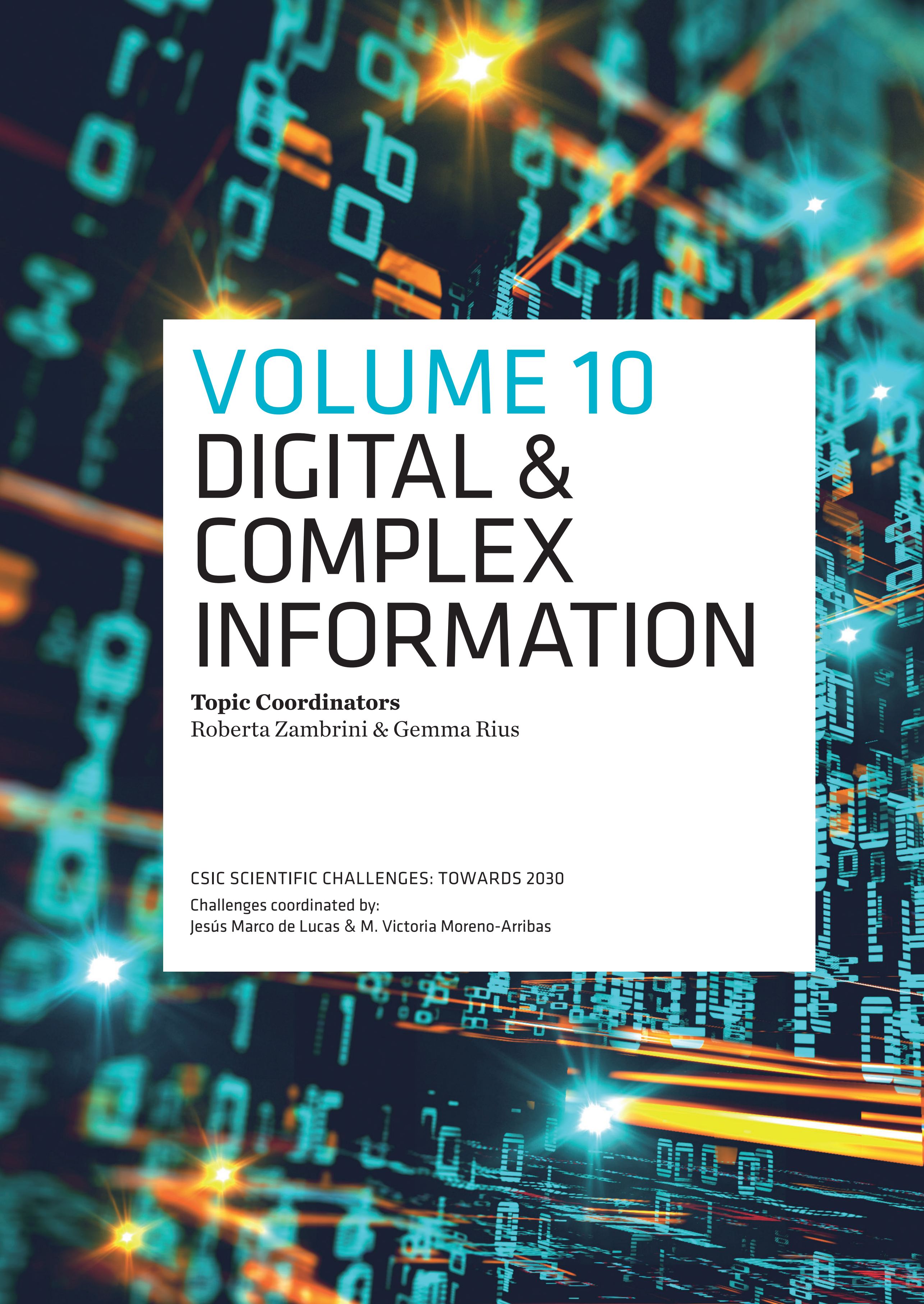

VOLUME 10
DIGITAL & COMPLEX INFORMATION

Topic Coordinators
Roberta Zambrini & Gemma Rius

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030
Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1 *New Foundations for a Sustainable Global Society*
2 *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3 *Genome & Epigenetics*
4 *Challenges in Biomedicine and Health*
5 *Brain, Mind & Behaviour*
6 *Sustainable Primary Production*
7 *Global Change Impacts*
8 *Clean, Safe and Efficient Energy*
9 *Understanding the Basic Components of the Universe, its Structure and Evolution*
10 *Digital and Complex Information*
11 *Artificial Intelligence, Robotics and Data Science*
12 *Our Future? Space, Colonization and Exploration*
13 *Ocean Science Challenges for 2030*
14 *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

Volume 10
Digital & Complex Information

Topic Coordinators
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Instituto de Astrofísica de Andalucía (IAA, CSIC)
Instituto de Análisis Económico (IAE, CSIC)
Instituto de Agricultura Sostenible (IAS, CSIC)
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ABSTRACT

Information, gathered, stored, processed and transmitted, is the cornerstone of the present era and shapes every aspect our daily life, thus permeating cultural and social deep changes. A multi and cross-disciplinary approach is needed to cover all present challenges of the Information Age, ranging from both the more technological aspects to the social ones. This duality is reflected in the title of this volume, Digital and Complex Information. The current Digital Transformation is enabled by developments in physics and engineering and entails several fields including electronics, optics, material science, and quantum technologies. Nowadays challenges include sustainable and energy efficient electronics, integrated photonics with new functionalities, quantum computing and machine learning, and operation within the Internet of Things. Nonetheless the Digital world generates an ever-increasing amount of data in which security and trust play a critical role. The advances in digital technologies call for a new scientific research approach: an Open Science, reproducible, interoperable and accessible. New avenues are open in how we deal with Humanities and with individual/social security and rights, within digital citizenship. This is the broad spectrum of challenges that drives research across about the 40 CSIC institutes in line with the latest developments in digitalization worldwide.

DIGITAL & COMPLEX INFORMATION

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WHAT IS "DIGITAL AND COMPLEX INFORMATION"?

Information is one of the main traits of the contemporary era. Indeed, there are many perspectives to define the present times, such as the Digital Age, the Big Data era, the Fourth Industrial Revolution, the fourth Paradigm of science, and in all of them information, gathered, stored, processed and transmitted, plays a key role. Technological developments in the last decades such as powerful computers, cheaper and miniaturized solutions as smartphones, massive optical communication, or the Internet, to name a few, have enabled this shift to the Information Age. This shift has driven daily life, cultural and social deep changes, in work and personal activities, on access to knowledge, information spreading, altering interpersonal relations or the way we interact in public and private sphere, in economy and politics, paving the way to globalization, ...

A multi- and cross-disciplinary approach is needed to cover all present challenges of the Information age, for they range from most scientific and technological aspects to complex social and cultural ones, and they are all deeply interconnected. This document is the result of a collective effort by CSIC scientists to identify them and envision a consensus roadmap in the context of Digital and Complex Information.

Digital information refers to all engineering and physical aspects associated to sensing, storage, computation and transmission of data. The term 'digital' is here used beyond its binary, discrete nature, specific connotations that reduce it to the opposed of 'analogue'. In a broad sense Digital here rather identifies all involved scientific and technological advances driving the current Digital Transformation in physics and engineering and entails several fields including electronics, photonics, material science, and quantum technologies.

Beyond the technical aspects, Digital Information is the cornerstone of the present era and the Digital world generates an ever-increasing amount of data and requires the broadest approach, in which all knowledge disciplines are actually involved. *Complex* information refers to all aspects inter-dependencies, needing a new paradigm blurring the traditional borders between 'hard' and 'soft' sciences, where the advances in digital technologies pose new challenges in how we deal with Humanities in a broad sense or with individual/social security and rights, for example. Furthermore, complex is also the framework of applied sets of methods to describe interconnected systems and networks

Many examples of several distinctive aspects entailed by the Digital Age come immediately to mind when writing this document during the pandemic of COVID-19: social relations, home working, distance education, remote attendance to conferences and meetings, embracing all life spheres form governmental, to professional, personal, cultural events, or commerce. Keeping worldwide activity has been possible and realized thanks to a wide toolbox of digital technologies: a plethora of software applications deployed for mobile phones and computers; fast and massive communications; secure and reliable data transmission gained an even more crucial role in most countries; from disease detection to the search for therapies and vaccine, the deployment of digital instruments or computational power have been crucial and also a challenge for the true capability of open science; furthermore, the contention measures of the pandemic sharpen the tension in democracy between citizen privacy and governmental control. These are just some of the aspects, still sufficient to have a first sight of many complementary issues entailed by Digital and Complex Information.

The importance of information as a main trait of the present era undeniably qualifies it as a key and strategic topic for the CSIC research roadmap for the next years. One can actually expect digitalization pervading all the CSIC white paper across most books. Still, there is a common set of issues and approaches that defines Digital and Complex Information as a field by itself, and demands for a unified analysis and agenda. This ranges from more technical aspects related to information as for instance computation, data storage, and communication, to the science and social handling of information aspects related for instance to culture, participation, and openness, to mention some. Complementary to this book is the volume 11. Indeed, one of the most recent and promising developments of the digital era is Artificial Intelligence addressed in a separate and complementary book of the CSIC roadmap.

INTERNATIONAL CONTEXT

The Digital Transformation is at the core of worldwide economies and society with prominent initiatives in USA and China. Beyond ICT sector and considering other traditional sectors that have been integrated with digital technology, China's digital economy size is expected to raise from less than 15% of the GDP in 2007 to 50% by 2025. North America digital transformation market figures are also continuously growing. The impact of Digital in R&D is expected to be enormous, thanks to numerous breakthrough technologies, such as genomics, nanotechnology, sensors and the Internet of Things, big data and advanced analytics, artificial intelligence, 3D printing, to mention some.

Focusing on Europe initiatives, to "make Europe fit for the digital age" is at present a core mission of the Commission work program, the Horizon Europe. In 2010, the Digital Agenda for Europe (DAE)[1] aimed to ensure a fair, open and secure digital environment, launching in 2015 the Digital Single Market Strategy to rule and foster digital economy. Further recent important steps have been the Regulation on the free flow of non-personal data, the Cybersecurity Act, the Open Data Directive and the General Data Protection Regulation. Also since 2015, the European Commission has been monitoring Member States' digital competitiveness by using the Digital Economy and Society Index (DESI)[2]. DESI is based on indicators such as broadband connectivity (from 2019 including 5G readiness), digital skills, use of the internet, digitisation of businesses, digital public services (from 2019 including online consultations and voting, medical data exchange and e-prescriptions), ICT competences (from 2019 female specialists, graduates), etc.

During the preparation of the CSIC roadmap (from February 2020),

1 Accessible at: https://www.europarl.europa.eu/factsheets/en/sheet/64/digital-agenda-for-europe
2 Accessible at: https://ec.europa.eu/digital-single-market/en/digital-economy-and-society-index-desi

several documents have been published, starting to set the digital priorities for Europe on Artificial Intelligence and Big Data. The roadmap for the next five years on digitalization in Europe[3] is centred on 3 main objectives: technology for people, ensuring digital solutions for engaging all society in terms of skills and ensuring technological sovereignty; technology for economy, fair and competitive; and envisioning a digital transformation which enhances democratic values and contributes to a sustainable, climate-neutral and resource-efficient economy. Several initiatives are planned including a digital development hub and white papers and strategies on quantum, block chain and supercomputing, cybersecurity, data, digital cooperation, standardization, to mention some.

These measures aim to close the digital and AI gap, within a framework based on trust and sustainability. In fact, Europe underperforms on its digital potential relative to the United States and China[4]. To scale up and close the gap, research is a priority, for the acceleration of digital transformation and AI innovation, as well as for the development of professional skills to foster and handle these technological advances. This is indeed a clear priority within Horizon Europe, the next research and innovation framework programme (2021-27), with strategic planning on 'Global Challenges and European Industrial Competitiveness' (Pillar 2) that aims at boosting key technologies and solutions underpinning EU policies and Sustainable Development Goals of the United Nations. Several Clusters have been already identified (like Health, Culture, etc...), and of course one deals with 'Digital, industry and space'. This Cluster reflects the broad perspective we have described above, including domains such as data and computing technologies (for e.g. data sharing in the common European data space or Cloud to Edge to IoT tools for European Data), digital and emerging technologies (addressing, e.g., ultra-low-power processors, electronic and photonic value-chains, multi-sensing systems, quantum as a technology paradigm shift), and a human-centred and ethical development of digital and industrial technologies (an Internet of trust, digital learning technologies, also for upskilling the workforce). Furthermore, as for the CSIC roadmap, digital means are also strategic in the other Clusters: for instance, the sixth one also deals with "Innovative governance, environmental observations and digital solutions in support of the Green Deal".

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3 EU Communication: Shaping Europe's digital future. https://ec.europa.eu/info/publications/communication-shaping-europes-digital-future_en
4 McKinsey Global Institute, Notes from the AI frontier: tackling Europe's gap in digital and AI, Discussion paper, February 2019

The Digital transformation can be achieved though innovation and research but also the reverse is true, as the digital transformation also provokes a change in the way of doing Science and generating knowledge. Several aspects are identified in a recent report of the Organisation for Economic Cooperation and Development (OECD)[5] from digital tools, to digitised scientific outputs (publications, data and computer codes) and data-driven research. At present European Open Science Cloud (EOSC) Partnership is arising as a legal entity in Europe to store, share and re-use research data and software[6].

The potential of the Digital transition is recognized as crucial and the Digital Europe programme has just announced (June 2020) a budget of 8.2 billion euros (9.2 billion in current prices) to accelerate the recovery after the Pandemic and drive the Digital Transformation of Europe, strengthening investments in supercomputing, artificial intelligence, cybersecurity, advanced digital skills, and ensuring a wide use of digital capacity across the economy and society. "Its goal is to boost Europe's competitiveness and the green transition towards climate neutrality by 2050 as well as ensure technological sovereignty"[7].

NATIONAL CONTEXT AND CSIC PERSPECTIVE

Spain ranks 11th out of 28 EU Member States in DESI 2019, with improved Connectivity and Digital Public Services, thanks to the wide availability of fast and ultrafast fixed and mobile broadband networks and to the implementation of its e-government strategy. However, still around one fifth of people in Spain is not yet online and close to half of them still does not have basic digital skills while ICT specialists are also lacking. An average tending to low performance was also reported, through independent assessment of readiness for enabling economy growth. In innovation capacity, ICT connectiveness and human skills, Spain was ranked below the EU average, while performing better in automation and digital readiness. The current Spanish Digital Agenda dates back to 2013[8] and marked the onset of the ICT roadmap in Spain. The current Government has a Ministry of Economic Affairs and Digital Transformation responsible of government policy for the digital transformation and including two secretariats, Digitalisation and Artificial Intelligence, and Telecommunications and Digital Infrastructure.

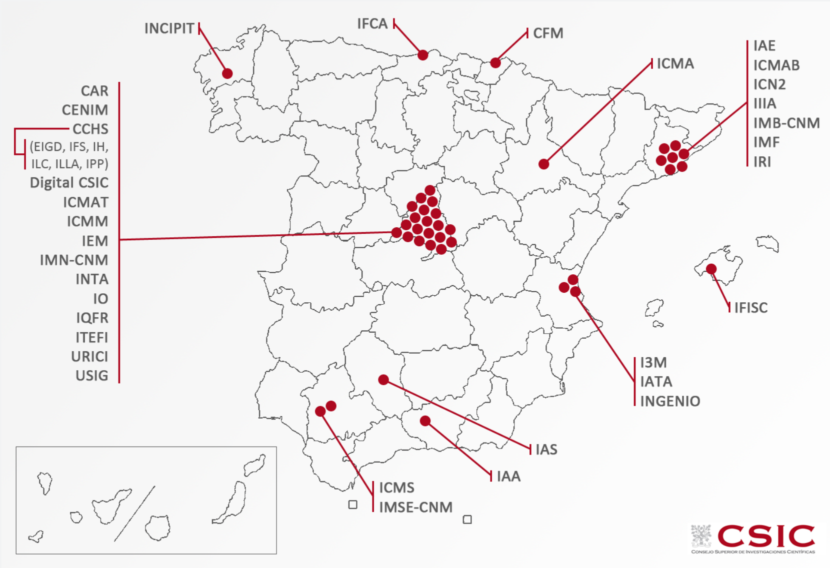
5 OECD (2020), The Digitalisation of Science, Technology and Innovation: Key Developments and Policies, OECD Publishing, Paris, https://doi.org/10.1787/b9e4a2c0en

6 Draft proposal for European Open Science Cloud (EOSC) Partnership (28 May 2020) https://ec.europa.eu/inf o/sites/info/files/researchandinnovation/funding/documents/ec_rtd_hepartnership open sciencecloudeosc.pdf

7 Accessible at: https://ec.europa.eu/digital-single-market/en/news/digital-europe-programme-proposed -eu82-billion-funding-2021-2027

8 Accessible at: https://www.plantl.gob.es/digital-agenda/Paginas/digital-agenda-spain.aspx

FIGURE 1– Map with the acronyms of the 38 CSIC institutes authoring the T10: "Digital and Complex Information"



Fundamental research and technological development in several fields is at the basis of digitalization. Being the largest research body in Spain, CSIC is actually leading several of these fields. In the T10 of the CSIC roadmap, eight main challenges have been identified, including hard sciences such as Electronics, Photonics and Quantum Computing, applications such as Internet of Things, key issues such as Security and Open Research and changes of paradigms in Digital Humanities and Citizenship. Their respective key challenges and their specific impact are summarized as follows, where some cross-cutting aspects, connections and common strategic goals can be identified.

Intelligent and sustainable electronics – In the field of Electronics a main challenge is to improve performance by achieving almost zero power consumption. Indeed the environmental footprint of the ICT sector is estimated to be between 5 to 9% of the world's total electricity use and more than 2% of all emissions[9]. ICT equipment also requires Ecodesign, to last longer, to be properly maintained, to contain recycled material and to be easily dismantled

9 A European strategy for data https://eurlex.europa.eu/legalcontent/EN/T XT/?uri=CELEX:52020DC0066

and recycled. This circular electronic initiative is planned for 2021 by the European Commission[10]. The main goals set by CSIC researchers of eighth institutes are the technological advance towards almost zero power electronics and the massive integration of sensors in a sustainable way. Main research lines focus on new structures in semiconductors and also new materials for magnetolectronics and spintronics, as well as new devices based on analogue computation. Sensors play a key role in the digital transformation and improving their capability requires advances ranging from materials to architectures.

Advanced Photonics – Complementary tech for the digital transformation comes from Photonics. Research carried on in 15 CSIC research institutes and centers covers a broad spectrum but three main key scientific challenges have been identified. The first one is about materials allowing to interface optical and electronic information and signals, and explores solutions ranging from advanced optical materials to compact two-dimensional (2D) heterostructures and designs by advanced laser technology. A second main challenge is to achieve photonic integrated circuits and devices with more functionalities, flat, using spin-polarized modes, efficient at sub-wavelength, enabling novel light sources, and integrated with complex bio-environments. A further challenge focus on optical networks building on advances in photonic integration and optical fiber technologies to achieve complex structures with potential applications in sensing, optical communications, micro-wave photonics, and information processing for classical and quantum applications.

Quantum Computation– Among a broader spectrum of research on fundamental quantum physics across several institutes at CSIC, a main common challenge has been identified in quantum computation. We anticipate that quantum communications are instead discussed as part of the challenge of Trust and Security in the Digital Information. The activity of colleagues in nine institutes contribute to different aspects of quantum computation. A first challenge is related to computational tasks with goals in the context of algorithms that can display a quantum advantage, solving specific problems, for instance in quantum chemistry. Non-conventional computation approaches are also promising in the context of machine learning, as in neural networks and reservoir computing. The potential of complex mathematical tools such as tensor networks is also explored. A second challenge is to achieve resilient

10 Accesible at: https://ec.europa.eu/info/files/communication-shaping-europes-digital-future_en

FIGURE 2–Word cloud generated from all the T10 challenges.

qubits and scalable architectures for quantum processors, with both experimental and theoretical contributions. The former pursue molecular based and semiconductor based qubits. Alternative topological qubits are theoretically developed. A further challenge is in advancing fabrication and manufacturing tools that will allow to scale the number of qubits and gates for quantum computing and simulation, and also for the development of quantum sensors.

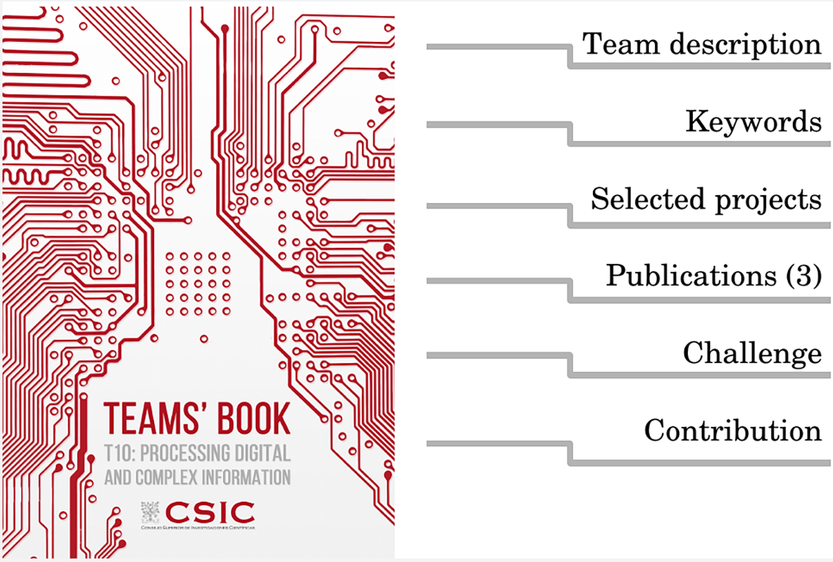
Cyber-Physical Systems and Internet of Things – A most relevant example of both push and pull effect of the deployment of advances in Digital technologies are Cyber-Physical Systems (CPS) and Internet of Things (IoT). Digital Transformation enabled by CPS and IoT impacts the whole socioeconomic spectrum, which is termed as Society and Industry 5.0. Its realization demands, pulls, the development of sensors and actuators, hardware designs and platforms, architectures and computational frameworks, as well as modelling, control and optimization, while, at the same time, e.g., new materials and novel sensing principles boosts, pushes, the progress of CPS and IoT and their potential. All these and a few other elements, both scientific and technological in nature, are the identified challenges, which are being addressed by the involved CSIC researchers for the next coming years. Smart capabilities in mobility, logistics and transportation, manufacturing or health-care are examples of sectors benefiting from disruptiveness of CPS and IoT.

