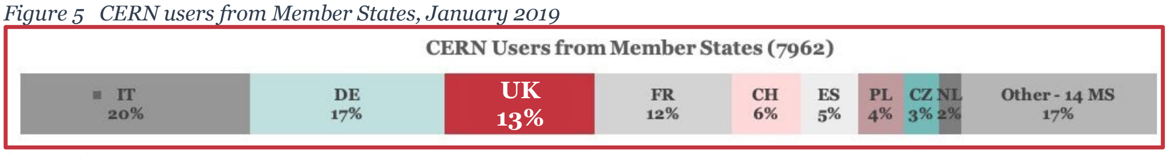
The UK's investment in CERN provides its scientists and engineers with access and opportunities not otherwise available, including technology, capabilities, theories collaborations, techniques and training. There are currently over 1,000 researchers from UK organisations using CERN, the third highest amongst Member States. These researchers cover a broad base of disciplines, from theoretical and experimental particle physics to engineering, and from astrophysics to computer science.

The UK's investment in CERN provides UK scientists with the opportunity to access co-developed (and co-owned) instruments and facilities and to participate in (and lead) research underpinning CERN's technology development projects. This includes access to, amongst others: technology and capabilities not otherwise available; international collaboration and knowledge networks; world-leading / frontier science and experiments; the latest theories; new techniques; and training / learning opportunities.

Consultation with the UK science and engineering community also highlighted other important features of CERN, which make the opportunities available there stand out in comparison with other national or international facilities. This included CERN's "truly international" nature, its openness to all and its collaborative environment, as well as the long-term and large-scale nature of the project, the pooling of multidisciplinary expertise and the strong belief in the importance of fundamental science.

STFC's Core Programme (alongside investment by other research councils) funds UK-based researchers to enable their participation in the experimental programmes hosted by CERN. The numbers involved varies over time, but at January 2019 there were 1,042 researchers from UK host institutions. This represents 13% of researchers from across the 23 Member States - the third highest, behind only Italy and Germany. Researchers include physicists (86%), scientific engineers (9%) and technicians (5%).

Figure 5 CERN users from Member States, January 2019



Source: CERN

Around 900 UK physicists are *currently* CERN researchers (i.e. ~90% of all CERN researchers from UK host institutions in 2019). For a sense of scale (although not a perfect comparison), this is equivalent to one-fifth of all the academic staff in UK physics departments. The UK's science and engineering community is therefore accessing and using CERN's instruments and facilities on a significant scale.

Our survey of UK scientists and engineers demonstrates the breadth of the community benefiting from CERN. While half of respondents work mainly in experimental particle physics, there were also many from engineering, theoretical physics, nuclear physics, computer science, astrophysics, accelerator physics, and so on. They were located within 30 different universities and institutions across the UK.

CERN opportunities support the strength of the UK research community

The opportunities afforded by CERN support the strength of UK research, helping to sustain the UK as a world leading research nation. UK personnel have been involved in all the major experiments and discoveries at CERN, with many UK researchers holding key positions. CERN-affiliated publications have also significantly pulled the UK's citation metrics upwards, demonstrating the high-quality research that has been enabled.

UK personnel have been involved in all the major experiments and discoveries at CERN, with many UK researchers holding key leadership positions. The UK is also one of only a few countries involved in all four large LHC experiments. Such opportunities and access support the strength of the UK research community and its achievements and progress, helping to sustain the UK as a world leading research nation (e.g. with 5 of the top 25 research universities globally). Indeed, a majority of the UK scientists and engineers surveyed said that CERN had been 'critical' in supporting their community in undertaking R&D that is cutting edge, world-leading, international, significant, innovative and ambitious.

CERN-affiliated publications have been found to significantly pull citation metrics upwards in the UK, providing an indication of the high-quality research enabled. An already impressive 18% of UK authored nuclear and particle physics (NPP) papers were among the top 10% most cited in their field, but amongst those with CERN affiliation this rises to 26%. The bibliometrics also show more generally that the UK is a leading country in the NPP subfield and is 8th in the world for the volume of its publication output in this area. It is difficult to maintain a very high impact as production volume goes up. As such, the UK's combination of high output and high citation profiles in NPP is a very strong achievement.

Our survey of UK scientists and engineers also provided testimony as to the impact of CERN on the nation's research activities. For instance, most respondents claimed that access to CERN facilities and opportunities had a significant impact on: their ability to participate in international collaborations (90%); the strength of their international networks (82%); and the overall quality of their R&D (79%).

To explore this further, we invited respondents (UK scientists and engineers) to say what they would be willing to pay each year to ensure the continued existence of CERN in its current form and all of the research benefits that flow from it to them. Responses varied (£10-£100 each per year), but all were well above the £2.10 per year that the average UK taxpayer contributes towards CERN membership. Grossed-up results suggest that members of the UK scientific community (in relevant fields) would personally be willing to pay £30m over a decade (in 2018 prices) for the continued existence of CERN - a strong indication of the research benefits to this community.

CERN contributes to the UK's international presence, visibility and reputation

The UK's involvement in CERN increases its international presence and visibility, including through its network of collaborations and connections in science and technology. It helps to enhance recognition of the UK's research excellence and its perception as a great research nation and the place to do science at the highest level. This in turn helps to attract funding and the best international talent to the UK.

Scientific publications resulting from highly collaborative and international research (such as is often the case at CERN) tends to be cited at higher rates than national collaborations or single-author papers, and therefore achieve greater levels of visibility. Therefore, it is not surprising that bibliometrics analyses show participation in CERN has had a positive impact on both the UK's publication output and its impact, and that the UK would lose places in international rankings if it were to stop its involvement. Most (82%) of the UK scientists and engineers surveyed also reported directly that CERN had a significant (large or critical) impact on their own national and international reputation.

