International Science Council
The global voice for science

Open Science for the 21st Century

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Introduction

This document is a response to the UNESCO global consultation on open science. It brings together strands of work that have developed within the International Science Council's (ISC) community to create a draft working paper that will be further developed through consultation with the Council's members as a formal ISC position paper on open science.

The paper describes the rationale for and the origins of the modern open science movement, its dimensions and its applications. It makes recommendations to scientists, to universities, to UNESCO and to other science systems stakeholders about changes that are necessary for the effective operation of open science. The paper includes, at the end of relevant sections, an indication of ISC projects and programmes that are designed to support aspects of open science, as described in the current ISC Action Plan 2019 -2021 [1]. The appendix includes answers to specific questions posed by UNESCO for which the detailed arguments are presented in the main text.

Summary

Science is an essential part of the modern world's intellectual infrastructure. It is needed for the advancement of our societies, to inform our education, to improve our policies, to spur innovation, to safeguard human wellbeing, and as a stimulus to curiosity, imagination and wonder. Open science originated in the 17th century with the publication of scientific journals. The **record of science** that this initiated exposes the logic and evidence of scientific truth claims to scrutiny and potential invalidation, thereby creating the bedrock that is the value of science to society. It makes science accessible to all who would use it, whether scientists, governments or wider society with the potential for innovative use in a myriad of educational, social, economic and cultural settings.

The horizons of open science have broadened during the first decades of the 21st century, inspired by several convergent trends:

- a shift in the balance of scientific enquiry from a disciplinary to an interdisciplinary focus that engages with many of the global challenges that humanity faces and that science is called on to address;
- a digital revolution that offers unprecedented insights into many of these inherently complex problems;
- calls for free and open access to the record of science;
- the development of the world-wide-web and social media that have democratized access to information and by-passed traditional gate-keepers of knowledge, such that science must engage more publicly if it is to play its role in contributing its special form of knowledge to human development.

These trends have stimulated development of a new movement for open science, which the ISC defines as:

Science that is open to scrutiny and challenge, and to the knowledge needs and interests of wider publics. Open science makes the record of science, its evolving stock of knowledge, ideas and possibilities accessible and free to all, irrespective of geography, gender, ethnicity or financial circumstance. It makes the data and evidence of science accessible and re-usable by all, subject to constraints of safety, security and privacy. It is open to engagement with other societal actors in the common pursuit of new knowledge, and to support humanity in achieving sustainable and equitable life on planet Earth.

The essential attributes of open science are: open access to the record of science and to the data of science; access to the digital infrastructures that enable widespread engagement and communication; and open engagement between scientists and other societal actors.

Open access to the record of science is sub-optimal. The high pay walls erected by many publishers around the record of science that they hold inhibits access and is highly inefficient in ensuring that it is openly accessible in ways that maximize its value to science and society [2]. It should be treated as a global public good, freely and perennially available to citizens, other societal stakeholders and to researchers. UNESCO should recognize the record of science as an essential part of the patrimony of humanity.

Data that provide the evidence for scientific truth claims must be accessible for scrutiny. The ISC echoes the statement of one of its members, the International Union of Crystallography, that "*we urge the worldwide community of scientists, whether publicly or privately funded, always to have the starting goal to divulge fully all data collected or generated in experiments*" [3]. Scientists should not

act as data owners, but as their custodians on behalf of the public. Universities should create structures to support their researchers in meeting the onerous demands of data management. Funders should require those they support to deposit their data in open, well-managed repositories. Journals should accept the responsibility of ensuring that the data on which a truth claim is based is concurrently and openly available as a condition of publication. And international science bodies, including UNESCO, should address the major issues of governance of scientific data.

In a world where digital processes dominate the creation, dissemination and communication of information and knowledge, access to these tools is a necessary means of engagement with science, whether by citizens, scientists or other societal stakeholders. National bodies need to provide computational and communication tools, together with the policies, standards, processes, skills and relationships that are necessary to support open science in all its aspects. The disciplines of science need to embed open science practices in their ways of working.

The modern era is one in which science is arguably needed more than ever to help tackle the many profound challenges faced by human society. To do so effectively needs strong engagement between science and society in ways that enhance the practical applicability and socio-political legitimacy of processes of jointly created knowledge. The spectrum of potential engagement is broad, from open public access to the record of science, to joint scrutiny of the safety cases of developments that have the potential to generate public hazards, to deliberative processes of public policy development, to community engagement, and to citizen science.

Given the global dimensions of modern science, open science must also operate at the global level. It must be globally inclusive if it is to be globally effective. There must be equitable access to the record of science, irrespective of geography, gender, ethnicity or capacity to pay. International scientific unions and associations should collaborate with the ISC in seeking ways to support their colleagues in low- and middle-income countries in developing their capacities in open science. The ISC and UNESCO should discuss, together with other international representative bodies for science, the potential for a form of global open science commons.

1. Open Science for the Global Public Good

Science[1] is an indispensable contribution to the human endeavour. It is not a dispensable luxury. We need science for the advancement of our societies, to inform our education, improve our policies, spur innovation, and safeguard human wellbeing. We need science as a stimulus to curiosity, imagination and wonder. The benefits that science creates are not only financial, but lie in the knowledge, understanding and ideas that it creates.

Openness is at the heart of the scientific endeavour as a distinct form of knowledge based on evidence and tested against reality, logic and the scrutiny of scientific peers. The record of science[2], its evolving

[1] Throughout the document, the word **science** is used to refer to the systematic organisation of knowledge that can be rationally explained and reliably applied. It is inclusive of the natural (including physical, mathematical and life) sciences and social (including behavioural and economic) science domains that represent the International Science Council's primary focus, as well as the humanities, medical, health, computer and engineering sciences (From the ISC High Level Strategy - https://council.science/high-level-strategy/)

[2] **The record of science** is the published record of scientific knowledge and understanding from the earliest days of scientific inquiry to the present. It is contained in books, scientific journals and the "grey" literatures published in governmental and institutional reports, whether in print or digital formats. It is continually refreshed and re-evaluated across the disciplines of science by new experiments, new observations and new theoretical insights. It is a complex amalgam of novel contributions that withstand critical tests of experiment, observation or logic and are of general or local significance; those that will fail

stock of knowledge, ideas and possibilities is an essential part of the human patrimony. But the influence and the use of science have become so pervasive that it cannot solely be contained within the global community of professional scientists. Science must continue to evolve to become more accessible and more accountable to citizens and societies.

Science is at its most relevant and effective when its discoveries and knowledge are made freely and comprehensibly available as "public goods"[3], accessible to all who wish to understand or use them. Scientific data must similarly be accessible and re-usable, subject to constraints of safety, security and privacy. And science should be open to society in ways that engage wider publics in the common pursuit of new knowledge. These issues are at the heart of the modern "open science movement."

The vision of the International Science Council (ISC) is of science as a global public good [1]. Universal access to scientific knowledge, uninhibited by geography, gender, political boundaries, ethnicity or ability to pay is an essential prerequisite for human development and progress towards planetary sustainability. Advocating and advancing open science – ensuring that scientific knowledge, data and expertise are universally and openly accessible and their benefits universally and equitably shared – are fundamental to the ISC's work in achieving this vision.

2. Core values: scrutiny, scepticism and open communication

Open science is not new. It has been at the heart of the scientific enterprise for over three hundred years, inspiring an unprecedented era of scientific discovery. This modern era was initiated when the first scientific journals were created by learned societies in the late 17th century [4]. Not only were new scientific ideas openly exposed, but the first editors required the evidence, the data, on which those ideas were based, to be concurrently presented. It was a crucial innovation. It permitted others to scrutinize the logic of the connection between evidence and hypothesis, to repeat the observation or experiment that provided the evidence, and to test any predictions that arose from the hypothesis. Testing an idea against reality and logic, and rejecting ideas that fail the tests have come to form the bedrock of scientific rigour.