Trust and Security in the Digital Information – Related to CPS and IoT, a long anticipated, yet unsolved, foundational issue of Internet democratization is its implications in terms of Trust and Security of (massively) exchanging digital information. The risks and threats of Digital Society impose higher levels of data confidentiality and integrity, while keeping availability of the Digital information. Accordingly, CSIC researchers challenge to address data storage, as well as processing, and flow of information in network communications. Their investigations range from quantum to lightweight and post-quantum cryptography for secure communications and authentication procedures, to securing data processing based on hardware devices, in line with the coordinated European initiative to, ultimately, recover the necessary control on the microelectronics technology that is used.

Open Science – The wide variety of scientific disciplines covered by the different institutes, its volume and the nation-wide span of CSIC as a single institution is a convenient setting for putting Open Science in CSIC strategic research agenda for the next years. Together with CSIC researchers, Digital CSIC can be a powerful instrument for the challenges in this new paradigm. Research results are needed to be managed, communicated, used, and reused in an open manner. Therefore, an increase in reproducibility, transparency and reliability of scientific research is expected from Open Research practices. Its implementation will, in turn, promote a better perception of the value of scientific research among society, which, addressing researcher's accountability, supports the sustainability of the scientific research ecosystem. Exemplary initiatives and use cases of the Digital power are mentioned in the areas of biodiversity, earth and marine science, astronomy and astrophysics research at CSIC.

Digital Humanities – Gathering a number of CSIC researchers investigating in disperse topics of Humanities around the central idea of Digital Humanities has actually converged into a common vision. Digital Humanities contribute to closing the gap between engineering and art, science and literature. Challenges go from the production and standardization of meaningful and interoperable computationally processed data, to creating hybrid research profiles, to technical support laboratories, as well as, dedicated information systems for managing and distributing research data and dissemination platforms for the general public.

FIGURE 3–Cover of the Teams' Survey and descriptive items for each team.



Digital Citizenship – Fundamental changes caused by emerging Digital Citizenship are another powerful example of why and how research groups from diverse disciplines such as artificial intelligence, mathematics, anthropology, philosophy, economics, sociology, political science and geographical information technology can investigate towards common goals and challenge solutions. News relationship in political participation, and public sphere aspects such as organization, responsibility, transparency and inclusiveness, or the very structures of democracy are to be considered. These challenges will be addressed by CSIC researchers in three different hubs, which are, Digital Democracy, Big Data and Human Rights and Digital Activism.

MODUS OPERANDI AND T10 TEAMS' SURVEY

The realization of this book has been a choral work with a strong commitment of the CSIC community involved in research about the Digital topics. In late November, the two coordinators launched an open call inviting all CSIC scientists to include in a public questionnaire their research topics and challenging ideas for the research on Digitalization for the coming 10-50 years.

All the information has been compiled into the Teams Survey document[11]. By mid-December 2019, we had received already several contributions and the first meeting was held at IFISC in mid-January 2020, where in spite of the short notice about 30 researchers could join and we could already nominate some coordinators for the main challenges. Following this meeting, there was a second general call to the whole CSIC researchers' community, which allowed us to incorporate a significant number of groups. At the time of completion of the final draft, the mailing list has reached up to more than 240 contact e-mails, corresponding to researchers of about 40 institutes. The eight sections of the T10 have been developed during the following five months through virtual meetings and using digital platforms (Conecta.csic, SACO, overleaf, etc...) thanks to the effort of 16 coordinators and many colleagues, of several institutes and areas, that achieved a coherent vision in each challenge.

IMPACT AND NEEDED RESOURCES

Beyond the highlighted broad impact of the Digital Transformation and worldwide initiatives, which is the expected impact of this initiative within CSIC? There is a specific and essential trait in this strategic topic: the richness and variety of the challenges in Digital and Complex Information, embracing a strongly heterogeneous and large fraction of Institutes of CSIC. From anthropology to quantum technologies, from humanities to electronics, from geography to photonics, to mention some, the included contributions unavoidably join teams that neither had interacted nor known each other before this White Paper initiative. The heterogeneity of the challenges has been allowed by the CSIC diversified research fields and of course by the broad call to participate.

A first major outcome of this initiative has been indeed to open a dialog, to foster new links between researchers across institutes and joining a 'team of teams' in Digital and Complex Information, "aware" of the variety of challenges in this topics. Still, this is just a seed, an initial step that needs to be nurtured. In order to face this roadmap challenges, to pursue and achieve the goals of Digital and Complex Information, it is necessary a continued support action through national initiatives, providing support to this network.

11 The T10 TEAMS' SURVEY is available at https://cloud.ifisc.uib-csic.es/nextcloud/index.php/s/AYbk6z3pNwwBN7j and also in DIGITAL.CSIC.

An aspect to consider is that actually CSIC lacks of any kind of institute or other form of transverse structure dedicated to the research challenges of Digital and Complex Information described in this book. There are several institutes in Electronics, or Optics, or Artificial Intelligence, or Robotics, or Complex Systems, or Philosophy, to mention few, dispersed both in research areas and geographically (see Fig.1). Of course there is also Digital.CSIC, the CSIC online open access repository. But there is no research institute, nor any other structure of hub, with a multi-disciplinary focus on Digitalization in the broad sense described in this book. Therefore, given the importance of an ample approach to digitalization, a main question is how to create a coordinated if not focused initiative.

In each of the eight challenges, specific strategic initiatives have been identified by the coordinators. In terms of resources, research and technical personnel, as well as funding to foster collaborations, are the most common. Beyond the eighth challenges, a global CSIC strategy for the Digital Transformation should be supported through an ample initiative. At EU level several actions with such an ample focus (and conspicuous funding) are in place, as previously described. A CSIC initiative to promote a hub on Digital and Complex Information could be studied. The preliminary step would be a broad multi and cross-disciplinary workshop involving the T10 teams, as well as national and international stakeholders. This could pave the way towards a T10 network, platform or hub initiative that should be pursued in a short term.

CHALLENGE 1

ABSTRACT

This section is centered on the research actions addressed to increase efficiency in computation, to achieve low energy consumption, to reduce electronic material waste and to be less harmful to the environment. In order to achieve these objectives, the projected research strategies are addressed to combine disruptive technology with ground-breaking design innovations in devices and systems.

KEYWORDS

zero-power electronics
memory-centric architectures
neuromorphic computing
sensor systems

CHALLENGE 1

INTELLIGENT AND SUSTAINABLE ELECTRONIC DEVICES AND SYSTEMS

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1. EXECUTIVE SUMMARY

Nowadays, societies are being transformed to operate digitally. New devices are being incorporated into our daily dynamics, providing a high level of connectivity at work and at home. In this sense, both industrial production and society environment are being transformed by massive sensor integration.

Beyond this, the monitoring process has also been extended to the whole life cycle of products and infrastructures to contribute to the development of the European Circular Economy Strategy.

Along the decades, this process has been supported by the continuous increase of the computing performance, reinforced by a powerful development model based on hardware abstraction, and a completely new world of low-cost electronic products with lifecycles ranging from hours to years.

However, the inefficiency of this development model in terms of sustainability and the redefinition of the meaning of Moore's Law introduce challenges that threaten this digitalization strategy. Consequently, it is necessary to integrate the digitalization technology development in this Circular Economy Strategy. In this sense, both scaling and energy-efficiency are driving the research on beyond-CMOS devices.

This chapter is centered on research actions in electronics aiming to increase efficiency in computation, to decrease energy consumption, to reduce electronic material waste and to, ultimately, minimize its environmental impact.

The chapter is addressing two main technological drivers where CSIC has a strong position: technologies for ultra-high energy efficiency in electronics and the massive and sustainable integration of sensors. The research on emerging logic/memory devices, new computing paradigms and sensor systems takes advantage of the strong CSIC position on emerging materials for electronics such as functional oxides, 2D materials and organic materials. This capability of addressing from basic science to technological development and innovation, i.e. from low to high Technology Readiness Levels (TRL), places CSIC in a unique position for addressing the challenge referred to in this chapter.

2. INTRODUCTION AND GENERAL DESCRIPTION

Societies are being transformed to operate digitally. Citizens are increasingly required to interact digitally with businesses, service providers, banks and the various levels of government. New devices are being incorporated into our daily dynamics, providing a high level of connectivity in the home, work and social environments.

Industrial manufacturing is being massively sensed and this process of monitoring has also been extended to the whole life cycle of the product. In addition, health and infrastructures are also involved in this process, and transportation is now undergoing a revolution expanding the automation to the driving activity.

This ubiquitous digitalization involves a massive integration of sensors, a huge flow of data and requires an intensive real-time data processing capability. And, in addition, a completely new world of low-cost electronic products with lifecycles on average ranging from hours to months have been brought to the market.

Along the last decades this process has been supported by the continuous increase of the computing performance and by a powerful development model based on hardware abstraction. However, the inefficiency of this development model in terms of sustainability and the redefinition of the meaning of Moore's Law threaten this digitalization strategy.

Nowadays, energy consumption is critical and more efficient ways to compute and sense are increasingly needed. Furthermore, we need to create new electronics made from environmentally-friendly materials and processes, whose key characteristic will be the ability to decompose or be easily recycled at the end of its useful life.

This chapter addresses the core technological enablers of the digital transformation of society, i.e. the electronic components and systems. The scope and complexity of the electronics challenge needs a broad vision with the collaboration of experts able to provide solutions at every level of the technology.

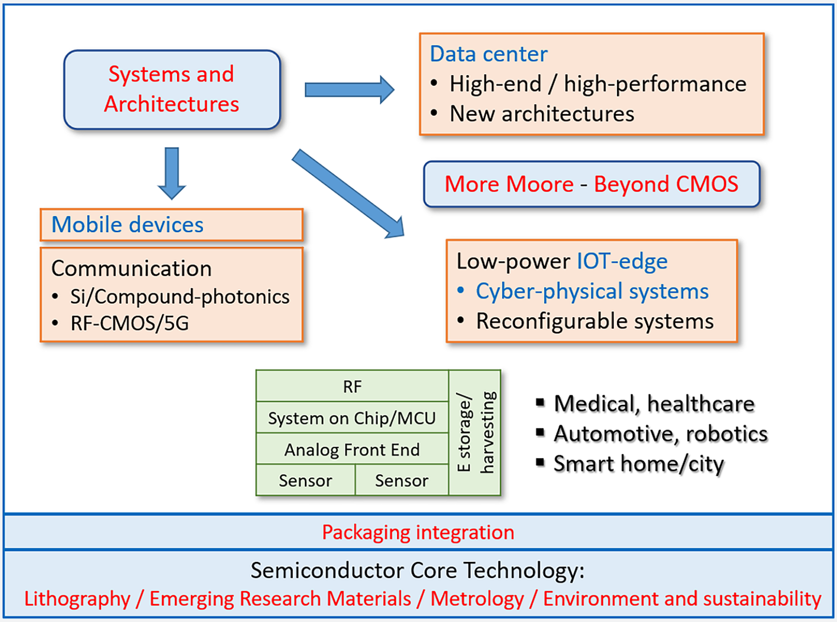
The current structure of the electronics ecosystem is shown in Figure 1.1. It is adapted from the International Roadmap for Devices and Systems (IRDS) [Institute of Electrical and Electronics Engineers, 2020]. The focus technological topics of the IRDS are written in red. The roadmap emphasis is on the systems written in blue, which are the basis to identify requirements for the technologies that make these systems and applications possible.

We are addressing this quest according to two technological drivers. The first one refers to the technological building blocks for ultra-high energy efficiency in electronics. At one end of the ecosystem, data centers are consuming a large amount of energy, with a negative impact on the environment. At the opposite end, the ubiquitous deployment of sensors will in many cases require essentially zero-sum power consumption for the complete sensing system. Increasing the energy efficiency of the basic components and functional elements of digital and analog electronics will require the implementation of new devices, in many cases based on new materials and/or on different computational variables.

The massive integration of sensors is specifically addressed by the second driver.

It will require sustainable sensing devices, both in terms of materials and energy, and new sampling and processing techniques.

FIGURE 1.1–Ecosystem of the electronics industry based on semiconductor technologies, adapted from the IRDS [Institute of Electrical and Electronics Engineers, 2020]. Red text: IRDS Focus Teams; Blue text: Systems and Architectures key market drivers.



The research in this challenge should be aligned with the existing roadmaps and research agendas of the Electronics Ecosystem, such as the IRDS [Institute of Electrical and Electronics Engineers, 2020] and the joint Strategic Research Agenda for Electronic Components and Systems of the European industry associations AENEAS, ARTEMIS-IA and EPoSS [AENEAS et al., 2021].

The overall goal of this electronics challenge is to provide hardware building blocks for the general topic of Processing Digital and Complex Information.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Electronic systems are the technological enablers for processing digital and complex information. One of the main challenges for electronics is achieving (almost) zero power operation. This would have a direct impact in the key market drivers of the semiconductor industry, shown in Figure 1.1: Internet of Things (IoT) (edge) devices, which operate in wireless networks to gather, analyse and react to events in the physical world; cyber-physical systems, which provide real-time control for systems such as vehicles and industrial systems; mobile devices and data centers. Achieving almost zero power electronics will reduce the energy consumption and the environmental impact of data centers, will increase the performance and the autonomy of mobile devices and will enable the massive deployment of sensors in the Internet of Things.

As an expected impact, the current vision of the European electronics ecosystem is to achieve the EU policy target of 30% energy savings for 2030 by utilising innovative nano-electronics based solutions [AENEAS et al., 2021]. This will be addressed through the reduction of power consumption by the electronic components and systems themselves. Specific examples of the impact of research actions are described below.

For emerging logic and memory devices, the use of the spin as a control variable will allow a substantial reduction of the power consumption as well as to modify the device architecture making possible to combine logic operations with data storage and transmission.

Spiking neural networks (also called neuromorphic systems) imitate the (human) brain operation by targeting low energy consumption per operation while pursuing high information processing throughput. Neuromorphic computing can be highly beneficial for a large range of applications, where low power and intensive processing is relevant and currently unattainable.

Despite their popularity, flash memories cannot be the ultimate technology because of intrinsic limitations. Ferroelectric memories may become a serious alternative. Scientific progress in the development of ferroelectric HfO_2 will have huge impact. In addition to economic benefits, extremely low switching power of ferroelectric memories would permit substantial reduction of power consumption of the TIC industry. Moreover, in the near future, development of electronics will require the introduction of non-traditional materials and structures, beyond CMOS logic devices. Charge-free spin manipulation and spin transport offers a possible alternative. Although spin-diffusion lengths in 3D oxides are well below 2D materials (notably, graphene), they offer matchless tunability of spin-charge conversion by electric fields. This may enable computation with devices based on spintronic/multiferroic materials for memory and logic devices.

Quantum materials include a wide range of systems with emerging electronic properties. The increasing exchange of data and use of digital devices will be a major source of energy consumption in the future. From the applications point of view, the research on quantum materials can be key to design new devices able to work with very low or null electronic power. Besides reducing power consumption these materials can be used in sensors and other equipment for digital, medical and electrical applications, as well as for memories, light and efficient motors, equipment for energy production, etc. Other examples of the potential of quantum materials include novel spintronic-based applications, e.g. a precisely twisted graphene bilayer can lead to a spin-glass (superconducting) phase that could be used to store data.

The development of new processing technologies that allow manufacturing memory systems at temperatures below those used for fabricating transistors interconnections, enables incorporation of memory devices above blocks of CMOS logic.

This integration is evolving the traditional computer memory hierarchy to a new computer architecture paradigm where data management will accelerate algorithm performance while reducing energy consumption.

Some works follow a brain-inspired approach to improve both computational efficiency and energy efficiency. Moreover, they are working on new computational paradigms based on relaxing determinism in arithmetic circuits. Concepts such as approximate, probabilistic, and stochastic computing methods, are also being considered, expanding at the same time the capabilities of the fault-tolerant response of the systems. The impact of these new technologies brings the opportunity to improve the hardware implementation of multisensor/multichannel computational systems. Over these new computational models, the future new sensor networks are being designed to be highly distributed, heterogeneous, densely connected, dynamically reconfigurable, self-managed, ubiquitous and sustainable.

In this sense, the key to energy efficiency in the future networks is determined at the sensor level, where organic electronic is being introduced as an alternative to silicon electronics. Compared to silicon electronics, the versatility of organic electronics offers flexibility, softness and stretchability, which can be applied to foldable devices, biocompatible electronics that can act as interface with biological systems, and other applications.

4. KEY CHALLENGING POINTS

4.1. Technologies for almost zero power electronics

Energy efficiency is the main challenge ahead in electronics. In the early 2000's, keeping Moore's Law required to limit the operating frequencies and to change the architectures of integrated circuits, due to their increasing power consumption. Now data centers consume around 200 TWh per year, and data networks around 250 TWh, which is about 0.8 and 1% of the global electricity demand (2019 data [IEA, 2020]). Their demand is in both cases steadily increasing, so the energy consumption can only be reduced if the energy efficiency of electronic devices and systems is largely increased. The ultimate objective is achieving (almost) zero power electronics.

This challenge is aligned with the vision of achieving the EU policy target of 30% energy savings for 2030 through innovative nano-electronics based solutions. Its scope addresses the reduction of power consumption by the electronic components and systems themselves.

Emerging logic and memory devices

Innovations in semiconductor core technology will enable continued dimensional/functional scaling and improved energy efficiency in logic devices, through new structures based on gate-all-around transistors with nanowires and nanoribbons, transistors with 2D materials channels, and 3D integration. In addition, one important forward-looking research objective is to find an energy-efficient switch device beyond CMOS for future integrated circuits. Many types of devices are being explored, based not only on electronics (e.g. single-electron transistors), but also on different computational state variables such as ferroelectric, spintronic or magnetoelectric.

This is supported by research on semiconductor technology, mostly related to patterning processes and the use of new materials. In a somewhat parallel path, devices made with organic, printed and flexible electronics are increasing both performances and integration, and can contribute to the sustainability of electronics by reducing e-waste.

Materials for electronics

Emerging materials for electronics will be important enablers for almost zero power electronics. Current technologies based on magnetic memories and semiconductor electronics are about to reach their physical and economical return limits, thus making it necessary to develop a new technology. A substantial improvement of the energetic efficiency and data processing speed of integrated circuits and memories requires the introduction of new control variables. The electronics based on electron spin handling, i.e. spintronics, is a potential alternative to develop multifunctional electronics that combines logic operations, data storage and transmission with an improved energetic efficiency. The study of thin films and heterostructures of complex functional oxides may lead to potential applications in magneto-electronics and spintronics.

Control of dielectric responses and spin degrees of freedom appear as promising routes for low power and fast processing electronics. In this context, oxides play a key role. For instance, pure spin currents generated nowadays by electronic injection in oxide heterointerfaces or spin Hall effect in metals, are used for active control of functional properties of devices (e.g., magnetization switching controlled by spin currents). Similarly, commercial memories use open circuit control of ferroelectric oxide devices. Current materials present challenging bottlenecks to downscaling that can be overcome using alternative architectures (ferroelectric tunnel junctions) or using novel materials (e.g. HfO_2). Furthermore, in memristive oxides the resistance state is fine-tuned by electric, magnetic fields or light within a continuous interval of values, thus offering a route to analog computing and decentralized non-von Neumann architectures and bioinspired optoelectronic and magnetoelectric devices. Additional classes of emerging materials for electronics with promising applications are topological materials with dissipation-less electronic transport, 2D materials and their heterostructures, as well as organic materials for flexible devices.

Currently, the leading memory technologies are based on charge or current trapping and ferromagnetic domains. Emerging new technologies for persistent and fast read/write memories are actively being explored. Research on quantum materials frequently comes across potential applications for data storage, particularly in two fronts: quantum memories and spintronic memories.

Energy efficient computing blocks

New devices and computing paradigms can result in an energy efficient implementation of the basic computing blocks. Spiking neural networks (also called neuromorphic systems) imitate the brain by targeting low energy consumption per operation while pursuing high information processing throughput per operation. This can be highly beneficial for a large range of applications, where low power and intensive processing is relevant. Spiking neural networks can be designed with emphasis on exploiting memristive devices, where co-integration of neurons and memory is essential.

Analog computation can improve the energy efficiency. If implemented in advanced integrated circuit technologies, analog computation can have important advantages. Its main attributes are parallel computation (with computation time independent of the problem size) and absence of time-discretization, which eliminates convergence issues. Hybrid (mixed analog/digital) computing units defined for specific classes of problems, such as solving nonlinear differential equations, can result in faster computation with lower energy consumption.

4.2. Smart and sustainable electronics for interaction with the world

The penetration of sensing technology has expanded the analysis capability of natural and social events and have provided an unprecedented opportunity to better understand and respond to the spatiotemporal dynamics of these events. In this sense, an entirely new world of low-cost electronic products with lifecycles on average ranging from hours to months has arisen to improve the efficiency of decisions around the environment, urban settings, health and disease propagation, business decisions or the maintenance of critical infrastructure.