The positive 'brand' of the UK as an important science nation, as well as the opportunities open to its scientists, engineers and institutions through CERN, help to attract funding, talent and other forms of recognition. As a result, for example, the UK has the highest share (~20%) of externally funded R&D amongst major industrial economies, while the UK is also able to recruit some of the top minds (internationally) to teach in its universities and conduct world-leading research (40% of all academic staff in physical science and engineering departments are from other countries). This international draw is also reflected in the fact that nearly a quarter of current CERN researchers from UK institutions are not UK nationals (such numbers of non-national researchers are not seen within most other members).

"The vast majority of the members of my group (PhD students, postdocs and faculty) are either very talented UK researchers who have worked at or with CERN before returning to the UK, or are excellent foreign scientists who have decided to come and work in the UK because of the excellent reputation that, through its affiliation to CERN, the nation has as a world-class science hub internationally." (UK scientist)

"The top scientific talent in particle physics wants, generally, to work on the questions that are at the cutting edge of particle physics. That physics is being done, almost entirely uniquely, at CERN. If the UK wishes to continue to attract such talent, membership in CERN is necessary." (UK scientist)

As a point of comparison, the decision to cancel the building of the US Superconducting Collider (SSC) in October 1993 (after some $2bn of investment) had a significant negative impact on the US particle physics community. A survey conducted by Science magazine in 1994 found that around half of the scientists involved in the SSC left the field of physics following the cancellation of the project.

Benefits and Impacts relating to World-Class Innovation

CERN technology has found wider application, across UK research and industry

CERN's breakthroughs have required major advances in technologies, which are then suitable for take-up and development for applications elsewhere. In several notable cases (e.g. the World Wide Web, PET scanners and GRID computing), CERN has provided the platform for major new technologies that have come into general use and have had transformative effects – bringing both economic and societal benefits to the UK. Further upgrades to the facility will continue to drive innovations that will similarly have the potential for wider benefits and impacts in the future.

CERN's scientific breakthroughs have often required major technological advances, both in terms of the core facility technologies (e.g. the accelerators and detectors) and the supporting infrastructure (e.g. microelectronics, GRID computing, data analytics, machine learning, modelling and robotics). These technologies, developed for CERN, are often suitable for take-up and development for applications elsewhere, in other research facilities and beyond. In several notable cases, they have provided the platform for major new technologies that have come into general use and have had transformative effects in all walks of life – bringing both economic and societal benefits to the UK. Future upgrades to the facility will likely continue to result in new innovations with wider applications and benefits.

The most well-known example of the wider application of CERN technology is the World Wide Web, which is estimated to contribute 2.9% to global GDP (2011). However, there are many others. Our survey of the UK research community identified a further 30 examples, which included:

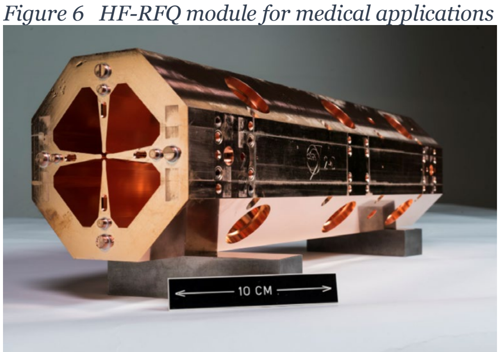
- The HTTP protocol that defines how messages are formatted and transmitted across the web, which was first successfully implemented for networks of computers installed at CERN
- Technology for next-generation radiotherapy, which uses hadron beams rather than X-rays to target and destroy tumours, causing less damage to healthy tissue and less side effects (see box below)
- Software tools (e.g. GEANT, ROOT, PAW, FLUKA) that are used both in physics and in other areas of research and industry (e.g. the space, nuclear, medicine and aviation sectors)
- Other ICT advances in e.g. grid computing and distributed processors, as well as advances in machine learning, pattern recognition and big data analyses, which have brought wider benefits
- Imaging technology, which has come to be used in medical imaging applications (e.g. current high-performance PET scanners comprise over 20,000 detector elements originally developed for CERN)
- Fibre optic sensors to help manage water shortages and for water pollution measurement
- Radiation hardened robotics for decommissioning and radiation testing facilities for satellites

The study has looked at some of these in more detail, including the examples of hadron therapy and the Medipix chips, which are summarised in the boxes below.

Linear proton accelerators and hadron therapy

The use of hadron beams instead of X-rays to treat cancer causes less damage to healthy tissues. This is especially important when treating tumours in critical areas, such as the brain, mouth, oesophagus, liver and prostate, or near the optic nerve or spine, particularly in children. Facilities offering such hadron therapy started appearing in clinical settings in the 1960s, but with a price tag of £120m per system, the cost can still be prohibitively high. To lower costs and enable more widespread use, more compact accelerators have started to be developed.

Figure 6 HF-RFQ module for medical applications



Source: CERN Photolab

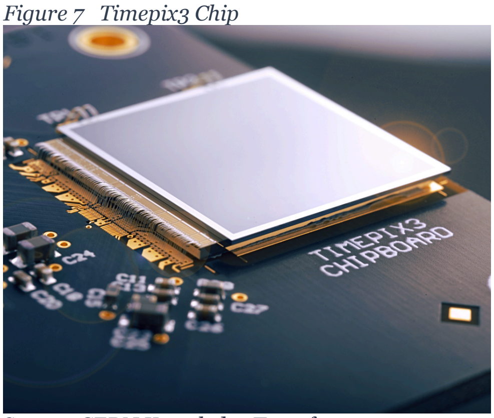
A first prototype linear proton accelerator (not circular and so causing significantly less stray radiation and allowing for a more compact architecture) was designed and built under CERN's leadership. This linac-booster for proton therapy (LIBO) was successfully tested in 2003 and followed by other proton accelerators in Italy and Austria (again with CERN involvement).

To further develop the LIBO design into a commercially available system, a CERN spin-off - ADAM - was then founded in 2007. ADAM continued to receive crucial support from CERN, via its testing facility, as well as involvement in the LHC experiment. With this, ADAM improved on LIBO's design, building and testing the first accelerator modules for the LIGHT accelerator from 2008 to 2010.