Peer review, a form of organized scepticism, was introduced by Henry Oldenburg, the founding editor of the UK Royal Society's first journal in 1665. Oldenburg began the practice of sending submitted manuscripts to experts who could judge their quality before publication. But the most formidable form of peer review is the concentrated focus of sharp minds on a published claim for important new truths. Such scrutiny can invalidate, but cannot validate. It is the basis of so-called scientific self-correction. New "truths" are provisional. In the words of Albert Einstein - "a thousand experiments cannot prove me right, but one experiment can prove me wrong"; and of Berthold Brecht - "the aim of science is not to open the door to infinite wisdom, but to set a limit to infinite error."

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such tests and lose currency; and those that are disregarded and rarely if ever remembered or quoted, though sometimes re-discovered as significant insights. Recognition and quotation by peers and publication in standard texts determine how this amalgam creates the evolving framework of understanding in a discipline or about a phenomenon.

[3] **A public good** has two essential properties, non-rivalrous consumption--the consumption of one individual does not detract from that of another--and non-excludability--it is difficult if not impossible to exclude an individual from enjoying the good. Stiglitz, J. 2007. http://www.worldbank.org/knowledge/chiefecon/articles/undpk2/w2wtoc.htm

3. The emergence of a new paradigm of open science

Changes in the environment in which science operates coupled with new opportunities arising from technological developments, have broadened the horizons of scientific openness. A new movement for open science is creating a new paradigm from the convergence of several trends:

a) In the later decades of the 20th century the hegemony of disciplinary science, each with its own internal hierarchies, driven by the autonomy of scientists and their host institutions (mode 1), evolved in part towards a developing paradigm of knowledge production which is socially distributed, application-oriented, trans-disciplinary (in the sense of involving interaction with non-academics) and subject to multiple accountabilities (mode 2) [5, 6].
b) At the same time, science has increasingly been confronted with calls for knowledge that addresses major global problems. A new social contract between science and society requires participatory approaches in the co-production of knowledge, primarily aimed at global challenges such as those embedded in the UN Sustainable Development Goals (SDGs). Of particular note are issues of global equity, with the imperative of "leaving no one behind" raising grave concerns about persistent and, in some cases, growing N-S divides in scientific capacities, with low and middle-income countries falling behind at individual, institutional and political levels.
c) The World Wide Web has revolutionized social communication, providing a means of accessing and contributing to the distribution of information and knowledge in unprecedented ways. Together with the development of social media it has introduced a new social dynamic that by-passes the traditional "gatekeepers" of authorized wisdom. National media, newspapers and journals are no longer able to act as high-level filters for public information. At the same time, pressure groups are able to use the new technologies to undermine scientific consensus on many critical issues such as climate change, vaccination, smoking and AIDS.
d) The technologies of the digital revolution have created new challenges and opportunities for science. Analogue has been replaced by digital means of acquisition, analysis and communication of data, information and knowledge, with universal implications for science, society and economies. The low cost and flexibility of digital systems have led to the creation of vast and diverse data series. Exploring modern data resources using AI technologies such as machine learning are means of unravelling much of the deep structure of the complexity inherent in many problems that humanity faces, from infectious disease, to the behaviour and functions of cities, to national and global economies, to climate change and global sustainability.

There are a variety of arguments for open science [7]. Some see it as a means of increasing the efficiency of scientific inquiry. Some see its benefits to inter-disciplinary science. Some see access to and integration of diverse, multi-dimensional data streams as a means of analysing inherently complex problems. And some see an opportunity for strengthening the democratisation of science as a public enterprise. These benefits all rest on similar foundations: open access to the record of science, open data, and access to the computational and communications tools of the digital revolution. Recognising this the ISC frames an inclusive definition of open science as:

> *Science that is open to scrutiny and challenge, and to the knowledge needs and interests of wider publics. Open science makes the record of science, its evolving stock of knowledge, ideas and possibilities accessible and free to all, irrespective of geography, gender, ethnicity or financial circumstance. It makes the data and evidence of science accessible and re-usable by all, subject to constraints of safety, security and privacy. It is open to engagement with other societal actors in the common pursuit of new knowledge, and to support humanity in achieving sustainable and equitable life on planet Earth.*

There is of course a beckoning ideal: that scientists routinely disclose their study plans; that progress is routinely reported; that lab notes are made available; that results are published in open-access journals; that articles are assessed through an open peer review process; that results and data are stored in trustworthy open access databases [8]; and that there are processes of transdisciplinary engagement with societal stakeholders, public and private sectors, NGOs and citizens, as knowledge partners in networks of collaborative learning and problem-solving, to improve practical applicability and socio-political legitimacy [9].

The crucial question is how to deliver the open science mission. The ISC identifies delivery within four main themes: open access to the record of science; open access to scientific data and evidence; openness to and engagement with societal stakeholders; and access to the computational and communication tools of the digital revolution that are essential for societal participation.

4. Open access to the record of science

The record of published science is a vital source of ideas, theories, observations and data that provide raw material and inspiration for further scientific enquiry and a profound edifice of knowledge for society and for education. It should be recognized as a public good, freely and perennially available to all.

There has been a great increase in recent years in the diversity of ways in which scientific work is communicated into the public domain, but it is still the case that the style of print journal publication has been retained in a predominantly digital era, and that most original research findings are presented in formally published journals, monographs and books.

4.1 Scientific publishing

One obstacle to open access to the record of science has been the dominant position that corporate, for-profit publishers have established in academic publishing. By 2015, corporates owned 64% of scientific journals [10]. They had erected high, subscription-based pay walls around their journals that require major subventions from university libraries' budgets or from national science authorities to permit access by scientists to a large part of the record of science that they and their predecessors have produced. In 2014, taxpayers in the United States spent $139 billion on scientific research, yet much of this research is inaccessible not only to the public, but also to other scientists [11]. At a time when the digital revolution has removed most costs of printing, distribution and production, and when authors are required to format their papers in the style of the journal, journal prices have increased far in excess of the rate of inflation, giving returns on investment of 25-35% [12]. Corporate publishers' high pay walls discriminate against access in poorer countries and drain budgets that would be better employed in funding research. The current market structure does not operate in the long-term interests of the research community. Market solutions are inefficient in delivering the 'public good' element of scientific work [13]. The record of science is priced beyond the reach of most citizens, who lack the institutional support that professional researchers can rely on to fund journal access. It is a model that discriminates against the interests of citizens at a time when access to scientific knowledge should be open to all. It is in conflict with the 1999 UNESCO Declaration on Science and the Use of Scientific Knowledge that "equal access to science is not only a social and ethical requirement for human development, but also essential for realizing the full potential of scientific communities worldwide and for orienting scientific progress towards meeting the needs of humankind" (article 42) [14]. It is also in conflict with the 2017 UNESCO Recommendation on Science and Scientific Researchers, particularly in the need to ensure the free circulation of scientific data.

Corporate publishers routinely demand transfer of copyright to them as a condition of publication. When doing so, researchers have, of their own volition, assisted in the privatisation of a public good at no cost to the publisher, whose first responsibility is to their shareholders and not to science.

The corporate scientific publishing companies operate a uniquely asymmetric business model in which scientists gift their work to them, then buy it back at inflated prices, either individually or as part of major bundled deals between corporate publishers and universities or government agencies. The trump card in publishers' hands is that they have cornered the market in so-called high impact journals, then promote and advance readership and citation of what they publish – thus inflating the impact factor. In turn universities use impact factors and citations as criteria for academic advancement. Such positive reinforcement persuades researchers and their institutions that it is worthwhile paying a premium for publication in a particular journal, rather than paying less for publication in a journal with equally high standards. The use of impact factors was roundly condemned in the San Francisco declaration of May 13, 2013 [15]:

> *Do not use journal-based metrics, such as Journal Impact Factors, as a surrogate measure of the quality of individual research articles, to assess an individual scientist's contributions, or in hiring, promotion, or funding decisions.*

It is the individual paper that has impact, not the journal. By early 2020, the declaration had been endorsed by over 15,900 individual scientists and 1,954 scientific organizations worldwide. Breaking the addiction to impact factors would do much to undermine excessive paywalls.