This challenge addresses the massive integration of sensors in a sustainable way. The real challenge that arises behind this is how to drive the transition from signal-driven systems to data-driven systems. Therefore, to formulate more specific challenges, both issues should be considered.

Autonomy of sensors systems

It is possible to remark some features that are desirable to achieve a sustainable sensor: it should be cost-effective, reusable and/or biodegradable, it should have low consumption and/or capability for energy harvesting, support micro-storage and/or communication or data preprocessing capabilities.

In this sense, materials are in the core of this subchallenge. Complementing well established and novel silicon approaches, there are other materials systems worth exploring that also show the required material and technology scalability. Metal oxide materials, for example, are adequate for the development of low cost, high-performance gas microsensors that have shown excellent compatibility with the microelectronic technologies. Organic active materials can produce photodetectors and make use of thermoelectric and piezo/triboelectric effects that would be able to produce energy powering units. Thus, opening energy harvesting technology at the sensor level.

Furthermore, several solvent-based functional materials are being considered to produce new biodegradable inks with electric properties that would be used to produce Organic Thin Film Transistors (OTFTs), diodes and other electronic components on biodegradable substrates such as PLA, silk or nano-paper adequate for additive manufacturing technologies.

Then, the integration of these new devices into low-complexity electronic systems can make functional prototypes of IoT devices powered by organic-based energy systems.

These eco-friendly circuits are expected to be too slow for general-purpose computing, but they are attractive for single-use devices such as sensors and displays. However, a new artificial intelligence architecture for low-scale systems can be introduced to improve sampling operation, processing capabilities and communication. The goal is to obtain technology to rise sensor ubiquity.

The management of massive and/or complex sensor systems

The organization of new sensor networks is also a challenge to the future global data network because of its density and because the big dataflow generated threatens to consume large bandwidth and requires data centers to consume higher power.

These sensor networks correspond to many different typologies and different applications. As an example, consider the medical sensor ecosystem where CSIC is participating. In this case, we can find from small disposable wearable sensors to big instrumentation, like PET, or many medium-size instruments, like echography systems. Some of these systems are evolving, increasing their capabilities and being implemented in new configurations such as portable or as unattended instrumentation that are opening new application areas. Other fields like cities, factories, vehicles or infrastructures show similar diversity and complexity.

In this sense, optimizing the sensor distribution to reduce the number of active elements, introducing on-board processing able to obtain information from signal, improving communication systems, or developing new sampling event-driven strategies are solutions that are being considered to reduce the dataflow and consequently to made the network more sustainable.

Furthermore, sensor distribution should be conceived as a fault-tolerant system. It should be able to perform auto diagnostic and to be reconfigurable to guarantee reliable information or a different application range. That is, it should be designed to increase system lifecycle and usability and according to a trade-off between performance and complexity. Sparse reconstruction and compressed sensing (CS) techniques can be used to optimize the number of data samples or sensors that are needed for successful reconstruction and reduce the magnitude of the reconstruction errors. In this sense, it can be used as a tool for design optimal sensor structure or reorganize the structure to maintain reliability in front of a fault-event. However, reduced data may save measurement resources, but it also means a lower signal-to-noise ratio (SNR) and possibly other artifacts. The hardware implementation of CS techniques will improve the efficiency of sampling and processing devices.

Communication is the other issue. The paradigm which 5G represents needs new functional materials supporting low-cost energy-efficient mm-wave devices. In this sense, a new family of ferrites based on ε-Fe_2O_3 with huge magnetic anisotropies are expected to present zero-field magnetic resonances in the mm-waves and THz bands, allowing to develop efficient communication systems.

New processing architectures for signal to data transition in sensor systems.

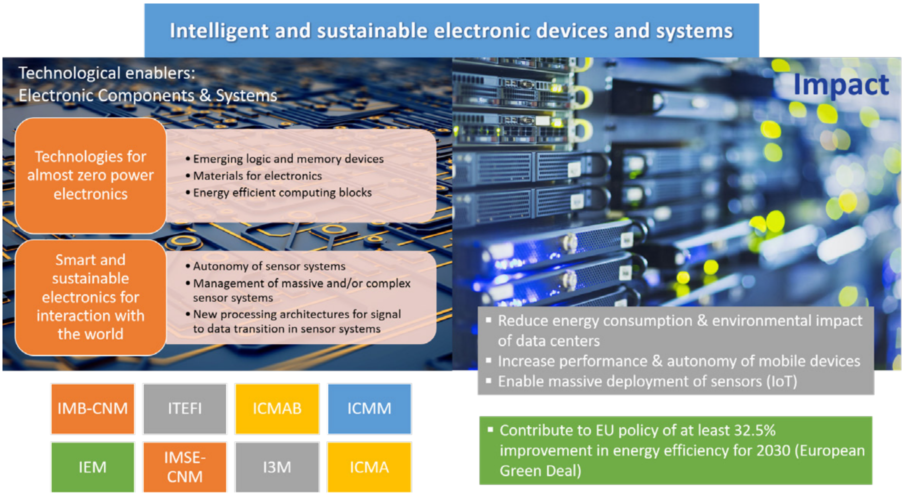
The scenario that is arising is well presented in the IRDS 2018 update (More Moore). *As the global data corpus continues to grow exponentially with a two-year doubling period and with that growth to come disproportionately in distributed CPS and IoT/edge systems, time of flight through wired or wireless communication systems in addition to bandwidth limits will continue to hold data at the edge, necessitating efficient computations capabilities to flow outward to the data [Institute of Electrical and Electronics Engineers, 2020].*

The traditional computer von Neumann architecture, based on a simple sequential programming model, has allowed a successful software development model based on the powerful abstraction model. However, nowadays, it is being questioned because of the benefits associated came at the cost of computational efficiency.

The implementation of algorithms on application-specific integrated circuits (ASICs, DSP and FPGAs) results in a better mapping of the operations of algorithms to a set of physical resources used to perform those operations. Furthermore, it improves computational performance and energy efficiency by one to three orders of magnitude if compared with the von Neumann architecture. The multichannel signal processing is one of the application areas where the design of specific architectures is an active research line.

Probably, the most promising solution is based on exploiting memory-centric architectures, mainly because they have been addressed in a limited way, through FPGA specific designs, in the development of sensor array systems (like PET or ultrasonic imaging systems). Memory access has been radically improved in the last decades. However, the data movement between memory and processor increases latency as well as energy consumption. The new technologies associated to memory development suggest that at the cost of some increase in architectural complexity concepts such as "memory in logic" could be the basis of the new memory hierarchy that will need a new programming paradigm. Ferroelectric memristive devices can be used as active elements for logic and computing beyond von Neumann architectures. New solutions should explore all concepts of low power computing such as memory-centric architectures, neuromorphic computing, error-efficient, or any mixed computing method. However, this process should be supported by the development of new hardware algorithm implementations and novel software paradigms able to exploit the advantage of the new architectures, including a new theoretical framework for event-driven algorithms based on brain-inspired processing and adaptation.

ANNEX: ONE SLIDE SUMMARY FOR EXPERTS



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

CHALLENGE 2

ABSTRACT

Photonic technologies provide key enabling components for the future digital transformation. This section includes an in-depth overview of the challenges that advanced photonics faces in the coming years in order to become a truly disruptive technology. Based on the expertise of numerous CSIC researchers, relevant key challenging points are identified, which range from the exploration of novel materials to the deployment of complex networks, including the development of photonic integrated circuits and devices.

KEYWORDS

photonic materials | photonic devices | photonic networks

CHALLENGE 2

ADVANCED PHOTONICS

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1. EXECUTIVE SUMMARY

Advanced photonics refers to technologies that generate, measure, and manipulate light. Importantly, advanced photonic technologies aim at providing key enabling components for the future digital transformation. Thanks to the contribution of researchers from 16 CSIC Research institutes and centers of different backgrounds, this document defines a scientific roadmap for the development of the advanced photonics field in the next decade.

This document is structured along three main key scientific challenges: (i) Novel materials as building blocks for efficient photonic systems: all-optical and active control, (ii) Development of photonic integrated circuits and devices: making systems smaller and more robust, and (iii) Programmable and interconnected optical networks and technology: towards photonics integration 2.0. Along these key challenges, we have highlighted research directions in the topics of functional optical materials, 2D materials for photonics, nanofabrication using laser techniques, information-processing photonic devices, photonic integrated circuits, biophotonics, fiber-optic technologies and photonic networks, and information processing in the optics domain.

Being a transversal discipline, photonics has the potential to disrupt a variety of technological fields such as information and communication, metrology and sensors, life sciences and health, industrial manufacturing, agriculture and food, automotive, and lighting and displays.

2. INTRODUCTION AND GENERAL DESCRIPTION

Photonics is a transversal discipline with connections to multiple scientific domains, with a strong presence in Europe and an associated 60 billion euro annual turnover [European Technology Platform Photonics 21, 2019]. This chapter covers the global scientific challenge of Advanced Photonics in the context of an envisioned Europe's age of light.

The word Photonics appeared around 1960, when the laser was invented by Theodore Maiman. Since its invention, the laser has become a paradigmatic example of how a scientific discovery can yield revolutionary benefits to society in communications, healthcare and many other fields. Arguably, optical fiber and its multiple associated technologies have also been one of the initial drivers of the photonics revolution. The key role of fiber optic early-pioneers in shaping today's hyper-connected society was recognized in 2009 with the Nobel Prize in Physics awarded to Charles Kao. Nowadays, fiber-based devices, systems and subsystems constitute ubiquitous and enabling technologies in industry, medicine, communications and sensing. Photonic devices also serve as fundamental components in advanced instrumentation design and basic research, becoming key building blocks in research fields as relevant to our future as quantum technologies and optical computing.

Currently, the development of photonics technology follows the pathway set by microelectronics technology long time ago. The advent of photonic integrated circuits opens the door to a drastic reduction in both the footprint of the setups and the cost of photonics equipment. In addition, this technology offers remarkable advantages to simplify the assembly process by providing simple and robust solutions. The field of photonic integration has evolved from the implementation of discrete components obtained by miniaturizing optical functions, up to the current monolithic photonic integrated circuits that can incorporate a large number of optical elements, allowing the realization of application specific photonic integrated circuits.

This chapter states the impact of Advanced Photonics in basic science panorama and its potential applications. The scientific dialogue for its elaboration has allowed to synthesize the investigations of more than 20 research groups of different background, representing a large spectrum of CSIC centers and institutes, around the following three key challenges:

1. Novel materials as building blocks for efficient photonic systems: all-optical and active control.
2. Development of photonic integrated circuits and devices: making systems smaller and more robust.
3. Programmable and interconnected optical networks and technology: towards photonics integration 2.0

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Photonics is being praised as one of the few key enabling technologies that are strategically important for Europe's industrial future [European Parliament et al., 2020]. European photonic industry is currently a global leader in the sectors of production technology, measurement and machine vision as well as optical components and systems. Predominant photonic functions that are sought after include sensing and imaging, transmitting and shaping, laser processing and laser-based therapy.

In the basic science panorama, photonics is very much present in the "Excellence Science" pillar of the European Horizon 2020 program. 10.4% of European Research Council (ERC) projects are photonic related, with an 8.2% share for the Infrastructure (INFRA) calls and 8.7% for Marie Skłodowska-Curie actions (MSCA). The share is as high as 23.3% for Future and Emerging Technologies (FET) projects. These numbers serve to illustrate that Photonics is a high-tech hardware industry that needs intense research to develop innovations.

Likewise, Horizon Europe framework program identifies Photonics as a key enabler for Europe's ambitions in Digitalization [European Commission, 2019], including Industry 4.0, artificial intelligence, smart farming, 5G, personalized healthcare and many other applications.

This enabling technology provides key strategic value to the automotive and medical industry, the aerospace, and to the quantum computing and communication sectors. As a result, advanced photonics is becoming a flagship science for innovation that is quite simply indispensable for driving Europe's digital transformation.

In short, advanced photonics is already having a clear impact in basic science and has the potential to disrupt several applications in:

1. Information and communication, e.g. a programmable optical infrastructure could be built by using multi-chip module technologies and could allow for a sustainable growth in data center interconnects.
2. Metrology and sensors, e.g. the substitution of electronic by photonic functions could allow for a higher accuracy, lower latency and better energy efficiency.
3. Life sciences and health, e.g. mobile photonic biosensors would allow for faster diagnostics and intervention, and photonic tools could be used for the development of new drugs.
4. Industrial manufacturing, e.g. photonic sensor technology can improve parameter monitoring for quality control in manufactured parts.
5. Agriculture and food, e.g. light-based technologies have much to offer through monitoring and measuring tools, on farms and in food processing plants.
6. Automotive, e.g. the deployment of autonomous vehicles and the improvement of road safety can be facilitated by photonic sensing.
7. Lighting and displays, e.g. miniaturization and improved power efficiency can increase sustainability.

With this in mind, advanced photonics has the goal of developing full systems, going beyond the production of independent components. Since photonic integration industry is said to be now like the semiconductor industry was in the 80s, the adoption of mass manufacturing packaging and assembly technologies will eventually be a driver for the future of an age of light.

The innovation potential of photonics technologies is of the utmost importance for our digital economy and society in the 21st century. There are, however, some significant barriers that impede a more widespread presence of photonic-based approaches. There are often issues related to the cost, size, efficiency, output power, or sensitivity that prevent photonic solutions from being adopted. Advanced photonic technologies play a key role to overcome these barriers by identifying novel **materials** for efficient photonic functions, making photonic **devices** smaller and more robust, and developing photonics modules to be used as plug-and-play in large **networks**. The path to achieve the aforementioned challenges requires increasingly interdisciplinary research and development, in addition to cross-fertilization from one photonics application area to another.

All in all, light-based technologies offer a great opportunity for basic research and technology transfer capable of producing a change towards achieving UN's Agenda for Sustainable Change [UN General Assembly, 2015]. Work in this context has foreseeable potential impact in areas related to sustainable development goals 3: good health and well-being, 7: affordable and clean energy, 9: industry, innovation and infrastructure, 11: sustainable cities and communities, 12: responsible consumption and production, and 13: climate action.

4. KEY CHALLENGING POINTS

Light technologies have the potential to impact the information and communication sector by delivering the required performance, resilience and cybersecurity while satisfying cost, energy efficiency and technological constrains. The scientific and technological response to these needs will make a cross impact in a variety of social challenges ranging from ICT, to health, through mobility, energy, and security. Photonic technologies are thus affecting many global challenges as a key enabling technology. In order to address the need for efficient acquisition of information, its delivery, and processing, a set of key specific challenges can be identified, connected with the three technological bottlenecks in the development of an all-photonic solution for information and communications handling. To achieve the overall goal of turning photonic technologies into a pervasive and integrated technology, eventually replacing electronic by photonic functionalities in as many applications as possible, the photonics community would need to address disruptive achievements in the following key challenges:

- Novel materials with specific optical responses as building blocks for interfacing acquisition, delivery, and processing of information.
- Multifunctional small and robust photonic integrated circuits and devices to enable fast, cost-efficient and modular operation.
- Optical networks capable of providing zero-touch operation, with instantaneous response, access anywhere, and intrinsic security.

The achievement of these specific challenges would set a practical and efficient photonic solution to integration, thus turning advanced photonic integration into a reality. We establish a set of technological milestones that can contribute to this achievement in the following three specific key challenging points.

4.1. Novel materials as building blocks for efficient photonic systems: all-optical and active control

The development of photonic devices and networks relies on the availability to fabricate novel optical materials capable to interface the acquisition, delivery, and processing of optical information with that of electronic means of information handling. The platforms to achieve this goal must rely on advanced optical materials and compact two-dimensional (2D) heterostructures. Furthermore, the use of advanced laser technology to fabricate optical building blocks is another challenging aspect to consider in this context. We outline the efforts along these lines in the following.

Functional optical materials

Integration of optical nanoresonators. The search for novel optical functionalities will require to explore different types of materials ranging from metals to insulators, through semiconductors, and combinations of them. Plasmonic resonances sustained by nanostructured noble metals have been exhaustively investigated and exploited as interesting optical resonators. Transitioning towards new materials will open other spectral ranges of the electromagnetic spectrum with new functionalities. In this context, organic semiconductors, conductive oxides and non-noble metals will be sought as inexpensive alternatives to extend the benefits of plasmonics towards the infrared and ultraviolet regions. On the other hand, there is an increasing interest in nanostructured high-dielectric materials (Silicon, Germanium, titanium dioxide, etc.), which exhibit similar resonant photonic effects as those in metals without the associated optical losses. Furthermore, these high-dielectric architectures exhibit simultaneously electric and magnetic resonances paving the way to new optical phenomena such as suppressed back scattering, directional emissivity, or near-zero epsilon optical response. There will be a technological challenge to integrate all or some of these individual building blocks in hybrid solutions for all-optical responses, ready to interface with the micron scale of photonic guides and devices.

Meta-optics systems and their scalability. The combination of optical resonators as building blocks of meta-materials, i.e. engineered materials with e.g. negative index or chiral properties, has produced the emergence of meta-optics. Such artificial materials give rise to novel optical functionalities based on the optical properties of the nanoresonating unit, as well as on the particular distribution in an array. However, the presence of meta-optics schemes in nowadays photonic devices is scarce, which illustrates how challenging harnessing these optical properties and apply them in current technologies is.

Transitioning from the lab to a commercial product imposes requirements on the nanostructure such as certain area coverage, optical response homogeneity and cheap and easy fabrication. Unfortunately, as the optical properties increase in complexity, the nanostructures become more demanding in terms of nanofabrication and hence less scalable. To date, the vast majority of meta-surfaces and meta-materials still rely on low-throughput nanofabrication. Scalable fabrication alternatives will need to be actively sought after.

Novel and hybrid materials for light emission. The development of semiconductor materials for light emission devices (LED) has been quite focused on improving the efficiency of the light emission process during the last years. In information technologies, however, the development of novel materials that improve other properties of the light emission process, such as the coherence and the quantum properties of the photons emitted, is still a challenge. To that end, the integration of single emitters and arrays of emitters in novel photonic platforms at the nanoscale can open new routes to quantum information, and manipulation of polaritonic states due to the interaction of emitters and the electrodynamical environment. Molecules, quantum dots, and fluorophores will compete in their respective platforms to achieve useful sources for information technologies. Furthermore, additional efforts will be devoted to the development of light emission in random lasers. Current attempts at applying random lasers are restricted to their use as low coherence illumination sources and essentially rely on inorganic semiconductor materials amenable to photolithographic processing. Their spectral features however are restricted and novel materials with the advantages of current laser dyes are desirable. These in turn suffer from ageing and bleaching. A major challenge is therefore finding and synthesizing, embedding novel light emitters (such as chromophores) in appropriate matrix materials to allow for the fabrication of extensive random laser platforms. Additionally, selective pumping schemes are required allowing individual lasers to be excited with a control over phase and intensity. A theoretical/numerical support for the analysis and interpretation of results will be essential bearing in mind the complex nature of the matter at hand.

Building blocks for active control and integration of electronics/spintronics and photonics. The interplay between the properties of electronic transport and those associated with photonic information will require the development of materials to perform cost-effective, reliable, and integrated exchange of information. Hybrid material solutions, as those pointed out above are a possibility for efficient photocurrent generation, optical rectification, and implementation of other nonlinear processes required in information technologies. Together with nanoscale and hybrid bulk material solutions, a strong effort in 2D materials implementation will be needed, as described in the next section. In addition to the possibilities offered by standard electronic transport, spin currents also offer additional advantages for transport/optics interfacing. Even if magnetism is not found in common materials at optical frequencies, the application of slowly-varying (or static) magnetic fields show the ability to modify the optical response in a variety of magnetic materials, providing a magnetic means of active control of the optical response. To this end, many spintronic materials, like those based on permalloy ($Ni_{81}Fe_{19}$), perform well at room temperature and require of very small magnetic fields. Spintronic-photonic concepts based on these materials have demonstrated magnetic field modulation of photonic systems with low processing requirements and without electrical contacts actuation. However, actual integration of spintronics and photonics materials and phenomena in true operating devices is unexplored. A common strategy to unite the efforts of the spintronics and photonics communities and their technical expertise is thus needed. This spintronic-photonic combination could serve as an efficient alternative to semiconductor low-dimensional structures for active-control of the optical response.

2D materials for photonics

Active photonics and graphene-based photonics. One of the long sought goals of the photonics community is to achieve nanostructures whose optical response can be tuned at will by an external agent. In particular, magnetic and electrically tuned nanostructures could have a great impact in optoelectronics. The advent of 2D materials, with graphene at the forefront, has opened a new pathway to couple light to atomically thin devices that can be externally actuated. Graphene-based plasmonics may enable the manufacture of novel optical devices working in different frequency ranges—from terahertz to the visible—with extremely high speed, low driving voltage, low power consumption and compact sizes. Additionally, coupling graphene and other 2D materials with ferroic materials (ferroelectric, ferro or ferrimagnetic) may enable non-volatile tunable optical responses, as a means towards fully programmable integrated photonic devices.

Fabrication of 2D heterostructures for optical systems. A great effort is to be done towards the growth of 2D transition metal dichalcogenides (TMDs) with specific properties as well as to enable the fabrication of heterostructures based on these 2D materials, occasionally combined with graphene. 2D TMDCs can host e.g. quantum emitters with exceptional brightness and spectral tunability. The possibility of such heterostructures to be integrated in a wide diversity of photonic platforms would offer opportunities for engineering nanoscale light-matter interaction but faces the following challenges: (i) Growth of large area high-quality 2D-TMDs; (ii) Design and fabrication of heterostructures of 2D materials (TMDs and graphene) for photodetection and light sources (light-emitting diodes, quantum well emitting diodes, single photon emitters); (iii) Band engineering of heterostructures for the efficient separation of photo-excited carriers; (iv) Controlled and reproducible creation of single photon emitters within 2D-TMDs with emission at room temperature, preferably in the infrared spectral range for biological applications; (v) Control of light extraction and integration in photonic devices; (vi) Combination of optic and electronic functionalities in the photonic integrated circuits.