In 2013, Advanced Oncotherapy, a UK company, acquired ADAM to continue development of LIGHT for commercialisation. The company now has 129 staff across the UK, Switzerland and the US and a market capitalisation of £80m ($100m). The first patient treatment is currently expected by 2021, in cooperation with the UHB NHS Trust. The fit-out of the first proton clinic equipped with the linear system on Harley Street, London, is in progress (within the space of two traditional terrace houses) and will be operated by the London Clinic.

Proton therapy currently represents only 1% of all external radiotherapy systems installed worldwide and only 0.1% of all cancers treated. However, recent forecasts project that the global proton therapy market will grow from $0.9bn in 2017 to upwards of $4bn by 2030, with 1,300 particle therapy treatment rooms open to patients. The relative ease of installation, combined with a cheaper production process and the much lower shielding requirement could give Advanced Oncotherapy's system a competitive edge against cyclotrons, synchrotrons, and more conventional LINAC systems - and allow it to secure a substantial share of this global market.

Figure 7 Timepix3 Chip



Source: CERN Knowledge Transfer

Detector chips used in other research fields

Medipix chips are hybrid pixel detectors, consisting of two thin layers of an absorbent material (e.g. silicon or Gallium arsenide). This enables the capturing of high-resolution, high-contrast, noise free images, making the chip uniquely suitable for imaging applications.

Hybrid pixel detector technology was initially developed to address the needs of particle tracking at CERN. The aim was to develop a 2D detector capable of time stamping high energy physics events at the expected collision rate of the LHC. In the course of this research, however, it became clear that the technology could also be useful for other applications – and the Medipix collaboration was born.

The initial partners were CERN, the University of Glasgow, the University of Freiburg and the INFN in Pisa and Napoli, but over the years the collaboration has been through various iterations and reconstitutions to further develop this technology and take it to new fields. As the cost of developing and prototyping these devices is challenging, each collaboration allows the partners to focus their efforts on developing chips with new features to support new applications.

Medipix is one of CERN's most successful examples of knowledge transfer. Each collaboration has triggered a significant number of commercial activities in a range of application areas, including medical imaging, space dosimetry, education, and material analysis. The family of read-out chips (Medipix 1-4 and Timepix 1-4) have, for example, been applied in X-ray computed tomography (CT), in prototype systems for digital mammography, in CT imagers for mammography and for beta- and gamma-autoradiography of biological samples. Other fields of application include electron microscopy, background radiation monitoring, dosimetry and education.

The Medipix Collaboration has also led to a UK spin-off, Quantum Detectors, based at the Harwell Science and Innovation Campus. The company was founded in 2007 to promote a wider exploitation of detectors developed for synchrotron radiation, LASER and other large-scale facility applications. One of Quantum Detectors' products, the Merlin photon counting detector system, is based on the Medipix3 ASIC and was adapted for electron microscopy applications (MerlinEM) in collaboration with the University of Glasgow. This is a primary example of how CERN developed technologies have found their way, through UK companies and universities, into other research fields.

The **STFC-CERN Business Incubation Centre (BIC)** (est. 2012) is another route through which CERN innovations may have wider uptake within the UK. The intention is to enable the transfer of IP and expertise from CERN into industry, through dedicated support and funding. The BIC currently hosts two companies and has seven alumni who have used CERN-based knowledge and technologies to e.g. improve manufacturing processes and develop diagnostic and sensing technologies. It is still early days for these firms, but the BIC has demonstrated its important role in ensuring that early stage high-tech companies in the UK are able to benefit from the innovation and expertise emerging from CERN.

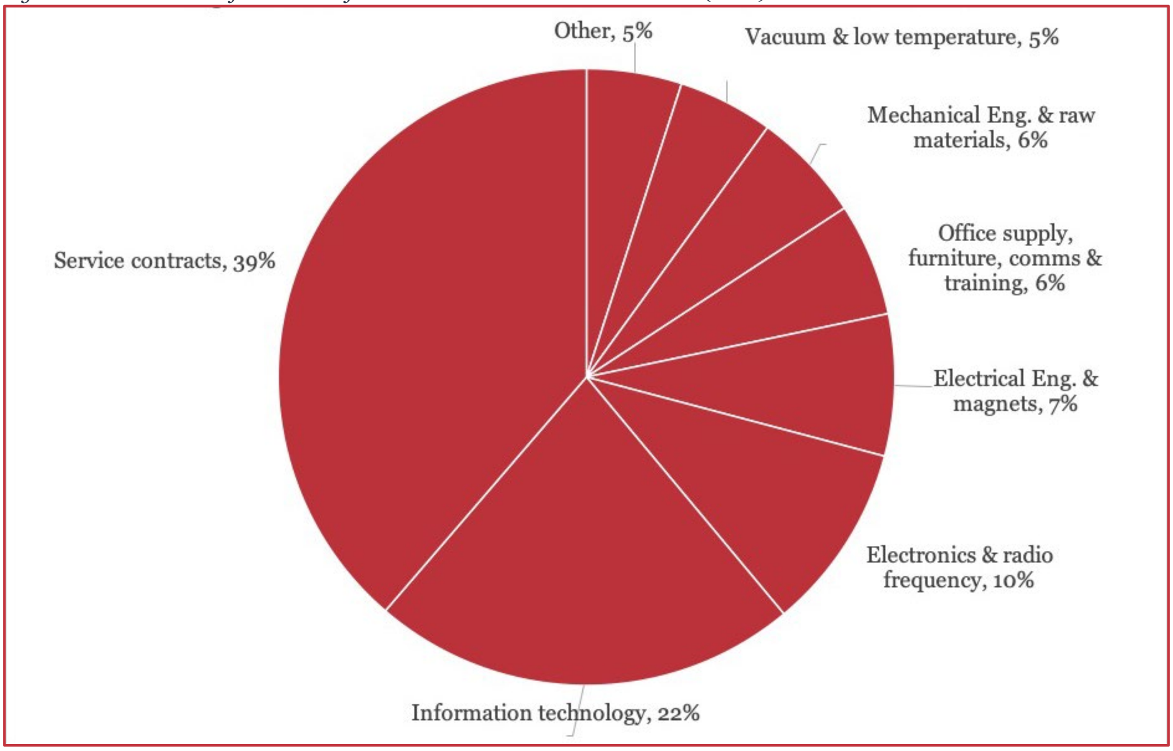
UK companies earn substantial income supplying CERN

UK companies have won around £183.3m in contracts from CERN in the past 10 years (2009-18) to supply goods and services to the facility, with UK suppliers particularly active (both overall and relative to other countries) in relation to service contracts, information technology and electronics and radio frequency products. In addition, at least £33.4m has been awarded to UK contractors in the past decade for CERN experiments (organised by collaborating countries) and the CERN Pension Fund.