The driver of demand in this highly lucrative academic publishing market derives from the growth in the number and size of universities internationally and the expansion of their research efforts as a means of embellishing their reputations and as an attractor for both students and sponsors. As publication metrics have been taken as the predominant measure of research excellence, they have become the primary index of academic performance and the primary incentive for career advancement. "Publish or perish" is now an almost universal axiom. The consequence has been an exponential growth in recent decades in the rate of scientific publication [16], with rates of production of about 2.5 million per year by 2017 [17]. A further consequence of this growth in demand for publication outlets has been the rise of so-called "predatory" journals that offer rapid publication without peer review or significant editorial oversight [18].

The reliance on proxy metrics such as impact factors, numbers of publications or citation rates creates a situation where these tend to become targets, which suffer from the consequences of 'Goodhart's law' that 'when measures become targets, they cease to be good measures', primarily because they can be and are 'gamed' [19, 20]. Initiatives to create alternative methods of evaluating contributions to science (so-called alt-metrics) are underway in many different settings worldwide [21]. They are gaining prominence as ways to more fully describe the significance of contributions to knowledge.

What is lost to society through this dysfunctional system has been amply illustrated by the Covid-19 pandemic. A petition with 2,000 signatures on 3rd March 2020 stated: "Thousands of scientific studies about the coronavirus are locked behind subscription paywalls, blocking scientists from getting access to the research needed to discover antiviral treatments and a vaccine to stop the virus" [22]. There has been a valuable but limited response from corporate publishers, who have allowed open access for a limited period of three months. Such a stance should be permanent and general.

The development of digital text and data mining in recent years has demonstrated a remarkable capacity to expose patterns and relationships between different findings embedded in the published record of science [23]. It is a powerful tool of scientific understanding, but one where major corporate publishers deny access to mining of their journal content by those who have created the content and are best placed to exploit it to the public good.

These problems have long elicited calls for change in a publishing model that is not well adapted to the needs of modern science nor to the needs of society for scientific information. Powerful and principled interventions such as the Budapest Declaration have played important roles in stimulating the development of "open access" publishing that adheres to its principles:

> *"The free availability of scientific literature on the public internet, permitting any users to read, download, copy, distribute, print, search, or link to the full texts of these articles, crawl them for indexing, pass them as data to software, or use them for any other lawful purpose, without financial, legal, or technical barriers other than those inseparable from gaining access to the internet itself. The only constraint on reproduction and distribution, and the only role for copyright in this domain, should be to give authors control over the integrity of their work and the right to be properly acknowledged and cited."*

Open access journals have progressively increased in market share. They are now estimated to make up about 47% of all scientific journals [24]. Some funders of public science have also taken up the issue. For example, the European Commission, a major science funder, launched "cOALITION S" in 2018, which sought an agreement from national funding bodies that from 2021 "all scholarly publications based on the research funded by public or private grants provided by national, regional and international research councils and funding bodies, must be published in Open Access Journals, on Open Access Platforms, or made immediately available through Open Access Repositories without embargo" [25].

Although cOALITION S is a bold intervention in an attempt to achieve a "global flip" towards open access [26], its adoption would mean that legacy publishers (those with long back runs of journals) would have to replace subscription revenues with article-processing charges (APCs). Its consequence would be a massive shift to a pay-to-publish system, with APCs ranging from several $100s to over $5,000 per article. Many low- and middle- income countries would find it difficult to fund APCs at this level, so that though their researchers would be able to read freely, they would be largely unable to publish. Important regional solutions have developed as bulwarks against excessive cost [27]. For example, the Latin American Council of Social Sciences (CLACSO) has created a virtual library with more than 40,000 open access documents and 1,000,000 average monthly downloads [28], as one of the world's largest virtual social science libraries. Such solutions are only partial, since they result in regional systems that inhibit the robust international circulation of ideas that modern science requires. It is an issue that needs to be addressed at the highest global level.

The business model for open access journals has been evolving rapidly. The model that represents the least departure from the traditional is the so-called "gold" model. In this, the journal price is simply transferred from a downstream, "reader pays' subscription fee, to an upstream, "author pays" article processing charge. It is the preferred route for the open access offerings of commercial publishers, but one that is at least as financially demanding as its predecessor, if not more so [28.1]. The other principle mode of open access publishing is the so-called "green" model, very much a child of the digital revolution. Rather than submitting articles to open access journals, articles are submitted to an open access repository. Moreover, more than two thirds of peer reviewed open access journals charge no fees, contrasting with 75% of conventional, non-open access journals that charge both author-side fees and reader-side subscriptions [28.2].

But what of quality? As early as 2004, it was found that in every field of the sciences "there was at least one open access title that ranked at or near the top of its field" in citation impact [28.2]. The number of high-quality and high-impact open access journals has grown since then. The quality of a scholarly journal is determined by authors, editors, and referees, not by its business model or access policy. The tide of open access is now flowing very strongly, supported by strong calls from the scientific community to support this trend [28.3, 28.4].

Global solutions require global involvement from the community of science and global access to its publications, both by readers and authors, irrespective of income. The Covid-19 pandemic has been a powerful example of multiple scientific collaborations across the range of scientific disciplines. Open access to scientific research is integral to the future of such collaboration.

4.2 Open Educational resources

Open access to the record of science is not only a priority for scientific researchers but is also essential for education, particularly at secondary and tertiary levels, for citizen scientists and for lifelong learning. Lifelong learning is of great importance in an era when the technologies of work and of daily life are changing rapidly and imposing new demands and creating new opportunities for individuals and organisations. It is a vital priority that the latest knowledge is available to equip people with the skills for contemporary work and for fulfilled lives as active citizens.

The development of massive open online courses (MOOCS) in recent years has demonstrated the potential of online lifelong learning. The closing of university doors in 2020 to many millions of students worldwide in the face of the global covid-19 pandemic has seen universities rapidly shifting to online tuition. These developments illustrate the enormous potential of open scientific resources being effectively exploited as an educational resource both within and beyond the normal boundaries of formal education.

The issue of Open Educational Resources (OER) has been the subject of a UNESCO recommendation that seeks to build on the capacity of the science and university communities to create, access, re-use, adapt and redistribute OER [29]. It should be recognized as an important strand of open science, thereby drawing attention to the need for pathways of open access to the record of science and its data.

4.3 Recommendations

a) The record of published science is a vital source of ideas, of observations and data that provide feedstock and inspiration for further enquiry and a profound edifice of knowledge. It should be treated as a global public good, freely and perennially available to all.
b) When publishing in scientific journals, researchers should publish in those that operate open access policies. They should not gift copyright to journal publishers. Publications should be published under an open license, preferably the Creative Commons Attribution license (CC BY).
c) Universities should adopt the principles of the San Francisco Declaration.
d) Funders should require those whose research they fund to publish in open access journals that adhere to the principles of the Budapest Declaration. They should regard the process of publishing as an integral part of the cost of doing research.
e) Science Publishers should operate within the terms of the Budapest Declaration. They should accept that the part of the record of science that they hold is a public good, therefore accessible to all. They should permit open access to it for the purposes of text and data mining.
f) UNESCO should recognize that the record of science is part of the patrimony of humanity, and thereby should be accessible to all. UNESCO should seek to obtain international agreements that ensure access to the record, either as authors or readers, in ways that do not discriminate on the basis of capacity to pay.
g) The ISC should advocate these principles amongst its members and partners and explore with them their potential to support the development of Open Educational Resources.