Beyond standard polaritonics. Alternative polaritonic materials with new functionalities based on novel physical properties, such as topological protection (for instance in MoS_2 and similar), non-standard dispersion relationships (for instance hyperbolic h-BN or biaxial α-MoO_3) and misaligned Van der Waals structures (for instance twisted graphene and heterostructures) can give rise to larger polariton propagation lengths under room-temperature performance, without losing the properties of confinement and field enhancement, thus overcoming the problem of intrinsic damping, a limiting factor in many polaritonic applications, usually hard to beat simply by clean sample-preparation. In this context, epsilon-near-zero materials with singular permittivity conditions may enable a control of both amplitude and phase of the transmitted light, allowing for an enhanced optical modulation by nonlinear effects.

Nanofabrication using laser techniques

Nanoscale control and modification of matter with advanced light-based technologies. The use of light-matter interaction to control and modify matter at the nano to macroscale can gear its response towards the optimization of specific functionalities. The study and modification of matter at scales ranging from the molecular to the bulk level requires the exploitation of advanced coherent light sources and complex irradiation schemes. In this field, the following challenges are identified: (i) Controlled and tailored fabrication of nanostructured materials with sought functionalities, in particular, those that make them useful for photonic applications; (ii) To apply advanced light sources for the modification and synthesis of materials, developing advanced optical schemes based on the generation of vacuum ultraviolet (VUV) pulses, multichromatic fields, phase control and spatial and temporal shaping; (iii) To understand the dynamics and possibilities of laser control of fast processes at the nanoscale.

Development of soft-matter materials for advanced photonic applications. A general and key aspect in advanced laser processing that affects all the challenges mentioned here for nanofabrication concerns the development of cost-efficient laser sources tailored to specific applications, which require particular wavelengths, peak powers and repetition rates. In order to produce 2D structures on polymer surfaces and explore the possibilities for producing 3D periodic structures, the following challenges need to be addressed: (i) Need for new cheap, easily portable and easy to assemble technologies for micro and nanostructuring; (ii) Development of new technologies based on laser light–matter interaction for low-cost lithography that does not require complicated infrastructures; (iii) Production of large area smart polymer patterned surfaces for enabling technologies nowadays restricted to inorganic materials.

Advanced laser processing and ultrafast lasers applications. Additional challenges in laser processing concern the identification of "killer" applications in sectors which are not limited to photonics itself (direct writing of active and passive photonics devices, like optical amplifiers, lasers, Bragg gratings and also optical circuits that include those for quantum operations/computing), but also extend to challenges in other general areas such as energy production (i.e. advanced materials synthesis for energy harvesting or lighting applications), or environmental friendly and cost efficient fabrication strategies (i.e. development of functionalized surfaces where laser processing confers the surface special properties: biocompatibility, improved adhesion, low friction, superhydrophobicity, antibacterial properties).

4.2. Development of photonic integrated circuits and devices: making systems smaller and more robust

The challenges in the fabrication and development of optical materials pointed out in the previous section ultimately target the establishment of platforms with functionalities to engineer optical information, and its exchange with other more conventional means of information handling based on electronics and/or spintronics. To that end, an assembly or composition of the aforementioned material platforms need to function in autonomous or integrated devices showing the possibility to control the polarization, amplitude and phase of light on demand, in order to replace traditional techniques. Future optical devices need to (i) expand the range of achievable functionalities, going beyond passive ones, opening new frontiers by considering active, nonlinear, quantum, and/or dynamically tunable systems, (ii) achieve robust and disorder-immuned flat photonic circuits, (iii) use spin-polarized modes as an additional degree of freedom for photonic circuits, (iv) accomplish efficient photonics with subwavelength components, (v) reach strong-interaction regimes to quantum emitters, enabling the design of novel light sources, and (vi) establish all-optical information platforms integrated with complex bioenvironments for multiplexed sensing and detection of biomolecules and substances. We outline some of these priorities in the following.

Information-processing photonic devices

Implementation of functional nanooptics. During the last years, the manipulation and control of light at the nanoscale has been made possible thanks to the capabilities developed in fabrication, self-assembly and engineering of nanoresonators composed of a variety of materials. Metallic nanoantenas where surface plasmons are excited have been at the basis of subwavelength control of light, and thus have turned into the paradigm of nanooptics. However, plasmonic nanoantennas often perform together with other material configurations such as dielectric resonators in hybrid systems, or quantum emitters built from semiconductor quantum dots, organic molecules, dye molecules, or nitrogen-vacancy centers, among others. At this point, the proof of principle of a variety of functionalities with the use of these building blocks has been demonstrated. Optical nanocircuitry, effective nonlinear response, including high-harmonic generation and optical rectification, strong light-matter coupling at the nanoscale, active control via external bias and magnetic fields, strong-field photoemission, ultrafast dynamics control, or optically-induced chemical reactivity are some of the processes which can now be routinely implemented at the nanoscale. Future challenges for the practical implementation of these optical nanodevices are (i) a systematic transfer of validated proofs of principle into realistic and systematic devices with reliable performance, compact and scalable in an innovation chain, (ii) push of nanophotonics in space and time by developing extreme optical platforms that allow for ultrafast control of photons at single atoms and molecules with extreme precision in space and time, and (iii) to merge nanooptics and quantum optics into effective quantum nanooptics, capable of generating single photon sources, entangled pairs of photons, correlations, and quantum states of light with generality, robustly, and on demand, giving a mature technological response to the requirements of quantum information technologies of the next decades. This latter aspect is further developed below.

Implementation of flat photonics based on novel concepts. The recently found interest in complex geometries such as super-crystals, quasi-crystals, topological insulating arrays, chiral architectures, magneto-optical and magneto-refractive layers, dielectric meta-surfaces and Moiré meta-materials is motivated by their potential to control the phase, polarization and spatial distribution of light, relevant for implementation of optical beams and optical engineering applications in flat layers and platforms. However, all of these intricate architectures pose severe challenges at both the numerical design and nanofabrication stages. Even if each family of novel materials optimizes the control of a particular aspect of light, they will require specific implementations and optimizations. A two-fold effort, theoretical and experimental one, will be required to implement these novel platforms for photonics. A considerable development both in the theoretical design and in the practical implementation will need to address the following challenges: (i) Define elemental building blocks, interactions and homogenization scenarios; (ii) Identify the contributions to the optical signal since different measurement schemes will be necessary to identify the underlying symmetries responsible for a variety of effects (chiral light for enantiomer separation, topological protection of light, optical beam steering, optical modulation and beam splitting, control of angular momentum of light, etc.); (iii) Establish optimal conditions for the performance of different topologies, material constrains, and wavelength specific geometries. In particular, the following devices can be envisioned: nanophotonic circuits for unidirectional light propagation extremely robust to perturbation and imperfections. Such devices could be key in the development of quantum computers with extremely reduced dimensions. Other important applications are optical insulators with nanometric dimensions.

Using quantum nanophotonics to exploit non-classical light at the nanoscale[1]. The development of quantum nanophotonics promises to deliver building blocks for a wide range of quantum integrated devices, including emitters, detectors, and quantum memories for optical qubit generation and manipulation. A main motivation is to combine the excellent quantum control techniques of quantum emitters with the engineering possibilities and subwavelength confinement of light of nanophotonics platforms. One of the more interesting perspectives here consists in designing non-classical states of light, such as multi-photon Fock states or cluster states, that can be harnessed for metrology, sensing, spectroscopy, or distributed quantum computing, among other applications. This requires both the design of new protocols as well as new theoretical tools to characterize them.

1 See Challenge 3 on Quantum Computing for the use of light in quantum technologies.

Photonic integrated circuits (PIC)

Technological improvements in silicon photonics. The short-term challenges identified in this category must serve to consolidate existing infrastructure and improve its capacity. In particular, the following goals are to be targeted: (i) Submicron resolution (< 150nm) techniques for wafer scale pattern transfer; (ii) Silicon nitride (SiN) photonic integrated circuits with reduced losses in the visible and near-infrared ranges; (iii) Expanding the PIC range to wavelengths in the mid-infrared for (bio)sensing and spectroscopy applications; (iv) Studies of new materials for integration onto PIC fabrication lines: Silicon rich silicon nitride (Quantum PICs in the visible), silicon carbide qubit sources, biomaterials (Silk fibroin for green lithography and photonic components), etc. In the mid-term, the main challenges in silicon photonics technology include a development of the following areas: (i) Sub-nanometer and meta-materials for new functional PICs; (ii) Microelectromechanical systems (MEMS) for zero-power consumption optical switching and variable optical attenuators (VOAs) for FPGA-like (FPGA stands for field-programmable gate array) programmable silicon photonic circuits; (iii) Wide wavelength range source integration for spectroscopy in the ultraviolet (UV), visible (Vis), near-infrared (NIR), and mid-infrared (MIR) spectral ranges. Finally, we note that epsilon-near-zero materials with Si-compatibility may enable the development of optical inter-connects in integrated photonic circuits that would allow for ultrahigh-speed information processing.

Monolithic integration driven by applications. Regarding potential future uses of photonic integrated circuits as enablers of novel applications, the following key challenging applications are identified: (i) Quantum PICs in the visible for computing and sensing; (ii) Quantum photonics for chemical analysis; (iii) Neuromorphic based photonic circuits; (iv) Light Detection and Ranging (LiDAR) technology. The first three aspects are developed in different parts of this white book, however, due to its direct social impact in connection with information technologies, we specify particular challenges within LiDARapplications. To make LiDAR accessible to the market, further research and development is necessary. The specific requirements and technological improvements to implement a fully operational LiDAR sensor in future are: (i) Development of accurate lasers-on-a-chip; (ii) Improvements in the spatial resolution and range, (iii) Improve the Signal-to-Noise Ratio; (iii) Improve receiver sensitivity; (iv) Anti-jamming, immunity to interferences and unambiguous detection range; (v) Being able to work under different real-world environmental conditions; (vi) Integration of a whole LiDAR system in a PIC with the necessary requirements to access the market. All in all, photonic integrated systems may find applications in open problems related to e.g. climate change, defense and security, smart and integrated transport, secure, clear and efficient energy.

Biophotonics

Portable point-of care (POC) devices for the achievement of universal Healthcare and Environmental protection. Nanophotonics-based biosensors (Plasmonics and Silicon Photonics, PICs) are the most suitable candidates to achieve these ambitious POC devices. In order to achieve this goal, the following developments will be required: (i) New nanoscale optical transducers and photonic principles; (ii) New material nanostructures, mass and affordable production, and flexible substrates; (iii) New strategies for universal biofunctionalization techniques (even at wafer level) of biological receptors (as proteins or genomic strands), ensuring selectivity, life-cycle, non-fouling properties and reusability, and (iv) Packaging for delivery of the pre-functionalized biochips.

Achievement of wearable and/or implantable photonic biosensors. Full demonstration of the applicability of biosensor technologies for real life requests will mainly be beneficial for clinical diagnostics (i.e. early cancer diagnostics, infectious diseases diagnosis in resource-limited settings), and food and environmental control (i.e. microbiological infections and rapid detection of toxins). In this context, custom packaging solutions and application-specific functionalities will need to be provided. Technology transfer and commercialization of the biosensor technology represents an important challenge that will need to be mediated by an enhanced usability to facilitate a smoother transition between laboratory prototypes to products, leading to increased commercialization potential. Such photonic biosensors will need to be equipped with pre-commercially developed platforms, tools, IP, open-source and custom applications targeted to filling gaps in diagnostics.

Integratability of photonic transducers with Microfluidics and Nanofluidics (Optofluidics). The exchange of information between bioentities and photons usually require performance in fluid media. Advanced microfluidic systems can be automated and remotely controlled by software, which dramatically minimizes sample handling and manipulation by the user and scales down the system's overall footprint. Full integration of optofluidic systems in hand-held platforms will be mandatory, including micro/nanofluidics, optical subsystems and interfaces, biocompatible encapsulation, thermal management, hardware, and software. In order to meet the evolving performance and functional requirements of the component technologies, the following aspects will need to be considered: (i) Deliver technologies to enable development of autonomous, reactive platforms that can be embedded in user environments, and (ii) Delivering technologies for building customized polymer microfluidic components.

Development of nanophotonic and/or plasmonic probes for optical interaction with living entities. Along the lines of the previous points, nanophotonic devices show an enormous potential to interact with small living entities, like cells, organelles, bacteria, viruses and even DNA molecules. The development and exploitation of this intercommunicated bio-photonics platforms, beyond standard sensing and detection schemes, will be a new area full of potential. As an example, nanophotonics is a key technology in optogenetics using neuron cells, which shows the potential of this approach for effective interaction with the brain using light.

4.3. Programmable and interconnected optical networks and technology: towards photonics integration 2.0

The advent of photonic integrated technologies offers the ability to fabricate complex systems that include a large number of interconnected elements. This brings the challenge to exploit that complexity for new functions, being able not only to manufacture these systems but also to control and stabilize them. The combination of advances in photonic integration and fiber-optic technologies are promising for a growing set of potential applications in sensing, optical communications, microwave photonics, and information processing for classical and quantum applications. Outstanding efforts along these lines are explored in the key challenges below.

Fiber-optic technologies and photonic networks

Scaling of the global optical fiber network capacity. Meeting the constantly increasing demand for information capacity beyond the “big crunch” will require finding a way to partially compensate fiber nonlinearity while at the same time increasing the usable bandwidth and implementing energy-efficient amplification solutions. New solutions and systems for multi-core or few-mode fibers will have to be developed, as well as more efficient methods for physical or digital nonlinear mitigation, signal encoding, distributed and lumped amplification, all without dramatically increasing energy consumption. These tasks require a deep understanding of linear and nonlinear interactions in optical fibers and represent formidable technological challenges, currently the target of multiple international collaborations.

Expanding the capabilities of optical fiber lasers. Over the past 20 years, fiber lasers have been steadily replacing other laser technologies in a variety of applications in all fields of industry and science, owing to qualities such as their reliability, stability, energy efficiency, compact size and reduced cost. Example of application fields include material processing, telecommunications, spectroscopy, and medicine. Still, additional potential areas of application are off-limits due to current technological limitations to characteristics, such as maximum pulse peak power, and will be the focus of important efforts over the coming years. Overcoming such limitations is not only a considerable experimental challenge, but also a major driver in fundamental studies about the complex dynamics of highly nonlinear systems.

Improvements for optical fiber metrology and distributed and lumped fiber sensors. The improvement of measurement standards for optical fibers and optical fiber technologies is of extreme importance not only to meet the increasing precision demands of research, but also to set the quality standards and product specification requirements for industry. In particular, distributed and lumped fiber sensors technology will have to improve their sensitivity and range, and new methods for real-time processing of the vast amounts of data recovered will have to be implemented. Applications in environmental sensing will become more relevant than ever, in order to face the global challenge imposed by climate change, as well as those dedicated to improving the efficiency and sustainability of smart cities, industries and communities.

Reconfigurable quantum networks. The experimental realization of reconfigurable quantum networks in photonic platforms is an open challenge with potential applications in different contexts such as computation, transport, or emergent phenomena. In particular, the use of frequency combs interacting with non-linear media offers a promising direction in the context of reconfigurable quantum networks, differing from other platforms as they allow for an easy reconfiguration of the topological structure. Beyond the challenge of an experimental demonstration, the platform based on optical frequency combs may open up the possibility to test several fundamental questions and concepts relevant for quantum technologies addressing both the role of quantumness through squeezing and entanglement, as well as of topology, and eventually exploring non-Gaussian states of light.

Information processing in the optics domain

Photonic platforms for analogue computing. Analogue computation is at the basis of information processing with neural networks as well as of quantum simulations or computation with Ising machines. Complex networks represent the core of most of these schemes and their photonic implementation is indeed a promising avenue subject of recent theoretical and experimental efforts. Future efforts to develop this field will need to consider both quantum and classical implementations of such computation schemes, comparing their performance and respective advantages. The definition of clear benchmarks to quantify possible advantage of integration of computation and communication in photonic platforms is also challenging.

Public data repositories for optical and digital image processing. Deep neural networks have significantly surpassed previous approaches focused on handcrafted image features for a range of image recognition tasks. One of the main challenges of deep learning methods is how to train models that are well adapted into real world settings not previously seen. An important related challenge in this area is the availability of appropriately annotated large-scale datasets. Public data repositories will be essential for the advance in the field. Promising applications in this field include super-resolution techniques and multimodal imaging in microscopy and astronomy, as well as innovative models for scene analysis and autonomous vehicles.

Improved processing methods for robot vision and medical image processing. Robotic vision must bear in mind that its immediate outputs will ultimately lead to real-world actions. It is important that computing systems, e.g. deep learning, can reliably estimate the uncertainty in their predictions in order to be integrated into robotics. Future trends will be to improve along three conceptual axes: learning, embodiment and reasoning. In turn, the medical applications making most use of computer vision technologies involve detection, segmentation, registration and classification. One of the key strategies for making full use of computing advances in medical imaging is getting involved experts from other fields, in particular Computer Vision and Machine Learning. Future efforts must also target the processing of information directly in the optics domain with suitable systems and devices.

Upscaling of event-based vision sensors. A dynamic or event-based vision sensor is an imaging sensor that responds to changes in brightness in a local manner. In an event-based camera, pixels report changes in brightness independently and asynchronously as they occur, and staying silent otherwise. The first dynamic vision sensors (DVS) prototypes were demonstrated with a resolution of 128x128 pixels. The upscaling of the DVS prototypes to higher resolutions requires solving some challenges. First of all, the pixel complexity compared with conventional active pixel sensors (APS) limits the achievable resolution. Furthermore, the output bandwidth requirements to keep the high-pixel-sensitivity, high spatial-resolution and high-temporal resolution may not be affordable. Promising prototypes are fabricated e.g. on advanced 3D technology, which include event timestamping on chip to preserve temporal precision and a digital event processor for dynamic bit compression where several spatial or temporal criteria can be applied to regulate the output event rate.

Full-system implementations for photonic reservoir computing. To keep pace with the requirements of new applications, infrastructure, ultra-fast data processing, and power consumption, novel computing concepts will be key. To meet these requirements, different structures and types of photonic networks, and compatibility with novel hardware developments need to be considered for information processing in the optics domain. During the next years, the co-development of photonic hardware and software to produce photonic computing more versatile and adaptable to the required tasks will be one of the crucial factors for qualitative advances. Photonic reservoir computing stands out as a promising approach to information processing in the optics domain. Ideal candidates for the implementation of photonic reservoir computers include random lasers and networks of coupled semiconductor lasers. Example of potential applications for photonic reservoir computing include the processing of optical fiber communication signals, video streams, and medical flow cytometry.

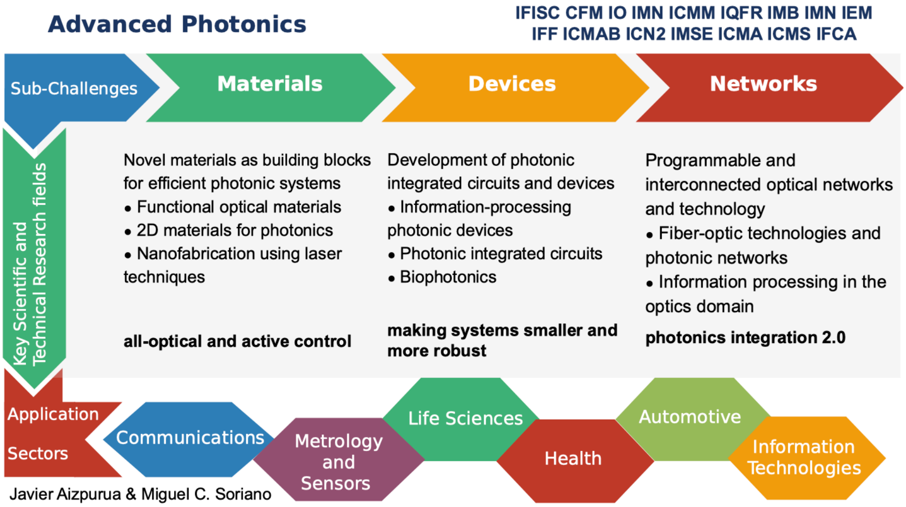
5. EPILOGUE

In the area of advanced photonics, CSIC has a privileged position enabled by a wide range of research centres and groups. These groups work in fields that cover all the photonics value chain, from fundamental studies (nonlinear optics, metamaterials) to applications (biosensors, laser semiconductors), while addressing all stages from design to (small volume) manufacturing.

CSIC is therefore in an advantageous position to tackle the challenges of Advanced Photonics due to its multidisciplinary nature, a key element that should be fostered and encouraged in order to further advance the leadership of CSIC in this field.

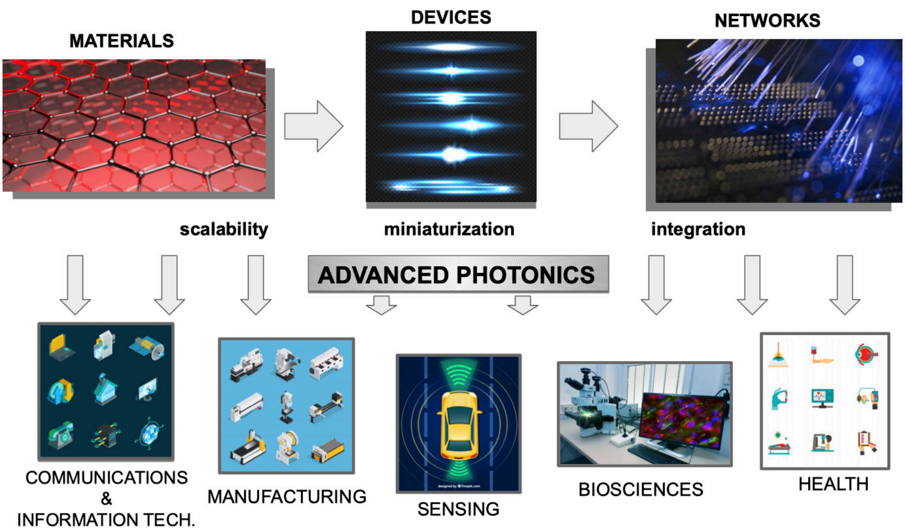
ANNEX: ONE SLIDE SUMMARY FOR EXPERTS

FIGURE 1.1–Advanced Photonics for experts.