CERN membership gives UK companies access to contract opportunities with CERN for the supply of goods or services to the facility. Individual research groups working on technology development for CERN may also partner with or contract companies as part of their projects.

500 UK-based companies have sold goods or services to CERN in the past decade, with notable sales in a wide cross-section of business sectors, from fund management to superconducting magnets. The UK is particularly active (overall and relative to other countries) in relation to service contracts, electronics and radio frequency products, and information technology (see Figure 8).

Figure 8 Distribution of the value of CERN contracts awarded to the UK (2018)



Source: CERN procurement report

These contracts bring additional revenue to UK firms and support employment (industrial return).

From the latest CERN procurement reports we see that UK companies won around £18.3m in contracts from CERN in 2018 and have received £183.3m (2018 prices) in total over the past 10 years (2009-18).

In addition to CERN's central procurement activities, further contracts are awarded to UK suppliers in relation to CERN experiments (where procurement is organised within collaborating countries), with at least £33.4m (2018 prices) awarded to the UK in the past decade. This is likely to underestimate the true value of UK contracts, as data is only collected when this procurement is done through CERN's central processes, rather than directly by the universities and national laboratories themselves.

Included within this figure are a number of sizeable multi-annual contracts awarded by the CERN Pension Fund to UK-based actuaries, auditors and other service providers. This is an area where UK firms do particularly well. Again, limited information is available, but £19m is thought to be the absolute minimum won by UK firms from this source over the course of the last decade.

UK suppliers realise a range of wider benefits, beyond the value of contracts

CERN is a highly-reputable organisation and its contracts bestow a degree of credibility and prestige on UK suppliers that is not easily replicated elsewhere. CERN contracts can also bring additional benefits to UK businesses through the development of new skills and knowledge amongst supplier firms, as well by providing access to new market opportunities through contacts made within international networks. Half of surveyed UK suppliers reported that their past CERN contracts had resulted in an increase in their income (beyond the value of the CERN contracts themselves). We estimate that the CERN contracts awarded to UK suppliers has supported a further £1bn in additional turnover and £110m in additional profit in the past decade (2009-18).

CERN contracts can result in the creation of new or improved products and services for UK suppliers, driven by the demanding requirements of a cutting-edge facility. Around a third of the UK suppliers to CERN who were surveyed for this study reported having seen improvements to their existing products and / or services as a direct result of their CERN contracts, while smaller proportions also reported the launch of new products, services and processes, all flowing from their past CERN work.

"The knowledge and expertise gained has allowed us to develop products for other larger markets"

"The increased skills in the machining of new metals (for the manufacture of CERN components) has enhanced capabilities across all internal sectors of our business"

"The CERN name encourages recruitment candidates to want to work with us"

"Having worked for CERN reflects well on us as a competent, reliable and stable organisation to work with"

"We have innovated to meet ever-increasing demands on our manufacturing technology" (UK suppliers to CERN)

CERN contracts can also bring additional business benefits through the development of new skills and knowledge amongst suppliers, as well as provide access to new market opportunities through contacts within international networks. CERN is also a highly-reputed organisation, and its contracts bestow a level of credibility and prestige on suppliers that is not easily replicated elsewhere. In a majority (75%) of cases, UK suppliers reported that there has been benefit to their reputation and global brand value. Between half and two-thirds also reported an impact on their access to new markets (in the UK or overseas), on their international competitiveness and on the overall saleability of their products.

"Improvements to our knowledge and expertise have allowed us to develop products for other larger markets. We now manufacture 1,000 units a year and generate £20M revenue, supporting 100 jobs" (magnet supplier).

"The opportunity has helped us to develop new materials and processes, and we have been able to showcase our expertise, which has resulted in additional sales" (precision engineering supplier)

"The CERN name impresses our clients and potential clients in the STEM sectors. Without our past contracts, it would have taken us longer to get where we are today" (communications supplier).

"In the 1990s in particular, CERN work allowed the company to establish itself. The company might not have survived in the early years. Now we are sustainable without CERN work" (manufacturer of meters and probes)

Half of surveyed suppliers reported that their past CERN contracts had resulted in an increase in sales income (beyond the value of any additional contracts with CERN), while a similar proportion reported an increase in profitability. Across the sample, the average (self-estimated) impact on turnover was +4%.

The current turnover of respondents to the supplier survey averaged £7.8m in 2018. If this were to hold across the full 500 UK suppliers of CERN, then an average +4% CERN-related "boost" to their collective turnover would equate to around £157m in additional income for UK businesses in 2018. Based on assumptions about growth rates, we estimate that the total additional turnover for 2009-2018 is £1.05bn, with additional profit (based on assumptions about profit margins) of £110m (2018 prices).

Benefits and Impacts relating to World-Class Skills

The UK workforce gains new knowledge, skills and experience through CERN

There is significant uptake of CERN training opportunities in the UK. In the past decade, a thousand individuals from the UK have participated across schemes that CERN offers, receiving training (for free) worth more than £4.9m. In addition, large numbers of UK personnel acquire skills and knowledge 'on the job' each year, including ~1,000 researchers, ~300 CERN staff, 40 fellows and hundreds of UK suppliers. Through this, the UK workforce has gained knowledge and skills across a variety of areas (technical, scientific, digital, problem solving) through an experience that is considered near-unique. Young UK researchers engaging with CERN are estimated to earn 12% more across their careers as a result (an extra £489m in wages in the past decade alone).