The International Science Council is currently engaged in a project on the future of scientific and scholarly publishing. The project's first output will be a discussion paper, to be published in July 2020, designed to stimulate debate within the international scientific and scholarly community about the purpose and process of publishing, and the extent to which it serves the interests of the community. It will be discussed in a series of science community debates in Q3 of 2020, which will include consultation on possible consequential actions, including the creation of a global coalition for change.

5. Open Data

5.1 Imperatives

The data on which published truth claims are based, whether derived from scientific investigation or from some other source, must be open and accessible at the time of publication in a form that can be scrutinized in order to sustain the vital principle of scientific self-correction (see section 2) [31]. To do otherwise should be regarded as scientific malpractice. It is the failure to adapt this well-established scientific principle to a data-rich and computationally-intensive era that has contributed to the crisis of replicability of the last decade in which only a small proportion of results across several disciplines can be replicated [30]. Much of this is not simply the failure of a hypothesis to survive a stringent test, or a failure of logic within the hypothesis, but the absence of sufficient data and metadata to enable scrutiny of the logic or test of the hypothesis.

The ISC also advocates the principle that all significant data produced by science should in principle be open and available for re-use [31]. The benefits of doing so are: greater efficiency when the same data can be re-purposed; the need for cross-disciplinary studies to access varied data streams, as when analysing complexity; and as evidence for science-society engagements. A ringing challenge to the scientific community to observe this principle was issued by the International Union of Crystallography [32].

> "*we urge the worldwide community of scientists, whether publicly or privately funded, always to have the starting goal to divulge fully all data collected or generated in experiments*".

5.2 Interoperability and FAIR Data

If scientists are to be able to utilize the diverse and voluminous streams of data now available, to re-purpose existing data, to address complexity by integrating multi-disciplinary data series, or to test logic, calculation or replicability in a published truth claim, they must have access to meta-data that enables data use and interoperability. For research where complex computational methods are used, details of code and metadata are increasingly needed, and in some cases, details of the machine that has been used are required. The metadata that is required for such re-use have been formalized as FAIR – Findable-Accessible-Interoperable-Reusable [33] as follows:

Findable

F1 – data are assigned globally unique and persistent identifiers.
F2 – data are described with rich metadata (data about data).
F3 – metadata explicitly include the identifier of the data they describe.
F4 – (meta)data are registered/indexed in a searchable resource.

Accessible

A1 – (meta)data are retrievable by their identifier using a standard communication protocol
(the protocol is open, free and universally implementable; it allows authentication and authorisation where necessary).

A2 – (meta)data should be accessible even when the data is no longer available.

Interoperable

I1 **– (**meta)data use a formal, accessible, shared and broadly applicable language for knowledge representation.

I2 **–** (meta)data use vocabularies that follow FAIR principles.

I3 – (meta)data include qualified references to other (meta)data.

Reusable

R1 – (meta)data are richly described with a plurality of accurate and relevant attributes.

R2 – (meta)data are released with a clear and accessible data usage licence; are associated with detailed provenance; and meet domain-relevant community standards).

These are onerous requirements, but promotion and adoption of the FAIR principles and turning them into reality [34] is an important enabling priority for open science.

It is vital however that the practice of FAIR principles is made easy for data providers and creators, as well as data users. Researchers need to be supported and assisted in rendering data FAIR. Discipline-specific communities and infrastructures are increasingly playing an important role in such support. Simplifying the current fragmentation of the research data landscape, and achieving economies of scale are important priorities. Disciplines where there are major research infrastructures, such as in high energy physics, bio-informatics, crystallography and demographics, where the data categories tend to be well-defined and homogenous, are relatively readily able to access and combine data. Combining data is more difficult when data tend to be heterogeneous, as in the humanities and social sciences. However, considerable progress has been made in many areas of the social sciences, particularly those concerned with longitudinal data reuse [35], and where disciplines have successfully implemented FAIR principles. Such data have become an essential part of their research infrastructures, widely used by the scientific community in its daily research work. They include the European Strategic Research Infrastructures (ESFRI - www.esfri.eu) in the humanities, DARIAH (https://www.dariah.eu) for Arts and Humanities, and CLARIN (www.clarin.eu), a language resource for Humanities and Social Sciences. Grassroots approaches relying on informal or formal agreements on common data models and use of shared service application programming interfaces (APIs) are common in the arts and humanities, such as Pelagios Commons, which provides online resources and a community forum for open data methods for working with historical places (http://commons.pelagios.org). FAIR data approaches are also being made available to citizen science communities (e.g. www.citizenscienceglobal.org) [36].

5.3 Artificial Intelligence Technologies

Artificial intelligence technologies should be considered as an integral part of open regimes and their governance. Computers execute our commands, but learning machines learn like humans, from experience. Their 'experiences' are derived from the powerful and diverse fluxes of data that stream through them at high rates, and their learning experience lies, as it does in humans, in the progressive identification of patterns in the data that pass through them. This enables them to identify patterns that have hitherto been beyond our capacities to recognize [37] and it is this that is the basis of their value to science and to society. Machine learning algorithms enable the recognition of patterns in the complexity inherent in business and industrial processes, health systems, governance systems and public affairs, leading to profound increases in efficiency and reductions in cost.

The power of learning algorithms to identify individuals and their characteristics from data that in themselves do not seem to infringe privacy, and their capacity to make judgements that have been assumed hitherto to be intrinsically human raises the issue of how they are to be regulated and governed.

5.4 Data Governance

Rapidly evolving data and automated learning technologies threaten the maintenance of private spaces in unprecedented ways. Well-conceived data governance is an urgent priority at national and international levels if public trust in the beneficial potential of these technologies and of the utility and safety of open processes is to be maintained. Existing data governance concepts, such as privacy and consent, are under unprecedented strain, and their meanings in policy, law and public discourse have shifted, and will continue to do so in new and unpredictable ways. It is important to articulate high-level principles to shape evolving modes of data governance to ensure the trustworthiness that open science systems require if they are to be effective. Principles that have been proposed to protect individual and collective rights and interests [38] are:

- ensure that trade-offs affected by data management and data use are made transparently, accountably and inclusively;
- seek out good practices and learn from success and failure;
- enhance existing democratic governance.

Stewardship bodies that would support such principles could have the role of anticipating, monitoring and evaluating changes; building good practice and setting standards; and identifying and remedying developments that threaten fundamental principles. The inherently international nature of science suggests the need for an international level of governance, which might either be through international agreements implemented at national levels, possibly brokered by bodies such as UNESCO, or alternatively through a specialized body established for this express purpose.

5.5 Recommendations

a) A change of mindset is necessary within the scientific community. Many publicly-funded scientists, or their institutions, have regarded the data that they acquire as their data, as private intellectual property. They should rather regard the data they collect, not as theirs, but as data of which they are custodians on behalf of the public, and with a duty to make it available as a public good and as an integral part of the open record of science.
b) Data and any relevant software used to support a truth claim in a publication must be made concurrently accessible for scrutiny as FAIR data in a trustworthy open access site. Beyond this, all important scientific data should be made similarly accessible. They should observe FAIR data criteria. This is an onerous requirement, but one that science must progressively adopt as a standard if it is to exploit the benefits of the digital revolution for an age of complexity.
c) Universities and Research Institutions should create support structures and processes that will permit researchers to adopt FAIR data criteria without need for excessive effort.
d) Funders should require data that has been collected as part of research that they have funded to be deposited in open, trustworthy repositories using FAIR criteria.
e) Scientific Journals or Repositories should require that the data that relates to articles that they publish should be concurrently and openly available as a condition of publication.
h) International science bodies, including UNESCO, should collaboratively address the major issues of governance of scientific data, including: sustainability of the many databases that monitor global sustainability and change; international data sharing, particularly at times of emergency; and issues of safety, security and privacy.