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

FIGURE 1.2–Advanced Photonics for general public.



CHALLENGE 3

ABSTRACT

This section is centered on the challenge of finding near term applications of quantum computers in real-life problems and setting up the foundations for a national quantum computing industry. The chapter shows the strategic value of quantum computing research at CSIC, as well as the opportunities and challenges ahead.

KEYWORDS

quantum computing | quantum sensing | quantum technologies | nanofabrication | quantum machine learning

CHALLENGE 3

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1. EXECUTIVE SUMMARY

Quantum computing holds the promise to provide solutions for complex problems in engineering, quantum chemistry, finance, logistics and other areas. It is expected that, in the following years, quantum computers with an intermediate size and limited functionality will be commercialized. Unveiling the potential of even more advanced quantum computers will require intensive research on qubit design and fabrication methods.

This chapter summarizes quantum computing research at CSIC and the challenges that must be overcome for this technology to have a significant impact in real-life applications. Theory groups are working on developing quantum algorithms and quantum machine learning methods for short-term applications, as well as understanding what device characteristics are required to achieve a quantum advantage. Research is also focused on emerging quantum computing paradigms based on topological, semiconductor and molecular qubits. Finally, a transversal research effort at CSIC is addressing technologies that will be crucial for an eventual future quantum computing industry, like fabrication and detection methods.

In addition to direct applications in quantum computing, quantum research at CSIC will contribute to other scientific and technological advances. For example, it will provide new insights in computational problems, leading to quantum-inspired methods. Quantum computing research will also provide us with a deeper understanding of complex phases of matter. Finally, the battery of experimental methods used in quantum computing have a clear potential in sensing or metrology.

More than a dozen research groups at CSIC are working on those topics. At the time of writing, quantum computation is a lively international research field involving academia, private companies and startups. For example, quantum algorithms developed at CSIC can be tested remotely in commercial computers. Also, theoretical ideas and specific technologies developed by the council may be often implemented in collaboration with international partners. The internationalization of quantum computing research offers us the invaluable opportunity of inserting CSIC's high-value research in the quantum computing ecosystem.

This chapter shows that CSIC is in a strong position in key areas of quantum computation. With the required amount of institutional support, CSIC can play a leading role in the development of an emerging quantum computing industry.

2. INTRODUCTION AND GENERAL DESCRIPTION

Quantum computing is the use of quantum physics to carry out computations with speed or efficiency that outperforms conventional devices. Proof-of-principle quantum computations were already implemented in the 90's, and in the last decade the private sector has given a decisive impulse to the field. Quantum computing will open new opportunities in data processing, material design or chemistry, for example.

Quantum computing is part of the more general field of quantum technologies, which also includes quantum sensing and metrology, quantum simulation and quantum communication. Technical and theoretical advances in quantum computing will have strong implications for a broader range of technologies, an aspect that is highlighted and stressed at different points along this chapter.

2.1. Approaches to quantum computing

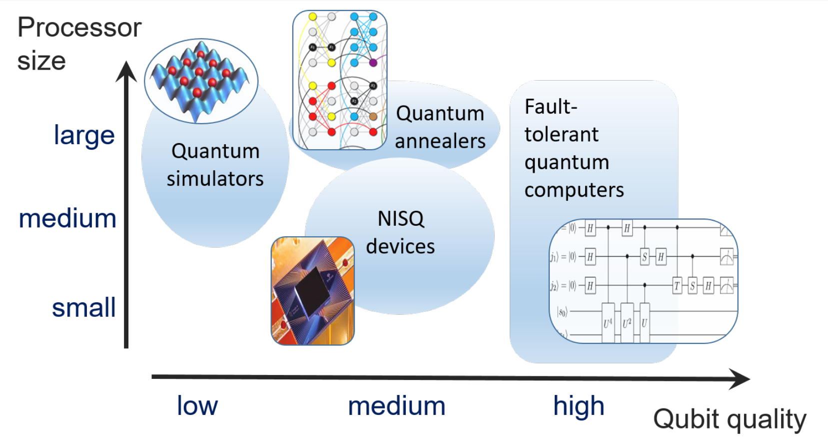
Harnessing the power of quantum implies enormous technical challenges. As of today, crystals of trapped atomic ions and superconducting circuits are the most advanced platforms, with each setup having its advantages and limitations. Other setups in an earlier stage include topological qubits and quantum computing technologies based on silicon. A recent perspective of the field from the European point of view can be found in [Quantum Flagship Initiative, 2020].

We can differentiate between two main kind of approaches: *fault* and *non-fault tolerant* quantum computation. By fault-tolerance we understand the resilience of a quantum device to noise and imperfections. Similar to the case of classical computing, resistance to error is achieved by a redundant encoding of quantum information which leads to error correction. Fault-tolerant quantum computing has a well-developed theoretical framework, and it is well established that it offers an amazing computational power. However, it requires very large quantum computers, due to the necessity of a large number of physical qubit to represent a single logical, 'useful', qubit. For example, to carry out a quantum computation that is able to break a current cryptographic code with 2048 bits, requires a number of physical qubits between 106 and 107.

Whereas the above mentioned challenge may be ultimately feasible, it is likely that in the following 5-10 years, quantum devices will not be able to fully implement the fault-tolerant quantum computing paradigm. They will instead belong to the generation of Noisy Intermediate-Scale Quantum (NISQ) devices, a term recently coined in Ref. [Preskill, 2018]. This has led to an increasing interest in 'non-fault tolerant quantum computing'. The latter does not require a high degree of control or very large number of qubits, but it may lead to the solution of certain computational tasks like optimization and the simulation of material properties. Non-fault tolerant devices include quantum annealers, which are specifically designed to solve certain optimization tasks. Another approach is hybrid quantum-classical computing, where a quantum device is utilized together with a classical optimizer. Finally, there are quantum devices where controllability is sacrificed for scalability. This is the case of quantum simulators, which are hardly programmable, but allow us to recreate complex states of condensed matter.

The division between fault and non-fault tolerant approaches shapes research on quantum computing. Fault tolerant quantum computers are very challenging to build but their working principles rely on a theoretical paradigm that has been developed in the last decades. The bottleneck here is in the hardware: we need to advance our theoretical understanding and technical capabilities in order to accurately control the millions of qubits that are needed for quantum error correction. We find the opposite situation in non-fault tolerant quantum computing: even when any technological advance in hardware is welcome, the

FIGURE 3.1–Approaches to quantum computing in terms of size and qubit quality. Noisy Intermediate Scale Quantum devices are of medium size and qubit quality with over 100 qubits are expected to be available in the following years.



main bottleneck is actually in the quantum software - work must be done to find out what is the real use and quantum advantage, if any, of those devices. Even in non-fault tolerant quantum computing we find approaches based on faulty quantum gates, as well as more radically innovative approaches beyond Von Neumann architectures, like non-conventional quantum computation both for quantum machine learning and quantum simulations tasks.

Finally, we mention that physical implementations of qubits beyond superconducting qubits and ions are under investigation, as well as realizations of computation in continuous variables and in photonic systems, offering cheaper and scalable opportunities.

2.2. The quantum computing ecosystem

At the basis of the emerging quantum ecosystem, we have academic research groups. In the last years many companies have started quantum computing projects, including Google, IBM, Amazon and Microsoft, some of which have already commercialized access to their own quantum devices, as well as provided open access to some of prototypes. Startup companies have been formed to offer quantum software or hardware services.

Governments have funded programs at national or European level (such as the European Quantum Flagship programme [Riedel et al., 2017] or the US National Quantum Initiative [Raymer and Monroe, 2019]), with the intention to coordinate academic and industry partners in quantum technology, with a strong focus in quantum computing. In the educational front several initiatives are being developed to organize graduate programs (see for example [Quantum Flagship Initiative, 2019] on the European perspective).

At the moment of writing, Spain lags clearly behind other European countries in terms of hardware and fabrication capabilities. Quantum computing research in the country is mostly theoretical and concentrated at a few, to some extent dispersed, research groups at CSIC, universities, and other research centers. Contrary to other countries, Spain has not proposed or committed at national level its own quantum technology funding program. This could lead to the wrong conclusion that the country has lost the opportunity window to enter in this exciting field. On the contrary, there is a vibrant quantum computing research community (see for example, www.ritce.hbar.es, for a national network on quantum technologies led by CSIC).

2.3. Structure of the chapter

Subsection 3.4.1 is focused on the short-term perspective for quantum computing, which mostly relies on non-fault tolerant approaches. A theoretical effort is required to clarify whether and how quantum computation can be applied to scientific and real-life problems in the following years. Furthermore, non-conventional approaches to quantum computing are presented in the context of machine learning. Strategies rely on a multidisciplinary effort involving theoretical physicists, engineers, mathematicians and experts in quantum chemistry [Preskill, 2018]. To bring fault-tolerant quantum computing into reality will require a leap in qubit fabrication technology and design, which is the focus of subsection 3.4.2. Any proposal for quantum computing hardware must fulfill at least two requirements: to be able to provide us with robust qubits that can be produced in large numbers and also to include a method to efficiently communicate distant qubits. Several candidates have emerged in the last decade, including molecular, silicon and topological qubits.

Finally, together with quantum algorithms and novel qubit architectures, research on quantum computing also involves the development of enabling technologies, like detectors and fabrication methods, whose development is the focus of subsection 3.4.3. Those technological advances are pursued by a transversal research effort that can bring large fault-tolerant quantum computers closer to realization. Also, enabling technologies may be crucial for more efficient and larger non-fault tolerant systems.

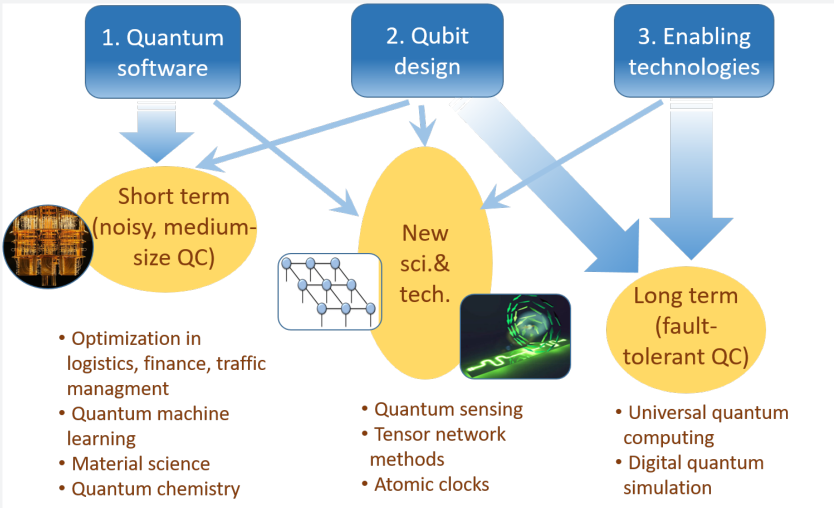
3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Quantum computing and closely related technologies have a huge potential for scientific, societal and economic impact. The next decade will be decisive to clarify how much of this potential turns into real applications.

Short-term impacts. - Applications of quantum computing are already being explored by startups, financial institutions and other companies with a strong demand of computational power. The next generation of commercial quantum devices may surpass conventional devices in a at least a few specific computational tasks. First real life applications are expected in sectors where numerical problems can be conveniently translated into the current quantum software paradigm for non-fault tolerant devices (see [Mckinsey Quarterly, 2020] for a recent perspective from the private sector). These include: quantitative finance (portfolio optimization, risk assessment), logistics, and traffic management, for example. In essence, the first generation of quantum computers could be utilized in a limited set of activities where, however, any improvement of computational performance may have a strong impact. In a longer term perspective (5-10 year) other economic activities could join the quantum computing ecosystem of applications. These could include a number of tasks beyond optimization, like quantum chemistry or material design, quantum machine learning and pattern recognition.

Longer-term applications. - The impact of quantum computing in a longer term perspective (beyond a 10-year time-scale) will fundamentally depend on technical advances in qubit and circuit fabrication. A game changer would be the availability of fault-tolerant quantum computing with large number of qubits. Societal implications include the breaking of current cryptographic codes and the need for the implementation of post-quantum cryptography for secure classical communication (see Chapter 5). However, fault-tolerant quantum computing would lead to the realization of the circuit model of quantum computation in full glory, which is a versatile tool to simulate any possible quantum dynamics. This would allow to a plethora of advanced applications in quantum chemistry and quantum machine learning, without the limitations of

FIGURE 3.2—Expected impacts of the main lines of work. Short-term impacts are expected from noisy, intermediate scale quantum computers, whereas universal quantum computers are a very ambitious, longer-term goal. New theoretical and technological advances will be a byproduct of quantum computing research.



intermediate quantum noisy devices. Looking at even cheaper solutions, photonic implementations currently explored in classical systems (Chapter 2) could become widespread in quantum machine learning and artificial intelligence.

Scientific impact: quantum computers to advance quantum science. - Quantum computing and related technologies will not only have a technological or economic impact, but they will also lead to a deeper understanding of quantum complex phenomena. This, in turn, will feedback into new applications. For example, short-term quantum computers will allow physicists to experiment and obtain a better understanding of non-equilibrium quantum dynamics, which may lead to novel proposals for variational quantum optimization algorithms. Furthermore, quantum computing can help us understand scientific issues which, not being of direct commercial applicability, will have consequences for our future, such as problems in chemistry or protein folding, for example.

Emerging new technologies. - Last but not least, quantum computing will necessarily lead to advancements with implications in other technologies like quantum sensing and quantum communications. An example is the development of Josephson nanocircuitry, which is key in qubit design, but can be also used in the development of, e.g., radiation detectors, quantum-limited amplifiers and magnetic sensors (see 3.4.3). Even theoretical quantum computation has already had a strong impact in condensed matter physics. For example, numerical methods based on tensor networks were originally developed to simulate quantum circuits, but they have evolved into efficient numerical tools to describe complex quantum systems.

4. KEY CHALLENGING POINTS

4.1. Quantum algorithms and quantum machine-learning for practical applications

Is it possible to address real-life problems with current quantum computing technologies? If so, what are scientific fields and economic and industrial activities where short-term quantum computing can offer a clear *quantum advantage*?

Quantum algorithms for real-life applications

Research groups and companies like Google and IBM are close to showing quantum computational capabilities exceeding those of conventional computers. Theoretical research will be crucial for an emerging quantum computing technology. Quantum software can nowadays be developed and tested remotely, thus 'democratizing' access to this experimental platform. Furthermore, the design and fabrication of the next (2-5 year) generation of quantum computers is going to be determined by what we learn now about the theory of quantum computing.

A key challenge (2-5 years) is the development of algorithms with a clear quantum advantage with respect to the best classical ones. It is likely that those algorithms will be hybrid quantum-classical methods, particularly efficient in solving optimization problems. A multidisciplinary approach will be needed here, with collaborations between physicists, mathematicians and quantum chemists, for example. If efforts to develop those algorithms succeed, the next steps (2-10 years) will consist of the creation of an ecosystem of quantum applications involving CSIC, academic partners and industry. We expect that knowledge gained here can be even further extended for quantum-inspired classical software, that is, standard software that benefits from ideas initially devised for quantum computing.

Simultaneously to the investigation of quantum algorithms, theoretical advances will guide the design of new hardware in the following years. In particular, theoretical research at CSIC has to be carried out to determine characteristics of quantum hardware that are optimal for practical applications, in terms of qubit design or connectivity, for example. Furthermore, this theoretical insight can be used to find out new applications of devices, such as quantum simulators with ultracold atoms which share many characteristics of quantum computers. For example, CSIC has recently participated in a theory collaboration that has shown applications of ultracold atom simulators in quantum chemistry.

Quantum machine learning

Artificial neural networks represent a rather advanced computation strategy whose potential has recently started to be also explored in the quantum regime. A main advantage of moving into the quantum regime is that even small networks composed of a few units have a large computational potential due to the large size of the Hilbert space. We expect developments in the following 5-10 years that will pave the way for experimental implementations either in photonic, solid state or atomic systems and for testing their performance in practical tasks. This will be the breakthrough that is needed to start to exploit the potential of quantum machine learning in big data processing in the next 10 years. Implementing machine learning in quantum devices presents several challenges from both the fundamental and experimental points of view. Different architectures and configurations need to be assessed in connection to specific tasks (pattern recognition or time series prediction, for instance). A common goal is the demonstration of a clear quantum advantage offered by the unconventional quantum approach.

Theory groups at CSIC will start considering specific architectures, like reservoir computing, collaborating with experts in its classical implementation, to later move towards its quantum generalization. Different physical platforms are being assessed both with networks of qubits and continuous variables, addressing their specificities and analysing their performance in different data analysis tasks. The acquired know how will be useful not only to bridge the fields of classical and quantum machine learning but also to address alternative computation strategies, neuro-inspired or based on complex networks, like Ising machines.

Exploring the uses of quantum computing in quantum chemistry

Quantum algorithms may be useful in physical-chemical applications. Here, however, the small number of currently available qubits and the existence of errors, impose severe limitations. One of the key issues is thus the identification of the precise quantum dynamics that can be simulated with present or near-term quantum devices.

The first challenge to be addressed is the translation of Quantum Chemistry problems from the usual language of functions and operators commonly employed in Molecular Physics into quantum computing algorithms. This translation has to be as general as possible so as to explore the largest landscape of applications. Formalisms such as the reduced density matrix constitutes an appealing alternative to explore. In the following 5-10 years, the development of this kind of strategies is subject to the progress in the design of the quantum devices, the ultimate limit for the full performance of this new technology.

Nowadays, the investigation of the most efficient hybrid quantum-classical approaches represents the best possible alternative in case the above mentioned progress in the engineering of the computing devices is slower than expected. The main efforts should be directed to identify the optimum manner to incorporate quantum computing solutions to specific steps of elaborated and complicated numerical calculations. A promising field to explore this procedure is Quantum Chemistry where the definition of proof-of-concept electronic structure calculations and cost-effective approximations can serve as ideal platforms for near-term simulations. A crucial benchmark is also found in the design of the necessary hybrid tools for a complete description of the dynamics of molecular systems covering from the treatment of the nuclei motion, the variational calculation of bound states, propagation of either wave packets or wave functions to spectral simulations.

Tensor networks for quantum inspired-algorithms
Tensor networks, or matrix product state algorithms, are currently one of the main mathematical tools to:

(a) simulate numerically the behavior of complex quantum systems, such as quantum computers, and at the same time, (b) understand such complex systems (e.g. topologically order).

Numerical methods based on tensor networks were originally introduced at the beginning of the 2000's to efficiently describe quantum circuits. They work by representing a quantum state with a controlled amount of entanglement that determines both the computational cost and the quality of the description.

Tensor networks can, to some extent, describe the physical state of a real quantum device. In what is known as a quantum-inspired approach, they can form the basis for classical software that mimics the working principles of a quantum computer but which can be executed in a conventional computer. Furthermore, one can also develop classical numerical methods that use classical analogs of tensor networks which are extremely efficient to handle correlations between variables in complex problems.

The mathematical theory of tensor networks is extremely complex: it faces computational complexity no-go issues and, it also requires to combine different mathematical disciplines, such as numerical analysis, combinatorics, probability theory, convex analysis, operator algebras, algebraic topology or category theory. More practical aspects are also relevant for real-life applications, like possible strategies to adapt the tensor network to each particular problem. An interdisciplinary approach is then unavoidable.

If those challenges are overcome, tensor networks could be an invaluable tool in the future, with a potential impact comparable to that of neural networks. The participation of the private sector has just begun with a few start-ups and the opening of a free access library for tensor networks by Google, for example. In the following 2-5 years these methods will be tested in real applications in finance, quantum chemistry or biophysics, for example.

4.2. Resilient qubits and scalable architectures for quantum processors

Which physical implementation of qubits will eventually dominate in future quantum computers is still unclear. Small or medium size computers (50-100 qubits) without error correction are already or will be soon on the market. This is the so-called NISQ generation.

In 2020, the leading technology is superconducting circuit qubits but others cannot be ignored. At CSIC, several groups are working on physical implementations for both the NISQ era and searching for noise resilient qubits that, eventually, will allow them to build larger computers.

Molecular and magnetically-based qubits

Replacing trapped ions or circuits by molecule based qubits may be an advantageous manufacturing strategy. Like atoms, molecules are intrinsically microscopic, thus perfectly reproducible and quantum by nature. Besides, their properties can be tuned via chemical design in order to increase spin coherence times, enhance their coupling to circuits or even integrate several qubits in each of them. The main advantages of this approach are then a significant reduction of fabrication costs, a higher integration potential and nearly unbound design possibilities. At CSIC, in the next 5 years, we target two specific experimental breakthroughs, which represent the two necessary milestones to realize a scalable and fault-tolerant architecture based on magnetic molecules. The first is the development of molecules able to implement specific quantum error correction codes, i.e. to incorporate several physical spin qubits that together act as a noise resilient logical qubit and to perform the necessary quantum gates. The second is the experimental demonstration of coherent coupling (the so-called strong light-matter coupling) of a superconducting resonator to a single molecular spin. Providing a suitable technology to wire distant molecules, thus making possible to fabricate NISQ-type processors. Combined with the first milestone it also provides a route to build large quantum computers. To fulfill this mission, the key figure is the single spin-single photon coupling between the molecules and the superconducting circuit. Several routes are being investigated using nanoconstrictions or optimized LC-resonators to enhance locally the coupling and reach the strong coupling regime. An additional relevant milestone is to investigate the potential of these systems as quantum simulators of magnetic materials. Here, an important advantage of molecules is the existence of multiple options to design them as qudits allowing to simulate spin systems with almost arbitrary spin or, in quantum computation, to use extra levels to self-correct the logical levels.