The cutting-edge technology and international setting of CERN can be an inspiring training ground for the STEM workforce. Individual employees and researchers using CERN, as well as staff within supplier companies, can acquire skills and knowledge 'on the job' and in informal exchange with colleagues. CERN also offers a number of dedicated training schemes, lasting for between eight weeks and several years, which are aimed at research students (from undergraduates to PhDs) as well as professional researchers that are more advanced in their careers (e.g. through fellowship programmes and long term attachments), while large numbers of students also earn their PhDs based on work carried out at CERN.

CERN data shows that in the past decade around 1,000 individuals from the UK have participated across the various specific training programmes and schemes that CERN offers. Based on commercial prices for similar courses, we estimate that UK involvement in CERN's student, doctoral and technical programmes alone (38 UK placements per year on average) can be valued at least £4.9m over the past decade (2018 prices). As this does not includes schemes such as the fellowship programme, the true value of all training received is likely to be significantly more.

In addition, there are currently over 1,000 CERN researchers from UK institutions, ~300 CERN staff and 44 UK fellows employed directly by CERN, all of whom are also developing their knowledge and skills on the job. Some 500 UK companies (and thousands of their employees) have also interacted with CERN through contracts over the past decade.

The acquired knowledge and skills, gained through these different forms of interaction with CERN, can relate to various domains, e.g. technical, scientific, digital, project management, multi-lateral / international team working, cultural awareness, problem solving and process improvements. Importantly, the experience at CERN is thought by those involved to be superior to that obtained in a university or national centre, because of the level of expertise available, the scale of projects and teams, the interdisciplinary nature of work and exposure to tools / techniques at the technological frontier.

We have monetised the value of these skills by considering the additional wage that can be commanded by young researchers that have engaged with CERN. The results suggest that young researchers from the UK (who worked or trained at CERN at any time during the years 1969-2017) have enjoyed an extra £489m "wage premia" (in 2018 prices) in the last decade alone. They are expected to benefit from this 12% boost to salary (on average) for the rest of their careers.

Knowledge and skills gained via CERN are deployed across the UK economy

Knowledge and skills gained via CERN are deployed more widely in the UK economy. Students, researchers and staff move in to various roles (analysts, scientists, engineers, developers, management), across a variety of sectors (IT and software, engineering, manufacturing, financial services, civil service, health, charity). Their capabilities are in great demand. Shortages of STEM skills reported by UK businesses (equating to some 173,000 workers) have been estimated to be costing these firms £1.5bn a year in recruitment, temporary staffing, inflated salaries and additional training.

The acquired knowledge and skills, gained through interaction with CERN can also be deployed and applied in a variety of fields – both relating to science and engineering, but also beyond, supporting an increase in the quality, productivity, and value of UK research and the economy more broadly.

"Those trained at CERN have leading roles in other technology-led areas. They seem to be the only ones who understand fundamental principles in the quantitative analysis of scientific data." (UK scientist)

"Students have now left particle physics and moved into areas such as financial services, proton therapy, and software development, using transferable skills picked up working at CERN." (UK scientist)

Various efforts have been made to obtain more concrete information about the subsequent careers of students and others who have been involved with CERN. These show a wide range of destinations, both in terms of roles (analysts, scientists, engineers, developers, management) and sectors.

For example, in a recent exercise STFC assessed the next destination of 86 UK students that had returned from Long Term Attachments at CERN within the past few years. This found that nearly all of these students (96%) were in work – mostly (79%) within the UK. Over half (57%) were employed by universities, research institutes or schools, a third (34%) were in the private sector (including finance, consultancy, manufacturing and IT/software) and 9% were working in the public sector (often the NHS).

In another study, commissioned by CERN, a larger poll of 2,700 past and current CERN researchers (mainly experimentalists) and over 160 theorists that had collaborated with CERN showed that nearly two-thirds (63%) of those that had left high energy physics were now working in the private sector, often in information technology, advanced technologies and finance domains. Respondents pointed to key skills developed at CERN as important in their current work, including programming, international working, data analysis, logical thinking, communication skills, working under pressure and flexibility.

UK firm Axomic Ltd (now OpenAsset) was set up in 2002 by two CERN scientists. It offers software for architects, civil engineers and construction firms to store and search for images and 3D plans on the web. The firm has grown quickly, from a Cambridge house, to a small office, to sites in London and New York, and now employs 30 staff, with a global client base of 600 architectural practices.

The CERN Alumni Programme, established in 2017, has over 4,000 members, including 349 that are either British nationals and / or located in the UK. A third are still working in research, but 5%-20% are accounted for by computer software, financial services, higher education, IT and internet sectors. Case studies already published on the Alumni website include several examples of the individuals now working in the UK, e.g. undertaking data engineering with the Home Office, working as a marine ecosystem modeler at the Plymouth Marine Laboratory, and heading up a private finance company.

The highly trained and experienced personnel emerging from employment, training and interactions with CERN are in great demand within the UK economy. Shortages of STEM skills reported by UK businesses (equating to some 173,000 workers) have been estimated to be costing these firms £1.5bn a year in recruitment, temporary staffing, inflated salaries and additional training costs.

"The skills young researchers are getting through their connection with CERN (especially experience with large data volumes) is in high demand and makes these graduates very desirable on the job market. Having gained experience at CERN and developed a huge skillset, they go on to get very good jobs in a range of areas that contribute to the UK economy (media, retail, banking and online services). The need for this talent is only going to grow. (Director of a UK Centre for Doctoral Training in Data Intensive Science)

CERN, its researchers and the media disseminate and reach out to the UK public

CERN has a wide reach to promote particle physics to the UK public. Each year from the UK ~12,000 school students and members of the public visit CERN in person, while 220,000 visit its website and 40,000 interact with its social media. There are also 2,000 mentions of CERN in the UK media each year, plus various UK TV/Radio broadcasts.