The International Science Council has two major activities in this domain. A decadal programme is designed to facilitate data interoperability between the different disciplines of science by resolving the semantic roots of inter-operation. Its underlying purpose is to enable integration of data streams from different disciplines in supporting inter-disciplinary work on global challenges. The programme is led *by the Council's Committee on Data (CODATA). The ISC is also working with partners in considering the basis on which global scientific data might be governed.*

6. Engaged science: open to society

6.1 The rationale

The modern era is one in which science is arguably needed more than ever to help tackle the many profound challenges faced by human society, something that has been brutally underlined by the Covid-19 pandemic. Science in the modern era is central to many of the needs and concerns of citizens (section 1), but for effective application it must be sensitive to the nature of policy and public debate, and must engage openly with society in that debate. The case for publicly engaged open science is unanswerable.

6.2 The spectrum of engagement

A deepening public engagement with science was increasingly promoted by many scientific organisations and universities during the later decades of the 20th century. The opportunity offered by the open science movement should be grasped to deepen this still further.

Free digital public access to the record of science as a global public good must be a first priority. Much of the research from which it has been derived has been funded by tax-payers. They should be able to see the fruits of their investments. Access to the data of science, though more difficult and more complex to engineer and make findable and accessible to the public, should also be open, through portals that facilitate non-specialist access.

A case where such access is relevant to both public and private sectors involves public access to the scientific safety cases for procedures that have the potential to cause public harm. Should they be accessible to public scrutiny? The principle that they should is exemplified in the case of radioactive waste from nuclear power stations. For example, the Swedish national Nuclear Fuel and Waste Management Company, SKB, [39] publishes all its scientific work designed to assess risk in Swedish nuclear waste management procedures, including the safety case for all potential waste management sites. SKB, as many other nuclear waste operators internationally [40] also undertakes engagement processes with communities in the vicinity of actual and proposed waste disposal sites based on open access to all scientific data and reports, in which communities are not passive recipients but active interlocutors.

The above case is one example of the many problems that face modern societies where scientific knowledge is important. But scientific knowledge is only one part of a more complex equation, where including values, costs, capacity to deliver and treaty obligations also play parts. Though some complex problems may be technically and scientifically resolvable, it is often the case that lack of public acceptability proves to be an unsurmountable barrier. The temptation for government is to take the route of 'decide – announce – defend', often followed by 'abandon', rather than 'engage – deliberate – decide - act'. Such early stage engagement and deliberation prior to decision making on many issues, whether local, national or global, should be a key priority for open science, involving scientists with decision-makers, policy-shapers and practitioners, as well as actors from civil society and the private sector as partners in the co-production of solutions-oriented knowledge, policy, and practice. It recognizes that there are multiple sources of relevant knowledge and expertise that need to be harnessed, such that all involved actors are both producers and users of knowledge at one time or another. It is a social process of creating actionable knowledge and promoting mutual learning in ways that foster scientific credibility, practical relevance and socio-political legitimacy. Scientific knowledge 'producers' must cease to think of knowledge 'users' as passive information receivers, or at best as contributors of data to analyses framed by scientists. Instead, scientists are involved in integration of the concerns, values, and worldviews of policymakers and practitioners, entrepreneurs, activists and citizens, giving them a voice in developing research that is compatible with their needs and aspirations [41]. It is a setting that can be greatly enriched by digitally enabled processes such as social media groups and crowd sourcing in developing a collective intelligence for problem solving.

There are a growing number of examples of such efforts from Africa, where communitarian values are often very strong and where many states are faced with immanent issues such as climate change, food security, biodiversity loss and water resource management [42]. It is an approach now also strongly emphasized in international scientific initiatives such as Future Earth (http://futureearth.org) and in the funding actions of the Belmont Forum (https://www.belmontforum.org). Because of their complexity the traditional singular, linear approaches to science are no longer appropriate.

An important part of the societal engagement of science is with governments. Scientific evidence is increasingly important to governmental decision making at all levels of governance, but the interface is problematic. Science is inherently sceptical and discursive. A discursive government is a confusing government. An ideological science is worthless. The interface is crucial. As the Covid-19 pandemic has shown, public confidence in science is high at moments of crisis, but confidence depends upon the preparedness of governments to permit science advice to be open and accessible. Otherwise, a government's claim that it "follows the science", is merely an attempt to absolve itself from responsibility.

The strong, possibly excessive, focus on research publications and commercialisation is strongly incentivized. In an academic world where incentives have increasingly been pre-requisites for action, the lack of incentives undermines the willingness of researchers to engage with policy makers and wider publics in the co-production of knowledge. This work is time consuming and, often, difficult. Researchers are rarely trained for it and hardly rewarded for it.

6.3 Citizen Science

A significant part of the "open to society" agenda is that of citizen science, a relatively recent innovation at the science/society interface. It has developed as a mode of scientific research conducted by non-professional scientists, but frequently carried out in association with formal, scientific programmes or with professional scientists [43, 44, 45] and with the web and social media as important agents of interaction. Citizen science may be embedded within a professional effort, associated with this effort, or entirely independent. An extension of the citizen science model into schools could have major impact on the science literacy of the new generation.

6.4 Recommendations

a) There is a wide spectrum of development of creative and innovative processes of engagement of science with society to meet societal needs at all levels, most of which depend on the principles of openness set out in this document. The engagement of science and scientists in these processes is essential, and the open science movement must include them within its vision. To do otherwise would be to restrict open science to be an inward-looking enterprise, of science talking to itself. The times call for a more radical view.
b) UNESCO should advance a broad view of open science as one that embraces engaged science as one of its pillars.
c) In so far as is consistent with safety, security and privacy (section 9), science advice to governments on matters of major concern should be open and accessible.

The International Science Council has programmes on the public value of science and knowledge production and diffusion as global public goods that relate to the priorities of open science engagement. The Council's international funding programmes – on Transformations to Sustainability and Leading Integrated Research for Agenda 2030 in Africa – support trans-disciplinary approaches to open, engaged science. The ISC works actively at the global and regional science-policy interface, co-leading (together with the World Federation of Engineering Organisations) the UN Major Group for Science and Technology. The International Network for Government Science Advice (INGSA) operates under the auspices of the ISC.

7. Infrastructures of Open Science

7.1 The Tools

In a world where digital processes dominate the creation, dissemination and communication of data, information and knowledge, access to digital tools is a necessary means of engagement with science, whether by citizens, scientists or other societal stakeholders. There are three major challenges:

- to national science systems in providing the necessary computational and communication tools, together with the policies, standards, processes, skills and relationships that are necessary to support open science in all its aspects;
- to the disciplines of science in embedding open science practices in ways of working that are well-adapted to the needs of the discipline;
- to scientists and societal stakeholders in developing engagement processes across the science/society interface.

All need access to "soft infrastructures" of policies, processes, skills and relationships, and "hard infrastructures" of computational and communication devices and the networks that link them together.

7.2 Open Science Commons

Many of the diverse functions and skills that are required to sustain effective open science in an interconnected, data-rich era require high levels of coordination, provision and expertise. It has proved efficient to scale up efforts to support a whole community, whether local, disciplinary, national or multi-national, so that community members are able to share costs and benefits. So called open science "commons" or "platforms" have developed to provide the functions in 7.1 as part of more or less seamless service provision, whether for some or all of IT infrastructure, high-level analytic and Artificial Intelligence procedures, access to scientific literature, thematic science priorities or community engagement.

The European Open Science Cloud (EOSC) [46] and the Australian Research Data Commons [47] are examples of multi-disciplinary commons, the first operating at a multi-national level, the second at a national level. Both are primarily directed towards the stimulation of open science practices amongst researchers, interactions with industry and the provision of the infrastructures needed to support these activities. EOSC extends its scope to include the practices of citizen science.