An appealing candidate for molecular qubits are radicals, because of their long coherence times the possibility of fine-tuning their magnetic/electronic properties by chemical synthesis. Despite these advantages, the technological development of molecular qubits needs the understanding of the intermolecular interactions, the decoherence mechanisms and the molecule/substrate (e.g. superconducting circuit) interaction. In the CSIC, in the next few years, we will investigate all of them together with the synthesis of radicals with longer decoherence times, stability and integration, e.g. in superconducting circuits.

A topic of increasing attention is the coupling of both circuits and molecular qubits or qudits to spin waves. The spin waves and magnetic oscillations have a strong direct coupling not only to the microwave photons of a cavity and to the molecule spin, but also to other physical degrees of freedom, as the mechanical modes (phonons) through the magnetoelastic effect. Indirectly, through the interaction with atomic electrons, spin waves couple also to optical photons. These couplings can be used to devise quantum transducers that encode the quantum information stored in the qubits into light or acoustic waves. Moreover, a promising but still unexplored possibility to devise a quantum computer is to couple a system of magnetic qubits (the molecule spins) solely through their interactions with the spin waves of a magnetic substrate. This possibility is supported by the recent progress in the ability to control the spin waves. The spin waves on modulated chiral magnetic ground states, like chiral solitons or skyrmions, are particularly interesting since they naturally contain confined modes similar to the phonons of a cavity.

Semiconductor-based quantum computing

Current computing technologies are based on silicon, and the semiconductor industry for mass production is very well developed. For that reason, the option of exploiting the full potential of silicon for quantum devices is actually being explored worldwide.

Silicon devices naturally generate binding potentials where single electrons, and their spins, can be controlled, thus providing a two-level system as the basic block where quantum information can be stored and manipulated. Long spin coherence times in silicon is another clear advantage over other possible semiconductors. If the current fabrication challenges can be solved, this platform could overtake the existing superconductor circuit-based quantum computers.

Most of the research in semiconductor-based quantum computing is focused on electron spin qubits hosted in quantum dots. They are highly tunable and they have been implemented in different semiconductor materials. In particular, hole spins in semiconductor quantum dots are attracting significant attention as candidates for fast, highly coherent spin qubits. Long coherence times are due to the weak hyperfine coupling to nuclear spins, and rapid operation times are due to the inherently strong spin–orbit coupling, which also allows spin states to be controlled locally with electric fields applied to gate electrodes.

One of the most important challenges faced by silicon and other semiconductor based quantum computing is the efficient coupling and transfer of quantum information between distant qubits. New ideas and proposals to address this challenge will be crucial for the future of this technology. One possibility is to use long arrays of semiconductor quantum dots, which have been recently implemented. Recent theoretical proposals from CSIC include adiabatic protocols, and shortcuts to adiabaticity to efficiently transfer spin entangled electrons between the outer dots of a quantum dot array. Planned research will extend the previous protocols to include spin-orbit interaction and the transfer of spin entangled holes.

As an alternative to generate interactions and quantum operations between distant semiconductor qubits, CSIC will also consider hybrid systems such as quantum dots coupled to superconducting cavities, which involves the design of refined methods to couple the electronic spin and the cavity electric field. Methods are being developed to induce strong spin hole-photon couplings.

Semiconductor quantum dots also allow for a radically different approach in which the hyperfine interaction is sufficient to initialize, read out and control single. Si nuclear spins, thanks to their long coherence times. High-fidelity projective readout and control of the nuclear spin qubit, as well as entanglement between the nuclear and electron spins has recently been experimentally demonstrated. This, together with the finding that both the nuclear and electron spin retain their coherence while moving the electron between quantum dots, allows to envision long-range nuclear–nuclear entanglement via electron shuttling and therefore to establish nuclear spins in quantum dots as a powerful new resource for quantum computing. To investigate spin entanglement between distant nuclei surrounding distant silicon quantum dots is one of the pursued theoretical research lines at CSIC.

Topological qubits

Majorana quasiparticles appear at boundaries between topological superconductors and topologically trivial materials (such as e.g. an insulator). Importantly, such bound states occur precisely at zero energy. Such zero energy quasiparticle has Majorana character since it contains an equal superposition of an electron and a hole and it is thus its own antiparticle. Two Majoranas localized at very far ends of a topological superconductor define a non-local fermion state whose occupation can be used to define a non-local (topological) qubit.

Remarkably, zero-energy Majorana quasiparticles do not follow fermion statistics—like the original particles predicted by Majorana in the context of high energy physics— but rather possess non-Abelian exchange (braiding) statistics. Using this exotic form of quantum statistics one can implement quantum gates that act on the topological qubit. This braiding statistics and their high resilience against local sources of noise owing to non-locality makes topological qubits based on Majoranas very attractive for quantum information processing.

During the last few years, there have been a great deal of efforts towards detecting Majoranas in various solid state platforms, including semiconductor materials proximitized by superconductors, topological insulators, graphene and van der Waals heterostructures, etc. A few experiments (mostly with semiconductors coupled to superconductors) have reported results compatible with the presence of Majorana quasiparticles, although qubits based on Majoranas have not yet been demonstrated. A great effort is now dedicated to make use of the know-how of the superconducting qubit community to implement Majorana-based qubits in topological superconductors.

In this context, alternative technologies are sought in order to replace the weak link in the Josephson junctions (every superconducting qubit contains Josephson junctions based on superconductor-insulator-superconductor tunnel junctions) and reach further operational functionalities. Such alternatives include semiconducting nanowires –also known as gatemons, two-dimensional gases and van der waals heterostructures, including graphene. The main goal of such alternative technologies is to have compatibility with large magnetic fields and tuneability by means of electric fields (gate voltages), both of which are key requirements to reach a topological superconductor state with Majoranas, as predicted in all these platforms.

A key challenge (2-5 years) is to acquire a full understanding of these alternative junctions and their microwave response in circuit QED architectures in order to accomplish the long-sought milestone of hybrid Majorana-based topological qubits in transmon geometries. Such hybrid qubits have already been demonstrated (although not in the topological regime). We expect that, very soon, hybrid quantum devices working with topological qubits will be available. A thorough theoretical understanding of such hybrid qubits is essential for achieving the great possibilities that non trivial topology offers in quantum computing, including resilience to noise, quantum decoherence and non-abelian braiding.

Apart from more standard platforms for topological superconductivity, other less-explored possibilities to obtain Majoranas include topological semi-metals, Weyl, Dirac and nodal lines with induced p-wave superconductivity. They have potential advantages compared to other platforms as it has been proven that topological properties in ultrathin films of Dirac semimetals could survive even at room temperature. Due to advances in the fabrication of thin films of different materials presenting Weyl or Dirac nodes in the Fermi surface there are currently experiments underway inducing superconductivity in the surface Fermi arcs of these systems. We expect a wealth of experimental results in the next five years. However, a theoretical research of superconductivity in these systems is still in its infancy. Our research aims at providing a deep theoretical understanding of superconductivity in these materials. As topological semimetals, are 3D materials, the formation of edge states for Majoranas may be more dependent on sample geometry and reduced dimensionality. These effects will be explored by our simulations. After a good theoretical description of the superconductivity of topological semimetals, both intrinsic and induced by proximity effect, is achieved the next step would be to study possible physical implementations of braiding in these systems. We foresee a clarification of the advantages and drawbacks of different kinds of topological qubits, leading to practical implementations in the next five to ten years.

4.3. Enabling technologies for quantum computing

CSIC is also focused in advancing fabrication and manufacturing tools that will allow to scale the number of qubits and gates. This work will be crucial for a future quantum computing industry. This research has the added value that some of these techniques can be actually used in other applications from quantum simulation to the development of quantum sensors.

Superconducting quantum detectors

Wiring molecular qubits (see 3.4.2) by means of superconducting circuits requires the fabrication of optimal resonator LC- arrays in order to enable the coherent control, communication and read-out of the qubits. Superconducting microwave resonators must show very long coherence times and interact optimally with the spins which can be achieved with a high quality factor and a specific geometric design. At CSIC, we are working in this enabling technology developing the fabrication of these circuits.

Lumped-Element Superconducting Resonators consist of a series inductance capacitance circuit coupled in parallel to a single transmission line. In contrast to coplanar waveguide cavities, these resonators allow a much larger freedom on the geometry design, which enables to control key parameters such as the resonance frequency, quality factor and the photon magnetic field, thus the coupling to spins, without affecting the transmission properties of the device. Furthermore, they are intrinsically multiplexable on-chip: i.e., a single line allows reading-out several qubits at different frequencies, thus contributing to the development of large-scale hybrid quantum processor as an alternative to the existing schemes based on superconducting qubits. Moreover, they can be used also as on-chip Electron Paramagnetic Resonance spectrometers.

Based on our expertise on the development of superconducting lumped element kinetic inductance detectors, we plan to develop optimized lumped resonators for its coupling to both spin ensembles and individual nanomagnets. Using microwave electromagnetic simulations, parameters will be tailored and optimized in order to maximize the expected coupling rate between the spins and microwave photons. Even though strong coupling between and spin ensembles has already been demonstrated, achieving strong coupling to a single spin is still a huge experimental challenge. For this goal, different approaches will be explored as the use of parallel plate capacitors for diminishing the parasitic impedance of interdigitated capacitors, concentrating the photon magnetic field in nanoscopic regions by locally reducing the width of the inductor line or even the development of hybrid carbon-nanotubes/superconducting resonators for the confinement of the resonant mode magnetic field. These developments rely not only on the study of different designs but also on the optimization of the nanofabrication processes that will be validated by low temperature microwave characterization.

Quantum grade materials and device-fabrication processing

In the short term, a promising option are the so-called quantum co-processors, a combination of a few qubits with classical bits, integrated in 3D platforms that will also require cryoelectronics. Yet, a main drawback continues to be how to guarantee and standardize the manufacturing and actual performance of physical qubits, for all, as well as each, of the demonstrated technologies. In a longer term (> 10 years), fault tolerant quantum computing or quantum machine learning will be determined by our ability to control the connectivity, scalability and (limiting) operation conditions such as cryogenics.

With this in mind, at CSIC plans to address the following challenging points. CSIC aims to realize quantum grade materials (that is, materials with the required qualities to be used in quantum computing) and device-fabrication processing for superconducting circuit qubits, towards grading domestic capacity and contributing to international standardization. Challenges include validation of superconducting thin film deposition, Josephson junctions fabrication, benchmarking superconductor materials, etc. Besides, correlation of macroscopic electrical characteristics with the performance of quantum devices, for enabling e.g. in-line characterization. It is not only that comparative performance of algorithms on different hardware technologies is not available, but parameters and characteristics to assess manufacturing quality control have not been delivered. Finally, to use and integrate 2D materials in the various qubit technologies (superconducting, photonic, silicon-based and topological), for novel qubit concepts, improved performance or applications in e.g. quantum sensing or metrology, to fully deploy the manufacturing efforts in other (less demanding) applications.

The research above may have applications beyond quantum computing, in areas from space and high energy physics, radiation detectors or advanced biomedical imaging to cryoelectronics. An example are single photon detectors such as superconducting transition-edge sensors (TES). TES are very interesting for quantum communications, because of their broadband high quantum efficiency (98%), excellent photon number counting capabilities and negligible dark count rates. TES have been used for Quantum Key Distribution and are very promising for linear optical quantum computing and optical quantum metrology. This research activity will also increase and specialize the portfolio of the national quantum community.

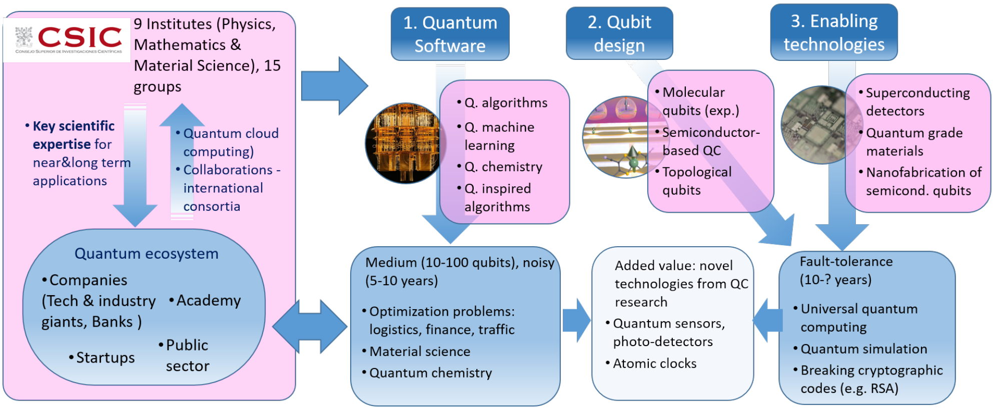
Nanofabrication of semiconductor spin-qubits

Within the quantum dot "industry" (see 3.4.2), the final aim is to integrate millions of qubits in a single chip, that would allow to implement an efficient quantum correction scheme and fault-tolerant quantum computing (see 3.2). This imposes critical challenges in terms of interconnections and fabrication accuracy, challenges that are related with the small dimensions of the quantum dots. Ultimately, the realization of one-million qubit chip requires research on multiple areas: semiconductor device physics, nanofabrication, circuit design, computer architecture and quantum algorithmic.

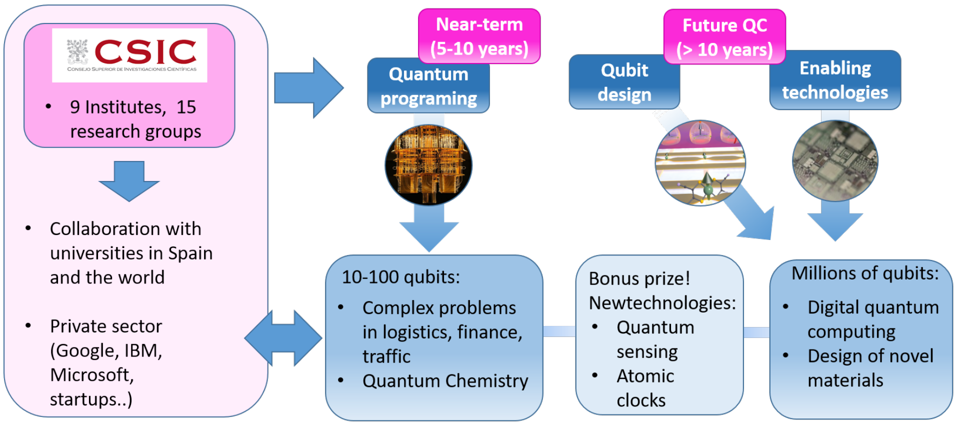
In terms of fabrication technology, high-density integration for semiconductor qubits requires an extremely dimensional accuracy in the nanofabrication process, which is beyond the present state-of-the art of the technology available in the semiconductor industry. While at present the preferred devices are based on electrostatic confined quantum dots, other approaches are being explored, like single atom transistors. In both cases, novel fabrication methods that will combine sub-5 nm dimensional control and high throughput need to be investigated. New paradigms combining top-down fabrication with self-assembly must be considered. The main advantages of self-assembly are intrinsic parallelism, nanometer precision and control of the process by proper definition of external guiding forces and/or geometries.

It is highly recognized that semiconductor qubits are a promising option for future highly scalable quantum computing (see for example the contribution on quantum computing at the last IEDM meeting, Proc. 2019 IEEE Int. Electron Devices Meeting). It is also accepted that the technological challenges are huge and could deserve more and longer effort than expected. However, the benefits from this high-risk challenge are large enough to presume a continuous progress in the area.

ANNEX: ONE SLIDE SUMMARY FOR EXPERTS



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC



CHALLENGE 4

ABSTRACT

Cyber-Physical Systems (CPS) and Internet of Things (IoT) are complementary paradigms in digitalization. Sensors and actuators, hardware designs and development platforms, architectures and computational frameworks, modeling, control and optimization, and potential applications are analyzed and presented from impact and main challenges up to strategic plan.

KEYWORDS

IoT sensors and actuators

IoT hardware designs and CPS platforms

architectures

computational frameworks

modeling

control and optimization

CHALLENGE 4

CYBER-PHYSICAL SYSTEMS AND INTERNET OF THINGS

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1. EXECUTIVE SUMMARY

Cyber-Physical Systems (CPS) and Internet of Things (IoT) are complementary paradigms of the digital transformation impacting all economy sectors/domain and society levels. Last decade, CPS and IoT have been growing, in parallel, in foundations and developments by sharing Internet, embedded systems and common targets such as tailored sensors and actuators, platforms and frameworks but also emerging methods and computational architectures. The next ten years require a big effort to produce new research-driven knowledge and breakthrough technologies to produce a qualitative change toward Society and Industry 5.0, the new paradigm led by Japan and included in the Horizon Europe framework program. The four areas of key challenging points identified are related with sensors and actuators, hardware designs and platforms, architectures and computational frameworks, and modeling, control and optimization. The impact on science and potential applications in sustainable agriculture, smart buildings and critical infrastructure, smart mobility, logistics, smart manufacturing, and health and well-being have been also identified. Furthermore, key

challenging points including scientific as well as technological and engineering issues are properly defined in new materials and novel sensors, specific hardware designs, computational architectures, signal processing and estimation, and modeling, control and optimization.

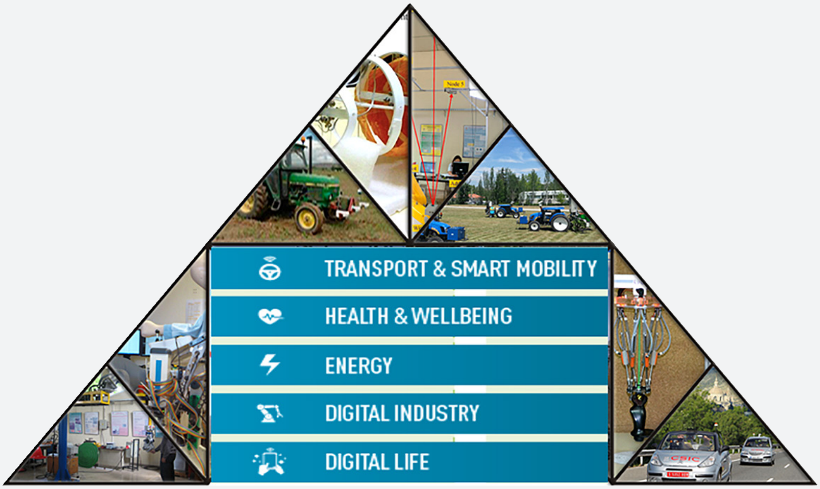
2. INTRODUCTION AND GENERAL DESCRIPTION

Cyber-Physical Systems (CPS) and Internet of Things (IoT) are complementary paradigms because both aim at integrating digital capabilities, including connectivity with physical devices and systems. Moreover, CPS and IoT include interacting logical, physical, and human components by integrating logic and physics. However, there are some differences [Greer et al., 2019]. IoT makes more emphasis on connecting "things" towards connecting "everything" whereas CPS put more attention on integrating computation, networking and physical systems. CPS and IoT are cross-cutting human-in-the-loop technologies covering a variety of all domains, Both paradigms have been driven in parallel by two independent scientific communities in Europe and USA, although CPS and IoT are closely related [Castaño et al., 2019]. Moreover, the core technologies for both IoT and CPS is the Internet as large-scale network and embedded systems. Therefore, nowadays both are considered complementary fields, and Industry 4.0 and the upcoming Industry 5.0 paradigm are special fields of application of CPS and IoT. Most initial IoT concepts were focused on traceable objects, with origins in the Radio-Frequency-IDentification (RFID) context [Greer et al., 2019]: low-power limited-capability "items" that are uniquely identified and can interact to provide location or simple information on state. The original IoT concept expanded over time to include "things" with sensors, offering new, more complex data streams that could be used for measurement and analytical purposes and to create value-added features and services [Griffor et al., 2017].

CPS are recognized as a top-priority in research and development. Although approaches in software engineering (SE) and control engineering (CE) exist that individually meet these demands, their synergy to address the challenges of smart CPS in a holistic manner remains an open challenge towards a System of Systems new paradigm [van Lier, 2018].

Worldwide research agencies such as National Science Foundation (NSF) in USA and the European Commission through the H2020 and the upcoming Horizon Europe framework program have identified CPS and IoT as a top

FIGURE 4.1—Relevant sectors of IoT and CPS in 2025 [ECSEL JTI, 2020].



priority for the next decade and allocated substantial funding to address the development of new paradigms, concepts, and platforms laying the foundation for future generations of System of Systems. CPS and IoT are becoming large-scale pervasive systems, which combine various data sources to control real-world ecosystems such as intelligent traffic control, smart production systems, smart buildings, urban water management, precision agriculture, among others. IoT and CPS have to control emergent behavior, be scalable and fault tolerant. In this book, the impact on the basic science panorama, potential applications and key challenging areas are analyzed.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

3.1. IoT sensors and actuators

At sensor level, techniques such as photon-counting are enabling radical departures from classical vision algorithms. New circuit structures improve the accuracy of depth measurements and are notably reducing the form factor of typically bulky systems. The race for solid-state LiDAR might be very well played in the field of CMOS image sensors.