Among the general public, CERN is well-known for its research into elementary particle physics at the LHC, and its 'celebrity status' was boosted by the discovery of the Higgs boson in July 2012. This work not only led to one of the most highly-cited publications in particle physics (with more than 8,000 citations to date), and to the award of the Nobel Prize in Physics in 2013, it also received broad (and likely unprecedented for particle physics research) attention in the media. Other recent CERN announcements have also had a significant impact on the UK public's understanding, interest or support for science and engineering, for example the operation of the LHC (the first collision and each restart).

CERN and its researchers undertake various dissemination activities and public outreach. For example:

- Over the past six years (2013 – 2018) there have been 3,192 groups of UK visitors that have gone on organised tours at CERN, with 72,108 individuals (mostly school students) visiting in total
- Over 220,000 UK researchers visit CERN's website each year (nearly 7% of total traffic)
- CERN is also active on Twitter, Facebook, YouTube, Instagram and LinkedIn, and recorded over 40,000 UK social media interactions in 2018 (followers, likes and interactions with 'CERN' / 'LHC')
- CERN's media monitoring shows around 2,000 mentions of CERN in the UK media each year.

We have also identified numerous CERN-related broadcasts on UK TV and Radio, as well as a series of public exhibitions, events and activities over the past decade that were attended by over 1 million people.

CERN increases the UK public's understanding of and appreciation for science

CERN helps to increase the UK public's appreciation of science, awakening interest in CERN, the science that it supports and the outcomes and benefits of this work. This can help promote scientific literacy and foster the development of a culture valuing science. The results of a separate study of public awareness and appreciation of CERN suggest that the UK public might be willing to pay in the region of £1.2bn for CERN over a decade.

CERN's mission, history, scale, and cutting-edge technology offers opportunities to inspire and help the UK public to become science enthusiasts, or at least engaged friends, as well as more supportive of public (financial) support for science (and in this case, CERN specifically). The various dissemination and outreach activities set out above help to support this by exciting the UK general public and by awakening interest in CERN, the science that it supports and the outcomes and benefits of this work.

"The first collisions at LHC sparked wide public interest, so much so that media web-sites (BBC, Telegraph, CNN) were overwhelmed by the demand for information (given the capacity of the Internet/broadband at the time)."

"Although the media may not have communicated the facts as well as the scientists working on these experiments may have liked, it is hard to deny that the public was flooded with buzz about the 'God particle'"

"The discovery of the Higgs boson brought ideas about fundamental physics to the public like nothing else I've known in my lifetime." (UK scientists and engineers)

The UK public's engagement with CERN's activities also help promote scientific literacy and foster the development of a culture valuing science, helping to increase interest in and engagement with science in general, as well as inspiring young people to take up and pursue STEM-related studies and careers.

The UK government's periodical surveys of Public Attitudes to Science show a positive improvement in the public's attitudes towards and perception of science and scientists. For example, more now see it as important to know about science in their daily life, and greater numbers are more comfortable with the pace of change. However, this and other public engagement surveys tend to work at a rather generic level and do not invite respondents to comment on particular institutions. There is also no reference to CERN or particle physics in these large-scale opinion polls. CERN does not carry out such studies.

Just one smaller survey, in France, explored the public's awareness of CERN[1]. This found that 46% of the general public was aware of CERN, which was significantly higher than for ESA and the ESRF. A separate analysis of French respondents computed a figure of €4 per person per annum as the amount taxpayers would be willing to pay for the construction of a new particle accelerator at CERN. This compares with the actual national payments for CERN overall (€2.70 per person per year). An estimate of €4 per person per annum (for 10 years) would equate to £1.2bn if applied to the UK (2018 prices).

[1] Scientific Research at CERN as a Public Good: A Survey to French Citizens, 22 August 2018, Massimo Florio (University of Milan) and Francesco Giffoni (CSIL – Centre for Industrial Studies and University of Milan)

CERN undertakes activities that engage, enthuse and educate young people

CERN undertakes activities to engage, enthuse and educate young people. These opportunities are taken up on a significant scale in the UK, with more teachers attending the CERN National Teacher Programme (~125 per year), as well as more schools and school students benefiting from on-site visits (530 and 12,700 respectively in 2016), than any other country. There has also been a clear increase in students studying STEM at UK universities in the past decade, with some evidence that CERN initiatives have played some role in this, by enthusing and preparing young people to pursue these subjects.

CERN inspires students and young people through its scale, the types of 'universal' questions it addresses, and its international nature. It also undertakes various activities to directly engage, enthuse and educate students and young people. In particular, CERN runs on-site programmes for teachers and students, while also providing additional resources to support further work in the classroom, in order to engage with young people and inspire the next generation of STEM professionals.

The UK has more teachers attending its CERN National Teacher Programme (which is tailored to fit with the UK curriculum) than any other country. Between 1998 and 2018, 1,351 UK teachers have attended, with an average of 125 teachers per year (2010-16). A polling of 78 of these teachers, found that more than 11,000 school students had been taught directly with context from CERN within three months of the visit. This was not just in physics, but also in maths, biology, chemistry, engineering and computing lessons. If such outcomes were to hold more generally, then over 175,000 UK students will have been taught with context from CERN as a result of the teacher programme over the course of a decade. The teachers surveyed also reported an improved understanding of the breadth and depth of STEM careers, and therefore more confidence in talking about careers in science and engineering.

Pupils can also directly engage with CERN through on-site visits. Nearly 2,300 UK school groups visited CERN in the past five years, with 54,500 teachers and students visiting in total. Again, the number of schools and students taking up this opportunity from the UK is more than from any other country.

The CERN@School initiative is a prime example of how CERN and CERN-developed technologies have had an impact on skills development and the engagement of young people. This UK programme, inspired by a school visit to CERN, builds upon the CERN Medipix collaboration and helps to engage students with physics through hands-on research. The scheme has been given 40 Medipix detectors and has used these to support engagement with over 460 schools and 20,000 students to date.