There are growing numbers of platforms or commons that provide these services at disciplinary or sub-disciplinary level, either internationally or regionally, such as in crystallography [48], political science [49], digital humanities [50], life sciences [51, 52] and astronomy [53], that have emerged from, are based in or are supported by international scientific unions and associations or funders. Most have primary purposes of ingesting, evaluating and publishing scientific data, information and publications in accessible and trustworthy databases at no cost to individual member depositors and users.

ELIXIR [51] is an example of a discipline-based platform that brings together life science resources from across Europe. These resources include databases, software tools, training materials, cloud storage and supercomputers. ELIXIR's goal is to coordinate these resources so that they form a single infrastructure that makes it easier for scientists to find and share data, exchange expertise, and agree on best practices. It includes 23 national members and over 220 research organisations, with an operational structure based on a series of integrated platforms: a *Compute Platform* for access, storage, transfer and analysis of large amounts of life science data; a *Data Platform* that supports the linkages between data and literature and ensures interoperability a *Tools Platform* that helps researchers to find the best software to analyse their data; and an *Interoperability Platform* that establishes Europe-wide standards, making different data sets easier to compare and analyse.

These examples of how open science is now being practiced and planned reflect the beginning of the next stage in the open science saga (8), when the benefits that have long been claimed for open science begin to be realized, in both the practice and application. Such demonstrations of scientific utility are the most powerful drivers of enthusiasm and commitment to open science.

7.3 Recommendations

a) National Science Systems **s**hould consider how best to ensure the provision of the "hard" and "soft" infrastructures needed to support an effective open science system. There is potential benefit, particularly for low- and middle-income countries, in joint strategies for shared, multi-national, regional open science platforms and the programme funding needed to motivate scientists to use them. Funding infrastructure is not as glamorous as funding cutting edge science, but it is a vital investment in the future of science.
b) Universities and Institutions should prioritize the provision of necessary local infrastructure and of research management support by expert staff.
c) The unions and associations of international science should investigate the potential to develop disciplinary commons or platforms to support their science. Interoperability should be an important consideration.

The International Science Council was centrally involved in initiating and continues to be a major supporter of the developing African Open Science Platform, which aims to create a platform of hardware and software that will support scientists and other societal actors in using modern resources to maximize scientific, social and economic benefit (see 8.2).

8. Global Inclusion

Given the global dimensions of modern science, open science must also operate at the global level. Most countries have open science initiatives within their science community, and in many, governments have adopted policies, processes and infrastructural investments designed to support open science. But open science must be globally inclusive if it is to be globally effective, and relatively poorly funded science systems in low- and middle-income countries struggle to attain the level of capability required to ensure such global inter-operation. It is here that bodies such as the ISC and UNESCO have particular responsibilities.

8.1 A North-South Contrast

It is instructive to compare ELIXIR [51] with the example of a platform in the same field of the life sciences, with a similar operating model, but operating in Africa amongst science systems that are less well-endowed than in Europe. The Pan African Bioinformatics Network for Human Heredity and Health, H3ABioNet [52] was established to develop bioinformatics capacity in Africa and specifically to support genomic data analysis by H3Africa researchers across the continent. It develops human capacity through training and support for data analysis, facilitates access to informatics infrastructure by developing or providing access to pipelines and tools for human, microbiome and pathogen genomic data analysis. Its mandate is to develop and roll out a coordinated bioinformatics research infrastructure that is tightly coupled to a sophisticated pan-African bioinformatics training programme [54]. The network is made up of 30 nodes across 15 African countries.

The contrast with ELIXIR is striking. The two have analogous purposes, but H3ABioNet has to cope with frequent power outages, poor internet connectivity for data access, transfer and remote computing, lack of significant computing infrastructure for data storage and processing, lack of bioinformatics skills in clinical genetics and genomics teams performing genomics research, and disparate pockets of bioinformatics expertise across the continent. ELIXIR can depend on high levels of computational, networking and cloud capacities that are provided by European states and the European Union as a matter of course for their science systems, whereas H3ABioNet has to confront these issues without external support and throughout its network, and to perennially make the case for their development. With ELIXIR, the case is already accepted at national and European Union levels such that their requests for development are accepted as parts of ongoing science system planning.

8.2 Bridging the Divide

This divide between global north and global south needs to be bridged [55]. A fractured international science community is at least sub-optimal. The bulk of global knowledge on the internet comes from the USA, Canada, Europe, China, Australia and Japan. The historically eminent journals of the global north that are largely in commercial hands tend to dominate global attention to the detriment of the south. It is vitally important for the south to be able to negotiate a point of entry into this system at affordable cost in order to participate in the global nexus of knowledge, information, innovation and exchange. Open access to the record of science at affordable cost is fundamental and essential. Open access is currently an exclusive club, dominated by a few developed countries [56].

Unless the countries of the global south can create more content, content from the global north, reflecting its own preoccupations, will increasingly displace southern perspectives and priorities that need to be expressed as distinctive contributions to international science. This is not an argument to the effect that physics changes when crossing national boundaries, but that international science needs diverse voices if it is to be globally relevant and effective. For example, despite Africa's surging interest in the Internet and other digital computational technologies [57], its participation in the creation of knowledge is negligible in comparison to the global north. A landscape survey by the Academy of Science South Africa (ASSAf) on open science/open data initiatives in Africa [58] reported an estimate of around "0.74% of global scientific knowledge" as Africa's contribution, although Africa has 17% of global population. The African Journal Online (AJOL) [55] laments that "mainly due to difficulties of accessing them, African-published research papers have been under-utilized, under-valued and under-cited in both the international and the African research arenas".

This being said, there are major initiatives under way. In Africa, an African Open Science Platform [59] is being implemented, coordinated by the National Research Foundation of South Africa. The AOSP is being built on a federated hardware, communications and software infrastructure, including policies and enabling practices to support open science in the digital era. It will also include a network that supports scientists and other societal actors in accumulating and using modern data resources in a transdisciplinary mode to maximize scientific, social and economic benefit. The Platform is in part a response to an African Union Report on Science, Technology and Innovation [60], which identifies two important structural weaknesses in African science: the absence of critical masses of researchers in key research areas, and very low level of intra-African research collaboration. The Platform will be a means of creating virtual critical masses and stimulating intra-African collaboration through the creation of pan-African research programmes that advance key issues for Africa through data-intensive science. The AOSP has the potential to help energize African science through an open science model and to develop an influential, distinctive African voice that is able to make a stronger contribution to the international scientific endeavour. The Platform is an initiative that is beginning to inspire emulation in South-East Asia [61] and Latin America, with the potential to enhance south-south collaboration and voice, to global benefit.

8.3 Open Science and Indigenous Knowledge

The principles guiding Open science must respect the rights and interests of indigenous peoples as expressed in the *United Nations Declaration on the Rights of Indigenous Peoples*[4] (UNDRIP) especially Article 18 which provides indigenous peoples with the have the right *to participate in decision-making in matters which would affect their rights, through representatives chosen by themselves in accordance with their own procedures, as well as to maintain and develop their own indigenous decision-making institutions*. Open science must also accept sensitivity to and acknowledgement of the historical context leading to marginalization of indigenous communities. It must not be an excuse for the theft of their resources and traditional knowledge. It follows that effective equitable participation and decision making by indigenous peoples must be a prerequisite in any scientific endeavour that directly affects them or makes use of their traditional lands or knowledge.

Recognition of the role of indigenous data sovereignty in the context of open data and open science is likewise implicit in principles supporting efforts to promote open data. Such efforts acknowledge the right of Indigenous peoples to govern and make decisions on the custodianship, ownership and administration of data on traditional knowledge and on their lands, and resources. This recognition also strives to understand that to indigenous peoples, open science and open data is not a simple binary issue and that many challenges remain in ensuring their full participation and prior and informed consent regarding access to and use of their traditional knowledge and information resources.