Benefits on environment monitoring and wildlife conservation are also remarkable. New and advanced wildlife monitoring technologies are shifting the paradigm of wildlife conservation and management for more precision and efficiency. The monitoring of wildlife includes tracking animal movements and habits, studying population distribution, and identification of species and possible threats. A major requirement for wider adoption of these units is ultra-low-power low-cost realizations. On the other hand, air-coupled ultrasonic efficient technologies in IoT devices include new possibilities to analyze and measure water content of plants for better water control in agriculture. Another field with new possibilities is in the medical field with generation of elastography images of cornea in vivo, or the work and to provide a feedback about the tissue being cut when using laser scalpels. Another example is in the food industry, where this technology can provide completely non-destructive and non-invasive mean to inspect different food products integrated in the production line.

3.2. IoT and CPS hardware designs and development platforms

Nowadays, big companies such as Microsoft, Cisco, Intel among others have consolidated the development of hardware and development platforms, including different processors performances, RAM availability and additional characteristics such as Wi-Fi/Ethernet modules, Input/Output ports, etc.

Overall, nowadays, Raspberry Pi, Beaglbone and Arduino, have fulfilled the demand in simple low-cost platforms, which could provide some basic functionality and widely used in many research and development projects and prototypes. Therefore, the impact on the current IoT and CPS hardware designs and development platforms is tremendous and cross-sectoral, for example in three cross-correlated fields of application such as smart mobility, smart buildings and energy efficiency.

3.3. Architectures and computational frameworks for IoT and CPS

The research on CPS and IoT architectures and computational framework has already produced significant impact, which may be analyzed taking into account different IoT layers: 1) application layer; 2) network layer; and 3) perception layer. The network layer is the most important layer in IoT architecture, because various devices (e.g., hub, switching, gateway, cloud computing perform, etc.), and various communication technologies are integrated in this layer.

Special attention has been given to cloud and fog computing. Nowadays, the integration between cloud computing and the IoT and CPS allows resource-constrained IoT devices to offload data and complex computation onto the cloud, taking advantage of its computational and storage capacity. However, the centralized nature of a cloud can lead to a considerable topological distance between cloud computing resources/services and the vast majority of end (user) devices, limiting the deployment of some cloud-based solutions. On the contrary, Fog computing is an evolution of early proposals with the objective of better addressing needs of the IoT and CPS, therefore cloud and fog computing will be essential for IoT and CPS in the upcoming years.

In order to adopt Cyber-Physical System of Systems (CPSoS) paradigm, new approaches on the integration in several digital functionalities in a cloud-based platform have been yielded. New research results will enable real time multiple devices interaction, data analytic and global reconfiguration to increase the management and optimization capabilities for increasing the quality of facility services, safety, energy efficiency and productivity.

3.4. Modeling, control and optimization for IoT and CPS

The first important area in this key challenging point is signal processing and estimation for IoT and CPS, which has several implications. For example, in the transition from the theoretical research on signal processing and conditioning into the real world applications. It implies facing the limitations of low cost sensors and limited processing power. The results achieved up-to-date have received a great international attention of the research community, as well as on the business sector, especially those companies offering services and solutions based on ultra-wide band technology, since it allows to become aware of the strengths and limitations of ultra-wide band components, and the challenges that still exist at the research level to develop more precise and robust solutions.

The second aspect and one of the cornerstones of CPS and IoT is the modeling, control and optimization, with an important impact in medium and long terms. Nowadays, the research is focused on system modeling and control. The design and implementation of networked control in CPS have posed several problems in time driven and event-driven computation, time-varying delays, transmission failures, and reconfiguration of the system. With the advent of CPS, co-design issues are reconsidered in various aspects. For example, since CPS are typically networked control systems, the effect of the network delay on system stability has recently been studied in terms of the trade-off between stability and real-time schedulability. The interaction among the sensors, actuators, physical systems, and the computing elements should be carefully incorporated into the design of IoT and CPS sensor-actuator networks. Certainly, verification and validation of CPS and IoT have received a lot of attention. In this context, hardware and software components, operating systems, and middleware are required to go beyond complete compositional verification and testing of CPS and IoT.

3.5. Potential applications

Long and medium term impact on society is analyzed, considering relevant economic and social sectors and potential applications, as follows.

Sustainable Agriculture: CPS and IoT sensors and computational framework will be essential in sustainable agriculture (IAS, CAR). The development of new sensors for monitoring crop physiological parameters in applications such as irrigation scheduling, early plant disease detection or plant phenotyping will have strong impact in short terms. This includes monitoring the soil-plat-atmosphere continuum using a suite of sensors technologies (e.g., thermal, hyperspectral, LiDAR, micrometeorological) at different scales (airborne imaging sensors, ground sensors and sensor networks).

Smart buildings and critical infrastructure: The challenge of the next decade is not only the development of IoT for smart buildings but also the application of this technology and its concept of intercommunicated networks to different problems that until now had been solved in a closed and autonomous way. The key is, therefore, how to migrate these applications to the technology and the concept of IoT. The drawbacks of this type of data-based environments have also to be assessed and solved, powered by devices connected to a network; the main one is the security aspect, both physical and cybernetic. Structural health monitoring enables to obtain information about the behavior and degradation state of construction structures. For critical infrastructures such as nuclear power plants, transportation networks, electrical, water, oil and natural gas systems, different techniques are rising. ITEFI is working to deepen in basic science and development technologies in which incorporates the knowledge acquired for structural health monitoring. The characterization of construction materials conjugates different degradation processes with the use of non-destructive techniques. Some of the structural health monitoring techniques are based on wireless sensor networks but it is still necessary the migration of some wired systems. Therefore, it is necessary the conjugation of basic science and technology. IRI develops model-driven and data-driven techniques for state estimation and real-time monitoring of critical infrastructure, predictive control techniques for optimal management and fault-tolerance methodologies for CPS efficiency, reliability, resilience and sustainability.

Smart mobility: During the last decade a large number of IoT and CPS technologies for smart mobility (CAR, IRI, IMB) have been developed by the research community.

Automated cars use today a huge amount of information that is gathered, processed and analyzed by the vehicles themselves. With the emergence of the IoT and CPS, autonomous driving services will be able to use information from a huge variety of devices both from the vehicle surrounding and from the cloud. In this connection, some limited functions traditionally located on the vehicles in the past, might now be processed, using multiple data sources, in the surrounding IoT-infrastructure or in the IoT-backend, resulting in more dependable functions. In addition, the recent emergence of high-performance edge computing will allow to embed intelligence that enables for consistency checks with the cloud data, and therefore lead to a safer and more secure mobility experience.

IoT and CPS are also relevant in artificial vision, ranging from the image plane to the interpretation of the scene. One focus is on intelligent transportation, where the impact can be especially significant at various levels: automation, traffic management, safety, security, etc. This is also directly connected with the lines on sensor networks and remote driving. Finally, the aforementioned paradigm of the Internet-of-Things is another massive technological (and market) framework where future advances in terms of power efficiency, 2D/3D embedded integration, energy harvesting, visual processing acceleration, etc., will find direct applicability.

Smart logistics and transportation: In particular, CAR is involved in very specific sectors including the development of technical aids for firefighters, making use of inertial sensors, virtual reality, use of maps and cooperative location, to improve safety and speed in interventions of burning or collapsed buildings.

In the logistics sector, the analysis of movement patterns in many not yet automated warehouses, where the operator has to travel dozens of kilometers per day for the preparation of on-line orders is very promising for IoT and

CPS. Tracking worker movements and applying data analysis will allow improving the efficiency in the plant. Another area of interest is the analysis of large flows of people, in common places such as shopping centers and airports. The objective is not advertising, but the creation of informative tools for both the common user and the operators of the spaces.

Smart manufacturing and emerging cyber-production systems: Industry 4.0 is evolving towards more automated data exchange beyond manufacturing technologies by unifying technologies of the third industrial revolution (automation processes and new production technologies) with technologies of the information age such as storage, processing and massive data transmission. Solving this challenge will have implications of great impact in robotics, computer science, mathematics and engineering, also in health and social sciences, as they will change the way we relate to the factory of the future. One strategic theme (CENIM,CAR) is to focus on Modeling and Control 5.0 to be able to understand and guarantee the manufacture on demand of custom metal prototypes and parts in short run productions, since this is one of the fastest growing areas in the industry thanks to advances in additive manufacturing.

Smart human motion, well-being and health monitoring: Monitoring the health of the elderly, to promote their independent life at home, is a classic line, but in which it is mandatory to introduce new non-intrusive monitoring techniques (e.g., RFID and UWB tomography), as well as ambient intelligence, supported by special sensors in the home which will not only allow to monitor the location and mobility of the persons in their home, but also to monitor their type of activity, their vitality or fragility, and the early detection of diseases predicted by changes in the behavior of the elderly.

4. KEY CHALLENGING POINTS

4.1. IoT Sensors and Actuators

New functional materials for IoT sensors and actuators are needed to enable low cost, energy efficient mm-wave devices of the new IoT paradigm. For example, a promising candidate is the aim at developing a new family of ferrites based on *s*- Fe_2O_3. A key concept zero field magnetic resonances in the mm-wavelength and THz bands, based on their large magnetic anisotropy, where the larger the magnetic anisotropy the higher is the magnetic resonance frequency.

The new materials and alloys, and processing to be considered in the next 5-10 years for IoT devices are:

a. New family of ferrites for efficient non-reciprocal devices for wireless communications in the mm-waves and THz frequencies.
b. Epitaxial quartz films on Si for new devices for IT and sensing applications.
c. Patterning those films and fabricating on-chip quartz-based MEMS for ultra sensitive mass sensors, high frequency oscillators and optomechanical devices.
d. Doped PMN-PT single crystal materials with gigant piezoelectric to produce a new generation of air-coupled transducers.
e. Novel fabrication technologies to produce thick film materials, stacks of thick film materials such as reinforced syntactic foams.

Another challenge in IoT sensors is the sensory plane as, for instance it is concerned with efficiency in extracting the relevant information contained in the visual stimulus. Any alternative representations of the scene that constitute an effective reduction of the visual data flow in favor of distinctive features can be the key to practical implementation of embedded vision systems, from compressive sampling to event-driven image sensors.

In a higher hierarchy level, the second challenge is the processing of visual information, which is very expensive in computational terms. Visual information processing has traditionally been a major issue for the practical realization of embedded vision systems. Consequently, the scientific community is focused on developing non-traditional strategies that efficiently cope with the computational load while keeping the advantages they have brought about. These strategies cover from the design of the sensor itself, to mixed-signal processing schemes, hardware acceleration, or dataflow organization.

These challenges will effectively leverage the various components for particular requirements of vision-based applications. Even when the data flow is suitable for a properly designed underlying processing architecture, only optimal selection of the different components will provide needed specifications and expected performance.

A comprehensive analysis of the operations to be carried out in terms of scheduling and parallelization, together with a deep understanding of the impact on different hardware platforms, is crucial to boost the application performance.

Another aspect to be considered is the power management, which is rather important in future applications related with smart mobility and smart buildings. A certain level of autonomy can prevent, for instance, the influence of noisy power lines inside a vehicle. It can also leverage the need of developing always-on traffic monitoring infrastructures. In these scenarios, energy harvesting permits vision nodes to operate exclusively on batteries. Extracting energy from the ambient is also pursued in application fields of IoT. Prototypes of image sensors simultaneously capturing images and harvesting energy, even embedding processing and memory have been recently reported.

Special attention will also receive the combination of electrochemical or optical transducers at the microscale in relation with microfluidic applications, fully automated with compact analysis systems, which can perform autonomous measurements of (bio)chemical parameters. Most analytical procedures require sample preparation/conditioning, frequent calibration, and the use of reagents in order to obtain the concentration of a chemical species.

For complete IoT systems, the following developments are to be delivered:

a. LiDAR and CMOS-SPAD image sensors for 2D/3D vision. Single-photon avalanche diodes (SPADs).
b. Low-power, highly-integrated and low memory requirements of sensors.
c. Autonomous operation in the measurement of chemical parameters with low power and compact systems suitable for IoT.
d. Doped PMN-PT single crystal materials with gigant piezoelectric to produce a new generation of air-coupled transducers.
e. Integration of all elements for a new generation of air-coupled transducers.
f. Technology standardization.

4.2. IoT and CPS hardware designs and development platform

New hardware design and development platforms with new embedded functionalities and computational processing capabilities are urgently needed for IoT and CPS. These platforms should meet new requirements of specific projects and research should be conducted on new knowledge about platforms, embedded operating systems and the corresponding sensors. For example, emerging and promising technology is being nowadays limited by conventional non-destructive systems to guarantee quality of components. This has a direct impact on the productivity and positioning of Spanish and European strategic sectors like carbon fiber reinforced parts for aerospace industry, where non-destructive tests are becoming the production bottleneck in the next years.

Key challenges in IoT and CPS hardware design and development platforms for specific cases are:

- **a.** IoT/CPS design and platforms for cognitive and resilient production systems.
- **b.** IoT/CPS design and platforms for adaptive ultrasound imaging in industrial applications.
- **c.** Fast the imaging frame-rate up to 20.000 images per second required for ultrafast scanning applications
- **d.** IoT/CPS hardware design and platforms for 3D ultrafast ultrasound imaging systems.

4.3. Architectures and computational frameworks for IoT and CPS

Research and development challenges of digital transformation in the next decades require new paradigms combining control engineering, information software and telecommunication engineering. Nowadays the **top-10 topics targeted worldwide** are: signal processing and estimation, computational models, architectures and design approaches, interfacing the computational and physical world, dependability, synergy between monitoring and adaptation techniques, distributed algorithms, monitoring and control, handling emergent behavior and uncertainty, modeling and simulation, scalability and evolvability.

Software platforms with well-defined and appropriate levels of abstractions and architecture are essential for the development of reliable, scalable, and evolvable CPS in various application domains. Methods and theories for high-level decision making based on information collected from different sources at different spatial and temporal scales are necessary for system-wide reliability, efficiency, security, robustness, and autonomy of CPS.

In this regard, reliable architectures and computational frameworks should be addressed in the next decade for the following aspects and specific applications:

- **a.** Monitoring, supervision and control 5.0.
- **b.** Holistic methods based on a multi-level approach.
- **c.** Dependable and cost-efficient high-definition maps for novel mobility paradigms.
- **d.** 5G-based collaborative perception and navigation for safe and efficient autonomous driving.

e. Seamless use of heterogeneous sources of information in intelligent vehicles.
f. Robust and resilient multi-sensor connected networks.
g. Smart irrigation based on remote and proximal sensing.

4.4. Modeling, control and optimization for IoT and CPS

A framework consisting in an integrated vision of IoT and CPS is needed. New theoretical foundations will allow to better understand and predict complex dynamical behaviors caused by tight interactions between cyber and physical domains. Furthermore, it is required to develop unified theories which enable us to capture and analyze the dynamics of the communications, computation, control, and applications at once in a unified theoretical framework. Moreover, complexity issues in the design and development of CPS should also be investigated. Further advances are also required to support automated transformation between models in different semantic domains, model-level execution and debugging capabilities, composition of models to build an application, and incorporation of verification and validation capabilities.

The specific aspects and elements to be addressed in the next decades are:

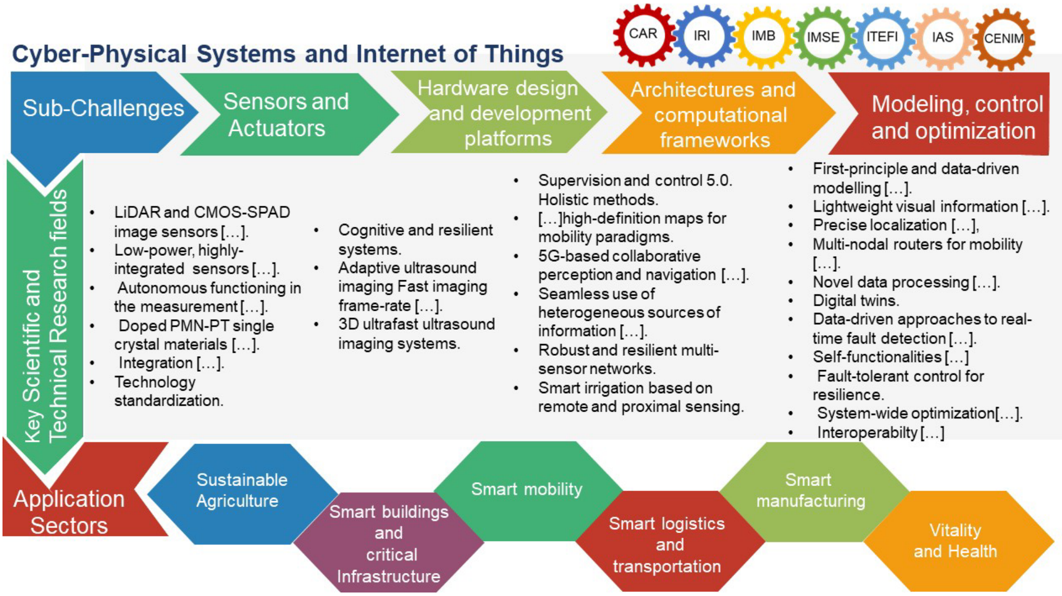
a. Lightweight representation of visual information.
b. Fast and computational efficient signal processing method.
c. Extended Kalman filters.
d. Precise localization in cities supported on Galileo system and multiband GNSS systems.
e. Multi-nodal routers for mobility as a service.
f. Novel data processing algorithms for the Internet of Crops.

While longer term challenges in modeling, control and optimization are:

a. Digital twins. Design and development.
b. First-principle and data-driven modelling in complex systems for real-time monitoring.
c. Data-driven approaches to real-time fault detection and diagnosis
d. Smart nonlinear control. Self-optimization and self-reconfiguration.
e. Fault-tolerant control for CPS resilience.
f. System-wide optimization for CPS efficiency and economic operation.
g. Interoperability of multiple systems for coordinating operation and improving efficiency and sustainability.

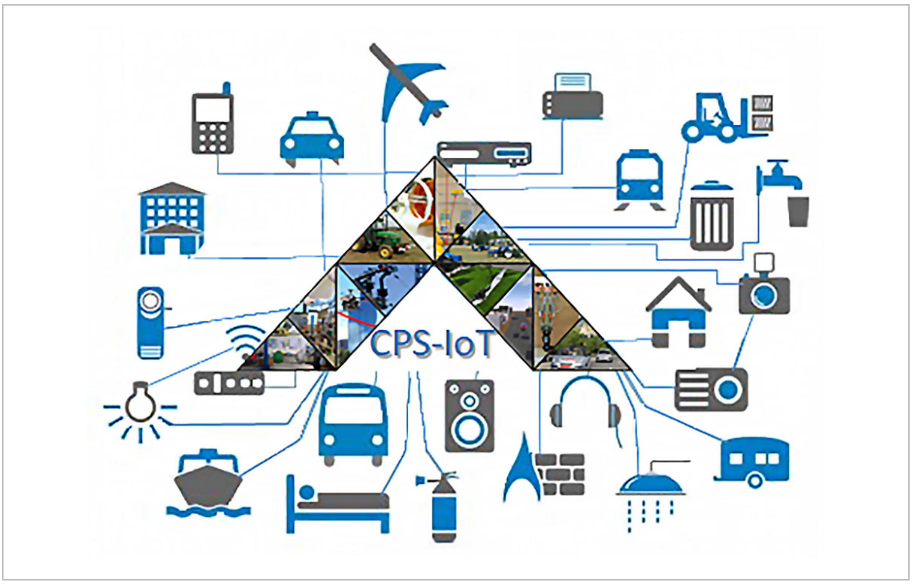
ANNEX: ONE SLIDE SUMMARY FOR EXPERTS

FIGURE 4.2–Internet of Things and Cyber-Physical Systems: Key scientific and technological research areas towards 2030.



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

FIGURE 4.3–Internet of Things and Cyber-Physical Systems: towards Cyber-Physical System of Systems



CHALLENGE 5

ABSTRACT

The popularization of Internet has meant a disruptive change in our way of life: from our social and professional activities to the mechanisms for generating and exchanging information. Despite this being generally beneficial, it has also implied an increased number of risks and threats from a security and privacy point of view. One of the great challenges of our society is the generation of trust and security in the management of digital information that we share and use daily.

KEYWORDS

confidentiality, integrity and availability of information and data

hardware devices | internet of things

lightweight cryptography

microelectronics developments of secure computing systems

post-quantum cryptography

quantum computing

quantum key distribution | RISC-V

secure computation

trustworthy and secure digital society

CHALLENGE 5

TRUST AND SECURITY IN THE DIGITAL INFORMATION

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1. EXECUTIVE SUMMARY

The exponential deployment and popularization of Internet access (the so-called democratization of Internet access) facilitated by the proliferation of the technological devices with connecting capabilities, has driven to the growth of the cyberspace, which has changed our society dramatically. Although this change has provided a large number of benefits, it has also generated a number of risks and threats that often go unnoticed. An obvious challenge would be minimizing such risks and threats through scientific research in order to improve the security of the digital information, thus contributing to enhance users' trust in the digital society.

Research will be carried out on the design of methods for ensuring the confidentiality, integrity and availability of information, as transversal requirements for digital security. Key challenging points are identified regarding the storage of data, the communication of information over networks, and the processing of data on hardware devices. To secure the storage of data, cryptographic protocols and algorithms will be developed taking into account fundamental aspects of authentication, lightweight cryptography and post-quantum cryptography. To guarantee the security of communications over networks, dodging the threat of quantum computing, quantum key distribution will be improved by means of new protocols and technological developments. For the secure processing of data on hardware devices,

microelectronics developments of secure computing systems and hardware roots of trust will be investigated, looking for a European technological sovereignty.

Addressing this challenge and achieving its goals will ensure that digital applications will be used in a trustworthy and secure way.