The success of CERN@school has also led to the formation of the Institute of Research in Schools (IRIS), which aims to develop an extended range of research fields within which schools and teachers can participate in authentic research. IRIS has developed research projects across a variety of areas within STEM, including space science, particle physics, material science, biomedical science and climate science. A study of a four-year intervention in one school showed that participating A-level students made six times the progress in education attainment compared to a control group of students at the same institution who did not participate in the IRIS-led research.

There has been a clear increase in students studying STEM subjects at UK universities over the past decade, with some of the largest relative increases seen in subjects including physics and astronomy, chemistry and materials science and mathematical sciences. While there are many factors at play, there is evidence that CERN has also played a role. A survey of 673 physics undergraduates in eight universities in the UK also showed 95% were attracted to study science because of activities in particle physics (such as CERN), with over 50% saying they were inspired by the discovery of the Higgs.

"Analysis of UCAS forms of students applying for physics at Oxford strongly suggests that CERN-based science is one of the primary drivers of bringing school students into physics at university." (UK scientist)

The upward trend in university STEM uptake should also continue, as the number of students taking A-level physics in the UK is rising (against a declining overall trend in students taking A-levels).

Benefits and Impacts relating to Science Diplomacy

CERN enhances the UK's influence in international Science and Technology

Membership allows UK involvement in various levels of CERN governance, providing UK ministries, funding bodies and the wider UK science base with an important platform for international engagement, leadership and agenda-setting. CERN also provides a platform for UK scientists and engineers to engage in global initiatives and networks.

CERN membership allows UK involvement in various levels of CERN governance (in formal decision-making bodies, as well as through staff and researchers). It has had a leading role in the establishment, design and governance of CERN from the start and UK personnel have served in central roles throughout CERN's history. For example, four former presidents of Council and two former Directors-General, five former chairs of the scientific policy committee, as well as various heads of department have all been from the UK. The UK has also provided the lead researchers for several of the biggest experiments.

Involvement in CERN and its governance provides UK ministries and funding bodies, as well as the wider UK science base with an important platform for international science and technology engagement, leadership and agenda-setting. Benefits include the ability to influence CERN decision making (e.g. in terms of scientific priorities, funding levels and new experiments), thereby enhancing the alignment of CERN activities with UK capabilities and priorities. As a result, the UK is likely to benefit from a better than average fit for its research community, with e.g. experiments that are more relevant to UK interests.

CERN priorities may also influence the decisions of other bodies (e.g. national funding bodies). For example, the European Strategy for Particle Physics is prepared under the auspices of CERN, but with the participation of other major European stakeholders and watched closely around the world.

Participation in CERN projects also provides a platform for UK scientists and engineers to engage more widely in other global initiatives and international networks. As an example, the Deep Underground Neutrino Experiment (DUNE) is an international flagship science project hosted by the U.S. Department of Energy's Fermilab, which will push the state-of-the art in neutrino science. It includes more than 1,000 scientists and engineers from over 175 institutions around the world. CERN itself is the single largest international sponsor and research partner: smaller prototypes of the DUNE far detector are under construction at CERN, while the full detectors and their computing systems are being designed and built by a collaboration of scientists from more than 30 countries. The UK is heavily involved in this new initiative, including through provision of the co-spokesperson.

CERN enhances the UK's image as a 'great science and innovation nation'

CERN is highly visible and well regarded internationally, which spills over to favourable perceptions of its members and greater engagement (in science, technology and beyond).

CERN is highly visible internationally and widely acknowledged as (one of) the most advanced scientific endeavours in the world. Its global reputation for cutting-edge research brings spillover benefits to its member states and has contributed in some measure to the UK's status as a 'great science and innovation nation', and a favourable perception of the UK as a country to engage with.

This has been confirmed by the UK science and engineering community, the majority of whom claimed that the UK's membership and involvement in CERN has a significant positive impact on international perceptions of the UK as a leading and committed science nation, open to international collaboration.

The image of an internationally-engaged science nation may also have wider implications, i.e. beyond the science and technology community. By fostering a positive attitude towards the UK, foreign governments, businesses, and the public may be more interested in and inclined to engage with the UK, with positive effects on diplomatic and economic relationships, e.g. collaboration and investment.

CERN brings UK benefits through international diplomacy and engagement

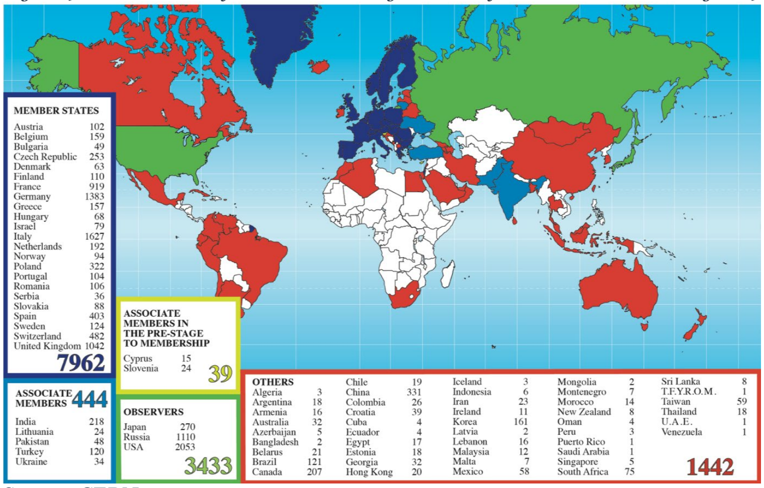
CERN has been instrumental in science diplomacy, with a policy of openness and as a neutral space for global collaboration. Today over 13,000 scientists from 100 different countries carry out research at CERN, creating better understanding across and within their respective societies. CERN also actively seeks to establish links with and promote research by countries across the globe and to promote wider international cooperation.