8.4 A Global Open Science Commons?

The emergence of self-organising discipline or regionally based open science commons begs the question whether it is timely to consider global dimensions. Are there ways in which regionally based platforms could cooperate in a relatively seamless fashion? Are there ways in which discipline-based platforms could interoperate? Are there principles and conventions that should be promoted and established globally? The ISC is exploring these questions with its membership and partners as a basis for understanding whether there are global actions that would be beneficial and tractable. In addressing these crucial issues, the Council will look towards UNESCO for strong support.

8.5 Recommendations

a) Equitable access to the record of science, both by authors and by readers, is an international priority. It is essential that the international science community and its funders seek and implement mechanisms through which this could be achieved.

b) National Science Systems should perennially make the case to government for investment in hard and soft infrastructures and open science policies and processes as essential elements of national intellectual infrastructure for the 21st century and the socio-economic benefits that they create.

[4] *United Nations Declaration on the Rights of Indigenous Peoples* (United Nations Resolution A/RES/61/295) (URL: https://undocs.org/A/RES/61/295)

c) International scientific unions and associations should collaborate with the ISC in seeking ways to support their colleagues in low- and middle-income countries in developing their capacities in open science.
d) The rights of indigenous people over their traditional knowledge, as expressed in the UN Declaration[5] should not be infringed in open science practices.
e) The ISC and UNESCO should discuss, together with other international representative bodies for science, whether there is potential for benefit in developing a form of global open science commons, and if so, how this might best be done.

In addition to its support for the African Open Science Platform, the Council has a programme on open science in the global south, which works with members and partners in Latin America and the Caribbean, Africa and the Asia-Pacific region to promote and support open science in these regions and to mutual benefit.

9. Limitations of and barriers to open science

It is important to differentiate between appropriate boundaries to openness and barriers that can impede otherwise desirable open flows of ideas and information. Such barriers occur within science systems, within society, and at the interface between them.

9.1 Boundaries of openness

There are limitations on openness, which are justifiable on the basis of safety, security, privacy and wellbeing, of both individuals and groups. How are these limitations on openness to be observed in practice? Some argue that openness should be the default position [62], that there should be an initial presumption of openness that can only legitimately be set aside if openness would infringe norms of safety, security or privacy. Others have argued for "as open as possible as closed as necessary" [63], which does not put the same onus on the researcher to demonstrate that the public interest is served by an exception. In this case, the initial position might be to presume that the material in question is closed; a weaker position than openness by default. Moreover, who determines what is possible and what is necessary?

9.2 Safety and Security

Open access to scientific results or to scientific data can create hazards through the potential for "dual use". It is important to ensure that such results are held safely (protected against unintended incidents) and securely (protected against deliberate attack). However, it is the nature of scientific discovery that its eventual use cannot be foreseen. Almost any research can create dual use, with potential risks as well as benefits. Research cannot necessarily be regulated before its dual-use nature becomes apparent. It is a dilemma that applies both to the publication of scientific findings and the release of data.

An instructive example relates to the H5N1 avian flu virus that rarely infects humans and does not spread easily from person to person. There is ongoing concern that the virus could evolve into a form transmissible to humans, thereby creating a serious global public health threat, so that research on factors that can affect the transmissibility of the H5N1 virus is vital in understanding this threat. But information that helps understand a threat and helps with prevention can also be misused for harmful purposes. This dilemma arose in 2003 with the submission of manuscripts for publication which described laboratory experiments showing that the H5N1 virus has greater potential than previously believed to be transmitted to mammals, including humans. The dilemma was resolved by an agreement between the authors and the editors of the journals involved. They agreed that the general conclusions should be published, with significant potential benefit to the global influenza surveillance and research communities, but that the details that could enable replication of the experiments by those who might seek to do harm should not be [64]. It was an instructive example of balance in an issue of dual use.

9.3 Privacy

Digital technologies are central to the evolution of open science, but raise many concerns about privacy and data use, with the need for greater accountability, intelligibility, and accessibility [64.1]. The power of automated reasoning also raises concerns about human autonomy which require a clearer understanding of the varied nature of human-computer interactions. It is an interface that requires the attention of legal scholars and ethicists in order to maximize benefits to human well-being and minimize the potential for harm, particularly in such areas as healthcare, education, governance, social development, and media and entertainment [65]. The maintenance of private spaces is threatened in the rapidly evolving field of automated learning technologies, where well-conceived data governance is an urgent priority at national and international levels if public trust in the beneficial potential of these technologies and of the utility and safety of open processes is to be maintained (see sections 5.3 and 5.4).

9.4 Motivations and incentives amongst researchers

The motivations of researchers and the metrics that are used to evaluate career progress are key determinants of the extent to which researchers are willing to adapt to open science practices [64.2]**.** The attainment of affordable open access to the record of science will depend upon the extent to which researchers, institutions and funders are prepared to grapple with these issues in the ways suggested in section 4. For open data, the willingness of individual researchers and their groups to adopt open practices is complex. There is an unwillingness in some even to release data that relates to articles submitted for publication, with examples of authors withdrawing submitted articles rather than acquiescing to an editor's request for submission of relevant data [66]. There appears to be a general tendency for researchers to hoard their data, partly because of the onerous demands of FAIR data submission, partly because of a desire to retain data so that it can be continually mined for publications and possibly because of a reluctance to expose their results to open scrutiny. It is suggested that these barriers will only be overcome as the scientific community, universities and funders progressively accept that doing so is in the interests of science, and as publishers accept a responsibility to require open deposition of data that is associated with a published truth claim (see section 5).

9.5 Openness versus intellectual property?

The latter decades of the 21st century saw growing governmental encouragement for universities to exploit the results of publicly-funded academic research for its commercial potential. It has been the view that much commercial value is locked up in such research, and that it is the university's responsibility to help unlock it [67]. Such views imported the concept of intellectual property (vested in the researcher or the university) into an environment where this had appeared antithetical to prevailing values, as it does now to the concept of open science.

Governments fund academic research for a variety of purposes, one of which is to bring tangible national economic benefit. Exploitation of intellectual property is one route to benefit through private exploitation of knowledge to create competitive new products or services. Publicly funded academic research can be used to create private benefit in ways that serve the public good, but this should be balanced against the aggregate benefits that can accrue when knowledge is broadly available to be exploited creatively by a wide variety of users. As the investment for most academic research is from public funds, the test for the preferred option should be that which delivers greatest public benefit. This is a difficult choice however, not only because of the uncertainty of commercial gain, but also because gains to the individual and their institution are not necessarily synonymous with the wider public gain. It should certainly not be the case that whatever can be commercialized should be commercialized.

Assertion of ownership need not however restrict access. Patents are designed to create a frame that can resolve the apparent conflict between open science and intellectual property. They reward the innovator by granting a quasi-monopoly, an aspect of patenting that is well-understood. In order to acquire a patent, applicants must cite the prior "art" that allowed them to develop this new knowledge but they must fully disclose the new knowledge underpinning the patent. This allows others to access the new knowledge and to build upon it, and thereby facilitate wider diffusion of new knowledge. It is a process compatible with open access as there is open and global access to the patent register.

The digital domain is one in which traditional legalities are proving increasingly difficult to apply, and reform is overdue. Copying of digital material has become so easy, whether of publications or data, that it has undermined the effectiveness of traditional copyright IP, and created new categories of ownership. The GNU General Public Licence and Creative Commons ShareALike licences have the explicit aim of maintaining the free flow of information[5]. The inappropriateness of conventional copyright to the progress of science in the digital era is reflected in the widespread flouting of copyright law by scientists making their work freely available and by others in copying it even when they have gifted copyright to publishers.

9.6 The Private Sector

It might seem that the natural boundary of openness should coincide with the boundary between publicly funded and privately funded research; with private business retaining ownership and publicly funded researchers practising openness. However, commercial exploitation of some publicly funded research is in the public interest and may require limitations on openness, and some commercial business models thrive on openness. An ever-present danger however is that of the potential for large scale privatisation of knowledge, which has already been advanced through commercial publishers in placing much of the record of science behind high pay-walls.