CERN has been instrumental in science diplomacy across its 60 years in operation. It was the first intergovernmental organisation that Germany joined after the war and the first post-war meetings between German and Israeli scientists took place at CERN. Collaboration between CERN and Russia continued throughout the Cold War, and provided a model for later USA-Russia collaboration. In the 1970s, scientific contacts between Europe and China were pioneered at DESY and later at CERN. In 1985, when USSR-USA arms negotiations in Geneva were stalled, the US delegation asked the DG of CERN to arrange a dinner at CERN for Russian and US advisors, which facilitated a breakthrough.

While it is not part of CERN's mandate to pursue international diplomacy as an end in itself, the laboratory has continued its policy of openness, which has if anything become even more important over time as a neutral space for mutually beneficial collaboration among the world's scientists and engineers. CERN has found that, although they are sometimes initially mutually suspicious, scientists and engineers with very different political or religious views who work together quickly develop technical respect. This then leads to greater understanding and tolerance of respective views.

Today over 13,000 scientists from 75+ different countries (and 100+ nationalities) carry out research at CERN. The collaborative work that these (mainly young) scientists carry out creates better understanding across and within their respective societies.

Figure 9 Distribution of all CERN users by location of institute on 28 January 2019



Source: CERN

"The UK has benefited from CERN contributions to the establishment of peaceful scientific cooperation. CERN brings together people and students, from different environments with different cultures to work together to a common goal, advancing human knowledge. This is precious and very valuable for young UK scientists. Where else do Iranians and Americans, Indians and Pakistanis collaborate on common goals." (UK scientist)

Successive Directors-General have shown deep commitment to the wider international cooperation agenda and CERN's exemplary contributions in the realm of science for peace were formally recognised in December 2012, when CERN was granted observer status at the UN General Assembly. One of CERN's most notable recent achievements is the SESAME light source in Jordan (see below).

The SESAME light source in Jordan opened in 2017 and follows the CERN model, promoting scientific collaboration in the Middle East (Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey). UK scientists have played an important role in the realisation of this new facility and were among those named in the American Association for the Advancement of Science 2019 Award for Science Diplomacy for their contribution to this project. The success of SESAME may be replicated in other areas too, including a new regional research institute where the Balkan states are joining forces to set up a South-East Europe International Institute for Sustainable Technologies (SEEIIST). This institute will be based on the CERN model and is intended to further mitigate tensions between the countries in the region.

SESAME

CERN places high importance on international collaboration, and actively seeks to establish links with and promote research by countries globally. For example, 2017 saw the first Africa-led experiment (facilitated by the UK); 'retired' CERN servers were donated to facilities in Bulgaria, Algeria and Jordan; and undergraduate students from Lower- and Middle-Income Countries participated in CERN's summer programme, of which 40 per year are supported by the UK Global Challenges Research Fund.

The UK may benefit *directly* from improved interaction / relations with other countries, e.g. through enhanced international influence. It may also benefit *indirectly* from improved interaction between countries, e.g. countries discussing global socio-political challenges, with global (including UK) benefits, or certain other countries improving their 'relationship' that may e.g. increase peace and security.

CERN helps to develop and expand the global physics community

CERN has contributed substantially to the expansion and development of the global physics, engineering and computing communities, e.g. through the development of young researchers and educational outreach schemes (particularly in less well-endowed scientific communities). It has also encouraged others to engage with and invest in CERN experiments, while also providing members and their scientific communities with a portal to scientific programmes, facilities and collaborations elsewhere.

Specialised CERN schools provide training on particle physics, accelerators and computing to several hundred young researchers each year, many of which are run internationally to improve participation of less well-endowed scientific communities. We see this community development activity at work in Asia, Latin America and Africa; and UK scientists have been at the centre of many of these capability-building activities over many years. Discussion with partners from these regions tell us that their involvement with CERN, e.g. as post-doctoral students, was a trigger for new national high energy physics research groups that expand in time into new departments within an institution, and then across to several universities or research institutes. This evolution has also persuaded governments of the importance of science– not just technology or applied research – and has led to countries joining CERN scientific collaborations (e.g. ATLAS) and expanding their financial and technological contributions.

CERN's efforts are not entirely selfless, as those young researchers expand the pool of brilliant postdoctoral fellows that can be recruited to work on research and applied physics, engineering and computing. Moreover, as national research groups expand, more countries will agree to join CERN's experiments, helping to finance ever more ambitious research collaborations and experimental programmes. CERN has also provided a portal to other scientific programmes, with new collaborations in other countries, such as the US, and with researchers taking up positions as visiting academics or involvement in international collaborative projects with partners in other countries (whom they first met at CERN). This can in time also lead to the investment in new national research facilities.

Future monitoring and evaluation

As part of the study, an outline proposal has also been prepared for an updated monitoring and evaluation framework for STFC to use as the basis for tracking the benefits of the UK's engagement with CERN in future. The framework (which is set out in Section 11 of the Evidence Document that accompanies this Main Report) is also designed to support independent evaluations that STFC may wish to commission in future, to ensure a wide-ranging and robust assessment of achievements across each of the four principal impact pathways that have been explored through the current study.

The experience of conducting this study has uncovered gaps in the available evidence base, as well as several data and methodological challenges that need to be fixed or at least improved. To that end, we have suggested the current monitoring system could be strengthened with the addition of several new periodical data collection exercises, including surveys of UK suppliers, researchers and the general public, plus regular bibliometric analyses and improved cataloguing of achievements. We have also suggested that STFC commission several targeted studies to improve its methodological toolbox (e.g. assessing approaches to monetising the economic impact of large research infrastructure) and enhance its basic understanding of several important benefit types (e.g. in relation to skills and career tracking).

The estimated costs of these additional activities are likely to go beyond current levels of resourcing, but they are not an unreasonable ambition, given the scale of public investment involved. The new and enhanced monitoring and evaluation activities will help to identify, quantify and monetise more of the total spectrum of impacts than was possible within this evaluation, enabling a more complete account to be given of the benefits being derived from the UK's investment and involvement in CERN.

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