The public/private interface is not a good guide to open/closed approaches to knowledge. Just as many universities engaging in commercial activities have come to exercise strongly protective control over some parts of their research findings, so do a number of companies whose operation depends on access to scientific knowledge, often with strong links to university research, increasingly disseminate their scientific knowledge openly [68].

A number of companies that are located at or near the technological frontier are moving towards an open data model. Most recently, Microsoft, which has in the past fiercely protected its technologies behind defensive ramparts, with one of its executives referring to open-source programmes as a "cancer", has joined the movement to liberate the world's data. Microsoft is launching an "Open Data Campaign" to help address the looming "data divide" and help organizations of all sizes to realize the benefits of data and the new technologies it powers. The OECD has calculated that if data were more widely exchanged, many countries could enjoy gains worth between 1% and 2.5% of GDP [69].

9.7 Resistance to Open Science

There is a very practical concern that a consequence of adopting an open science agenda in the global south would be to enhance a process whereby collaborative research between African and "northern"

[5] The GNU General Public Licence is explicit on this point: "The licences for most software and other practical works are designed to take away your freedom to share and change the works. By contrast, the GNU General Public Licence is intended to guarantee your freedom to share and change all versions of a program--to make sure it remains free software for all its users." Such licences are sometimes known as "copyleft", because they use copyright law to ensure that information remains freely shareable.

scientists has led to data migration from Africa and the loss of intellectual property, including from indigenous sources (see 8.3). Collaborations have proliferated in recent decades as international agencies have stepped up funding for research in Africa, particularly in the field of health. Yet many African scientists have often been little more than data-collectors and laboratory technicians, with no realistic path to develop as research leaders [70]. It is important that these issues are understood and that action is taken to ensure that partnerships are equal and not exploitative, both in relation to people and to data.

There are also principled arguments against open science, which may be conservative or radical [71]. The conservative critique defends the right of the individual against the collective. The radical critique [72] argues that the release of vast troves of data, papers or research results which, although potentially beneficial to science as an enterprise, exacerbates the trend towards increasing "marketization" and "corporatization" of science that disproportionately benefits large commercial interests. It argues that open science opens the door to:

- capture of publicly-funded research value by commercial platforms;
- introducing yet more "metrics" of productivity to "incentivize" scholars to work harder, and simply replace one form of game playing by another;
- focussing on system-wide progress of science, ignoring costs and benefits to individuals, whether scientists or non-scientists.

These critiques challenge the developing open science movement to resist the increasing privatisation of knowledge, to maintain or redevelop a "human centred" science and to adapt to the needs of different communities, whether small or large.

9.8 Recommendations

a) Collaborations between more and less privileged scientists should be based on an equality of respect and benefit. A UNESCO brokered commitment to the latter principle would be appropriate.
b) There should be consideration at international and national levels about regulatory and governance arrangements for the acquisition and use of scientific data, covering such issues as the privacy and the use of artificial intelligence technologies.
c) Universities sometimes face a difficult dilemma when publicly funded scientific results have *prima facie* commercial potential. They may choose to commercialize them to their own financial benefit, or release them openly into the public domain for potentially greater public benefit. The current efforts by universities to find a vaccine for Covid-19 may pose just such a dilemma. It is an issue that needs to be debated nationally and internationally.
d) There should be perennial discussion between public and private sectors about the ways in which the scope of open science principles and priorities can be enlarged and mutually shared.

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Appendix: Answers to specific questions from UNESCO

Many of the questions below are answered in greater detail in the recommendations at the end of sections 4 to 9 (see 4.4, 5.5, 6.4, 7.3, 8.4, 9.7). The arguments that underlie the following issues are to be found in the text as referenced.

a) Definition of open science

Open science is *science that is open to scrutiny and challenge, and to the knowledge needs and interests of wider publics. It makes the record of science, its evolving stock of knowledge, ideas and possibilities accessible and free to all, irrespective of geography, gender, ethnicity or financial circumstance. It makes the data and evidence of science accessible and re-usable by all, subject to constraints of safety, security and privacy. It is open to engagement with other societal actors in the common pursuit of new knowledge, and to support humanity in achieving sustainable and equitable life on planet Earth.* (3)

b) Elements of open science (scope)

- Open access to the record of science (4.4)
- Open data (5.5)
- Engagement with society (6.4)
- Digital enablement (7.3)

c) Actors of open science

- Scientists
- Their institutions (universities, institutes, private sector science)
- Funders of science
- International scientific unions and associations
- National academies
- International, representative scientific organizations like the ISC, the IAP and others
- UN bodies
- Scientific publishers
- Citizens and NGOs

d) Guiding principles for open science implementation

It is not clear what question is being asked here. The ISC offers the following principles:

- Open science should evolve in ways that are inclusive of geography/nationality, gender, institution, ethnicity, and financial standing.
- It should respect the motivations of different stakeholders as much as possible whilst adhering to essential priorities.
- It should be promoted as an enabling process, of benefit to all stakeholders.
- There are two areas where strong principles should be applied: open access to the record of science, and open, concurrent deposition of the evidence/data associated with a published scientific truth claim.

e) Opportunities of open science

Open science offers new ways of safeguarding scientific rigour, relevance and responsibility.
Achievement of the SDGs by 2030 will depend on the practice of open science.
Open science commons or platforms, particularly those that work at disciplinary or topic level, have proven to be a powerful stimulators of behaviour. They bring strong benefits to participants and clearly illustrate the value of open science processes. (7.3c)

f) Challenges for open science and how to overcome them

There are three major challenges, without resolution of which the open science movement could founder:

- Researchers to adopt open science principles and practices. Action for UNESCO – enunciate open science as a necessary value for science in the 21st century. It will be difficult to replace existing incentives for researcher behaviour, which militates against open science practices. An expression of the values inherent in open science could be UNESCO's most valuable contribution.
- Open the record of science for access by all. Action for UNESCO – become a partner with the International Science Council in its programme that has this aim.
- Require evidence/data to be concurrently deposited with a published scientific truth claim. Action for UNESCO – articulate this as an essential part of the scientific process.

And there is a broader geopolitical challenge, now presented in countries like the US but increasingly in Europe on issues of "research security". It is an issue that the UN is probably best placed to address.

g) Incentives for open science

- The current pattern of incentives for researchers and their institutions tends to work against open science practices.
- Work on alt metrics should be promoted and the terms of the San Francisco Declaration should be observed by all institutions and endorsed funders.
- The most powerful incentives are research programmes that require interdisciplinary, open science collaboration.

h) Infrastructure and capacity needs

Open science has great potential to benefit the scientific effort of the middle- and low-income countries of the global south as a means of creating virtual critical masses and enhancing south-south collaboration. However, these countries have limited ability to finance the hard and soft infrastructures that are vital in sustaining open science practices. A UNESCO role in encouraging action by major international funders, such as the World Bank, could be of great significance.

i) Collaborations and networking needs

- Support open science platforms
- Offer UNESCO's convening power in working with representative bodies of science to discuss practical global activities in support of open science

j) Financial considerations

See h) above.

k) Policy recommendations

- Open access to the record of science
- Open data
- Open to society

l) Best practices and lessons learned

Best practice is currently exhibited by the many examples of disciplinary commons that are referred to in the above paper. The essential lesson is that open science flourishes when it is adopted as a demonstrably beneficial norm of behaviour by practicing scientists. Top-down organisations tend to be in the early stage of development (e.g. EOSC, AOSP). Their success is likely to be determined by the extent to which practising researchers recognize that they deliver benefit. The development of the African Open Science Platform holds out the opportunity to demonstrate best practice through a major African initiative. .

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