The experience and previous achievements of the groups involved in this challenge show their ability to succeed in reaching results which will contribute to the progress of basic science, and to the development of new technologies and novel applications which will have a remarkable impact in many aspects of our society.

2. INTRODUCTION AND GENERAL DESCRIPTION

This chapter, in short, tries to contribute to the promotion of a trustworthy and secure digital society, considering the technological aspects of risks and threats and moreover, understanding their repercussions on the uses and actions of citizens. Information security is needed to preserve the defense of constitutional and democratic values, the citizens' fundamental rights, their personal data and its relation to General Data Protection Regulation, etc., and requires a multidisciplinary approach. In fact, digital security constitutes one of the main challenges of our society, which is not only the information society, but also the *data society*. The later term comes from the massive use of devices, which are continuously and ubiquitously connected to the Internet.

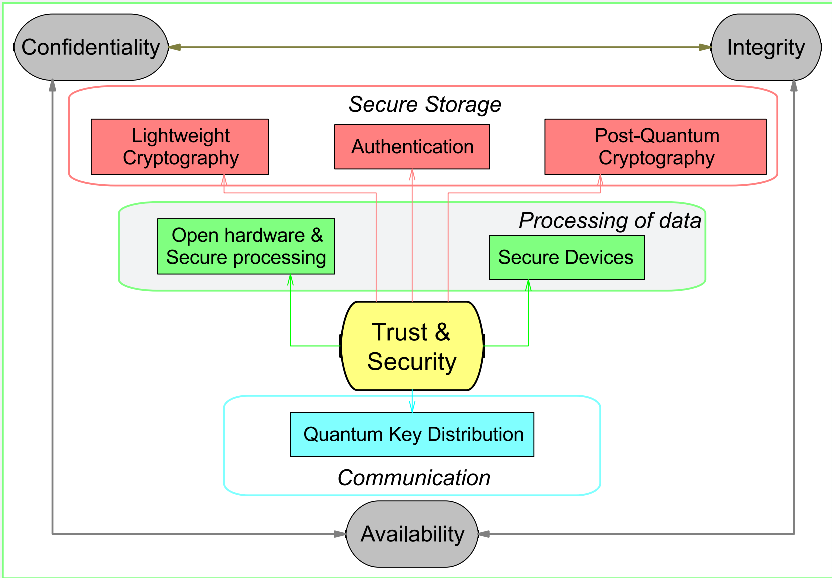
Along this chapter, the terms *trust*, *trustworthy*, and *trustworthiness* describe something which a person can believe in, that is, something that is completely reliable. Properties that something trustworthy must possess are: authenticity, accuracy, consistency, integrity, etc. The concept of *security* is typically applied referred to acts of an intentional nature. Security-related risks are often related to the actions of an intentional opponent or attacker, such as sabotage, theft, or other explicit attacks. This term also applies to something that is protected and resilient against failures or errors, malfunctions, whether caused or not.

Reports issued by relevant authorities, such as the National –Spanish– Security Strategy [Gobierno de España, 2017], the Annual National –Spanish– Security Report, the European Security Strategy [European Council, 2009], the NIS (Network and Information Systems) Directive [European Union, 2020], the Cybersecurity Act [European Union (b), 2020] from the European Union, and the Horizon Europe Cluster about Civil Security for Society, as well as the Digital Europe Program, stress the role of *Information Security* as a priority objective to ensure national security and create a *Trust-based digital society*. There are also of interest the international calls made by the National Institute of Standards and Technology (NIST) from USA. These calls are aimed to foster research to find new cryptographic algorithms, primitives and protocols which can contribute to improve the trustworthiness and security of digital information. Among them, it is worth to mention those related to the lightweight cryptography and the post-quantum cryptography.

Ensuring the **confidentiality, integrity and availability (CIA) of information and data**, either transmitted by networks or processed and stored in electronic devices (computers, smartphones, etc.) is nowadays a strong challenge, since users, organizations and companies must be sure that such assets are always available and cannot be accessed or modified by other entities or even by malicious users without the corresponding permission. In order to achieve this challenge and to reach the transversal objective of ensuring CIA of information and data (see Figure 5.1) by the design and implementation of cryptographic protocols and secure applications (transparent to the entities), three types of actions can be developed capable of ensuring: 1) Secure storage of data (authentication, lightweight cryptography and post-quantum cryptography), 2) Quantum safe communications (quantum key distribution), and 3) Secure processing of data on hardware devices (secure devices, open hardware, etc.). The benefits of such actions will permit to protect the entities from many threats and weaknesses like the (massive) password theft, phishing, ransomware and other malware attacks, and to provide to the users a real trustability in the management of digital information, methods for a secure generation of keys, and trusted hardware executing trustworthy computation.

The **protection of store data** can be addressed by considering several aspects related to the improvement of cryptographic protocols and algorithms. In this sense, *authentication* is a property of information security that allows users to confirm their identities and those of their devices, and thus avoids impersonation attacks by which impostors assume the identity of legitimate users. Moreover, *lightweight cryptography* addresses the security demands in resource-constrained hardware and software scenarios such as sensor networks, RFID tags, smart-home appliances and mainly Internet of Things (IoT)

FIGURE 5.1–Challenges for obtaining Trust & Security of data



devices. Lightweight cryptography denotes a wide range of cryptographic algorithms with different properties and diverse use cases. In fact, the only unifying constraint of all of them is the low computing power of the devices intended to run them. Under such conditions, specially designed algorithms are necessary. *Post-quantum cryptography (PQC)* refers to the design and implementation of new cryptographic protocols and algorithms which can be considered secure against the power of the quantum computation. The threat of quantum computing, in terms of security, is the possibility that in the medium-to-long term a universal quantum computer with sufficient computing capacity will be ready as to implement quantum algorithms capable of breaking the cryptographic algorithms currently used. The PQC concept was born after the publication of several quantum algorithms (Shor, Grover and Simon algorithms, mainly), which will break the main symmetric and asymmetric cryptosystems used today, if a quantum computer with sufficient computing capacity is developed. Indeed, the mathematical problems on which their security is based (integer factorization and discrete logarithms in the case of asymmetric cryptosystems) could be solved in just a few hours.

Quantum safe communications The aforementioned quantum computing threat is being considered internationally by agencies and governing bodies. It is therefore mandatory, in order to fulfil the national and international security agendas, to continuously evaluate the risks associated with the irruption of said technology, and to study alternatives to make the exchange of information feasible through confidential and secure channels capable of providing quantum safe communications to the general public. In this sense, it is worth to mention the *Quantum Key Distribution (QKD)*, a quantum technology that uses the principles and tools of Quantum Mechanics for the secure exchange of information. This is of enormous importance in information security since it enables the sharing of cryptographic keys among users with information-theoretic security, i.e., with security independent of the computational power of an adversary. It is therefore secure against a quantum computer attack and hence, the name quantum-safe.

In relation to the **Processing of data on hardware devices**, it is clear that microelectronics plays a fundamental role in the context of trust and security in digital data, both for being the Key Enabling Technology for the construction of the information processing and transmission elements that support cryptographic protocols executed in software, and for being increasingly used for *hardware implementation of specific devices* that allow to improve performance and security of the device itself, and reduce size and energy consumption of cryptosystems. Secure interconnection of devices and systems in different application domains is an open research challenge. So, new microelectronic solutions must be explored in order to provide efficient mechanisms to verify the identity of hardware devices and users, as well as to establish hardware roots of trust to store, communicate, and process sensitive information. Moreover, it is also necessary to ensure the security of devices against side-channel implementation attacks, particularly fault injection and power analysis attacks, and to develop countermeasures that allow implementing components and algorithms providing security together with efficient features of size, power consumption and operation speed.

Another aspect pertaining to security is the necessity of obtaining the European sovereignty in all aspects related to the development of trusted and secure technology, in particular, in the *development of secure computing systems*. In this sense, the challenge is to increase the technological autonomy by promoting a national (and European) industrial base of cybersecurity, R&D&I and the management of technological talent (European and National

–Spanish– Cybersecurity Strategy [European Commission, 2013]). Europe is technologically vulnerable due to the lack of control in the main technologies that process digital and complex information. These uncovered technologies range from advanced nanometric technologies to the design of complex digital intellectual property blocks and processor cores. The challenge is being able to reduce this gap through the concept of trusted chips creating the necessary hardware blocks needed to ensure the chip authenticity and the support of cryptographic algorithms based on open and known Hw/Sw processing systems.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The research needed for securing digital information and for reaching users' trust on the technology and applications will produce a relevant impact in both basic science panorama and worldwide economy, and will lead to the development of applications which will have a strong social impact. Some examples of this technology and applications are: protection of citizens' personal information; biometric recognition of citizens; new materials, components and developments for the construction of hardware devices and photonic; generalization and implementations of remote e-voting systems, etc. A more detailed explanation about the impact of this challenge is provided in the following paragraphs.

In relation to the transversal objective associated to *CIA of stored and transmitted information*, the design and development of new protocols and algorithms will obviously impact in many fields of science and technology, since the management of information is more and more a requirement in complex systems and advanced applications. The historical evolution of cryptography, as a basic tool related to trust and security, teaches us, among other things, that after some (supposed) secure algorithms are proposed and accepted for their use, the researchers study such algorithms with the goal to develop new attacks. When some weaknesses have been found, modifications of the accepted algorithms or new algorithms must be developed. With this perspective in mind, it is not easy to determine what topics will have an impact in the short and medium term or in the long term. Taking into account that achieving trust and security in digital data is a *very long-distance race*, most of all topics can be considered as long-term challenges, though some of them (as, for example several algorithms) could produce results with impact in the short or medium term.

One of the main impacts that this challenge will have is the protection of citizens' personal information in a way that avoids the traceability of their movements and the knowledge of their interests and hobbies, the safeguards their medical data from access by unauthorized third parties, the right to be forgotten on the Internet, etc. Protecting the information managed in everyday commercial and industrial activities will have an strong impact in the economy of any country, since corporate espionage and global threats will be avoided or mitigated allowing the proper development of banking, pharmaceutical, telecommunication companies, etc., as well as the correct functioning of critical infrastructures and services as security forces and bodies, nuclear, electrical and gas installations, transportation systems, hospitals, etc. Here, the development of post-quantum cryptography will have an important impact in the proposal of new security protocols. To get such impact, new algorithms based on specific mathematical problems will be needed, such as considered in the PQC call by the NIST: lattices, error correcting codes, multivariate quadratic polynomials, isogenies over elliptic curves, hashes, etc. Most of its results should be in the short-medium term since the objective is to protect the information against the quantum threat.

Another great impact of this challenge will be a relevant improvement of the biometric recognition of citizens. This type of recognition is widespread in certain areas and is usually used by the security forces to identify users or to access to certain buildings or parts of them. The improvements in biometric recognition techniques will have a clear economic and social impact, in a short-medium term, since they will allow the access to personal or private data only to those who have the right to know it. The owner of the data will be able to access such data without employing intrusive methods, the access grant being completely transparent to the user. Health authorities and state security agencies, etc. will also have access to this data. The new results of biometrics will impact on the used today features and traits for identifying users. Thus, in addition to use fingerprints, irises, voice, hand and vein geometry, etc., for which it will be necessary to improve their efficiency and effectiveness, in a short-medium term new identification features will be proposed; especially those based on the sensors of the smart devices like gyroscope, GPS, accelerometer, etc. These improvements will allow, in a long term, the use of personal devices with added guarantee of privacy, not only in the phase of access or initiation of such devices, but also through continuous authentication protocols that guarantee that whoever is using it at all times is its legitimate owner. An important impact of these new results related to biometry will be guaranteeing the safety and security of implantable medical devices (IMD). So, it would be possible to avoid attacks of an adversary for knowing the possible illness of a sick person (which is against your privacy) and, furthermore, to prevent someone from manipulating such IMD by altering the dose of the insulin pump, the pace of a pacemaker, etc.

This challenge will also have an impact on certain aspects related to digital citizenship (Chapter 8) such as electronic voting (e-voting). It is about generalizing the democratic uses of all citizens in electoral processes. This is another one of those issues for which solutions are known, but none of them, at the moment, offer enough security to be implemented in a generalized and efficient way. E-voting proposals will allow secure voting though Internet by using any mobile device (laptop, smartphone, tablet, etc.) and, at the same time, consider the possibility that each citizen may vote several times in the same electoral process as a possible measure to avoid coercion when exercising the right to vote. It must be considered that e-voting requires very special characteristics, which go beyond the vote cast in a ballot box. It is about guaranteeing that, as usual, only registered voters can vote, that the vote must be cast freely, be valid, be secret and recorded in the option chosen by the voter; but in addition, it is required that each voter, at the end of the process, be able to verify that his vote was accounted for the option he chose, maintaining the confidentiality of the vote at all times.

Improving security and increasing trustworthiness in new technologies will impact, in a short-medium term, in the development and generalization of IoT devices.

Moreover, their applications will be closer to the users and their popularity will be increased even more. At the same time, these improvements, will extend in a long term, their use in fields such as home automation, smart cities, smart meters, etc. It is a widely accepted fact that IoT devices were not designed with their security in mind. In this sense, the development of lightweight cryptographic algorithms will provide a bigger security to IoT devices (see Chapter 4). These developments will take into account their limited computation and storage capabilities.

Another aspect on which this challenge will have a great impact will be the development of international standards, in a short-medium term, in each and every one of the aspects considered so far. This will guarantee that the new developments will be compatible, available and interoperable at international level with an obvious positive economic impact.

Regarding Quantum Safe Communications, the expected short-term impact is extending the operability of current QKD systems to the demands of communication networks, which implies longer range, higher speeds and lower deployment costs. Consequently, the expected impact will be a wider use of these technologies by the society in general, governments, corporations, banks, defense sectors, etc. Security risks will thus be reduced and therefore, will not expose sensitive information from these sectors, which will have a positive effect on the economy. Moreover, secure interconnection of QKD nodes independently of their nature will impact in the applied science, in a medium term. Specifically, the development of hybrid networks where free-space and optical fiber QKD links coexist, will increase the flexibility and versatility of these networks and will better address the user needs. On the other hand, wireless networks are proliferating with the increasing use of smartphones, drones, autonomous cars, etc. Adequate confidentiality of these channels is mandatory, in the short term, to ensure the user's information. For this matter, the development of efficient free-space to optical fiber interfaces capable of counteracting atmospheric effects and relative movement is necessary. These solutions, which require, not only technological advances, but also increased knowledge of theoretical aspects, such as atmospheric turbulence and beam propagation, will also impact basic science.

Regarding longer-term impacts of quantum safe communications, within basic and applied science, are the development of QKD applications, including space applications that will enable long-distance ultra-secure links. This will benefit citizens and governments, as their data could be secure globally. Exploring the development of different types of QKD protocols better suited to different applications (whether the channel is free space or optical fiber, requires a high or lower bandwidth connection, it is mobile or stationary), will impact the society by providing a better choice to the users' needs. In addition, the development of the Quantum Communications Infrastructure (QCI) will allow public use of confidential channels to protect user's sensitive information. Potential applications will include the use of these links for critical infrastructures such as the energy, transport, telecommunications or water supply networks. In this sense, the foreseen impact will include the development of new solutions suitable to be deployed in this infrastructure, such as robust, compact and cost-effective systems, that could be easily integrated in standard technology; along with new hybrid encryption schemes including quantum and non-quantum cryptographic primitives.

The use of secure devices and secure computing systems in different application domains will impact in the applied science, in a short-term. For example, the efficient hardware implementations of circuitry for security, i.e., symmetric, asymmetric and post-quantum and lightweight cryptographic and biometric algorithms as well as primitives like ciphers, hash functions, etc., will spread the range of devices that are secure currently to cover wearable and implantable devices. The new microelectronic solutions will provide efficient mechanisms to verify the identity of hardware devices and users, as well as to establish hardware roots of trust to store and communicate sensitive information. Furthermore, the new results will ensure the security of devices against attacks to the implementations of cryptosystems in physical devices, particularly fault injection and side-channel attacks, and that their security will remain over time in spite of aging. Detecting not only counterfeiting but also tampering, that is, that a legitimate device has been manipulated with the objective of carrying out an unauthorized operation, is crucial in many applications. In addition, the fraudulent copy of hardware designs must be avoided among other reasons by their important economic consequences. In this sense, it is demanded the development of white-box cryptography and code obfuscation. In summary, as the citizens need to use certified devices from a safety point of view, new metrics have to be proposed and new methodologies have to be developed to certify the embedded systems and programming techniques from a security point of view.

Our society demands transparency and secure computing systems should also be transparent. Hence, the generalization of Open Intellectual Properties (IPs) will have a big impact to grow the universe of fundamental blocks for its usage on an open hardware environment such as RISC-V, and independent verifications and benchmarking for RISC-V implementations or for any open-IP. The development of on-chip strategies and utilities will help, in a short-medium term, end users to protect the different levels of Hw/Sw from the core processor up to the application software (Physically Unclonable Functions or PUFs, cryptographic coprocessors or accelerators, etc.).

Spain, in particular, and Europe, in general, need to have a secure electronic technology which makes it possible the design and fabrication from System on Chips till microprocessors that enable the secure implementation of cryptosystems in the devices of our daily life. In this sense, it is fundamental to guarantee, in a long term, the growth of the open RISC-V ecosystem and its application in many different application domains, from High Performance

Computing to Ambient Intelligence, IoT, Edge Computing, etc. The efficient generation of tools for the very large scale integration (VLSI) circuit design as well as the implementation of secure systems and IP modules on FPGAS and ASICs are strategic for the electronic technology in Spain and Europe.

4. KEY CHALLENGING POINTS

Besides those related to military, diplomatic, and governmental, there are other environments where it is very important to protect the information and data. Some of them affect to institutions and their relationship with citizens. For example, the necessity of enhancing the security of the personal identification devices like passports, ID cards, etc., in order to avoid impersonation of identities (see Chapter 8). It is also evident the need of guaranteeing the secure communications between the companies and their clients (bank transactions, cloud computing, access to databases, IoT devices, etc.), as well as the security of IMD in order to avoid patient data theft, therapy manipulation, etc.

The best way to guarantee the transversal objective of **Confidentiality, Integrity and Availability of information and data** is to develop cryptographic protocols and algorithms which fulfill the security requirements established by the international organisms and associations. In fact, the development/evolution of our digital society requires to guarantee the CIA of the information managed, for example, in the contexts of smart cities (by smart meters or autonomous cars), or e-governance (electronic administration, remote electronic voting, etc.).

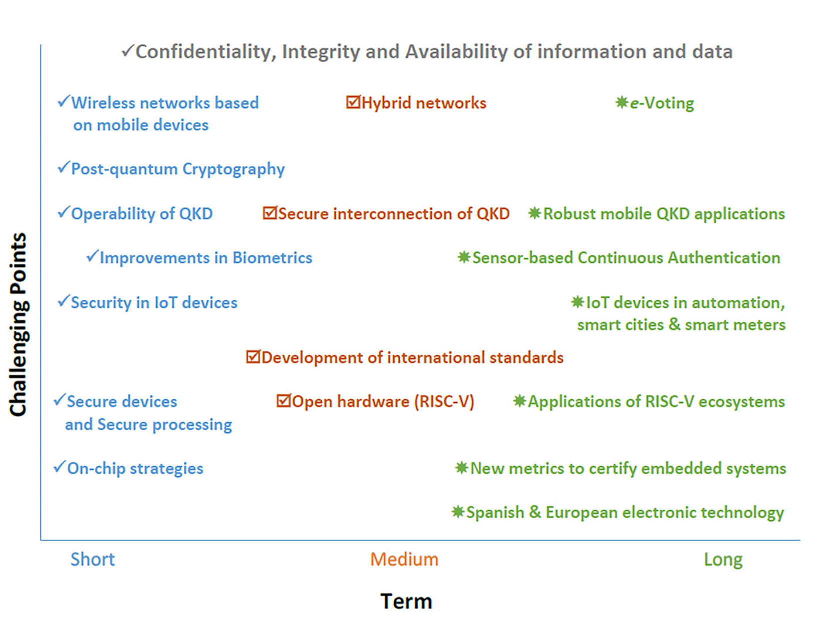
In the following, descriptions of the key challenging points to achieve effective trust and security in the digital information are provided. Figure 5.2 shows a scheme of the foreseen terms to achieve the different challenging points.

4.1. Guaranteeing secure data storage

Authentication

Several European regulations impose trust and security norms concerning the electronic identification of subjects making transactions within the European Economic Area: General Data Protection Regulation (GDPR, EU Regulation No. 679/2016), The Strong Customer Authentication (which came into force on September 2019), and U.S. regulations follow similar issues: Digital Identity Guidelines from NIST establish that the highest Authenticator

FIGURE 5.2—Timeline of the challenges by term



Assurance Level is based on a) proof of possession of a key through a cryptographic protocol, and b) use of a hardware-based authenticator and an authenticator that provide verifier impersonation resistance by using biometrics. In order to be authenticated, claimants shall prove possession and control of two distinct authentication factors using approved cryptographic techniques. Moreover, many applications require that genuine individuals prove with their physical presence that they are associated with the origin and storage of information. In this sense, Biometrics authenticates the physical presence of the user through physical features (fingerprint, iris, etc.), physiological characteristics (heart or brain signals, etc.) or behavioral traits (gait, handwritten signatures, etc.).

The adequate combination of cryptographic and biometric techniques into crypto-biometric systems is demanded not only by economic applications but also for e-health, e-government, e-learning, digital rights management, etc. Some of the tools to be improved for solving the identification of users based on the sensors of smart devices (gyroscope, accelerometer, etc.) and for guaranteeing the safety of IMD, are those related to cryptography for encryption and user authentication, template protection, data storage, secure and multi-party computing, etc. The fusion of multiple sources of information (fingerprint, face, voice, etc.) is employed by multi-modal biometric systems to achieve higher performance in individual recognition. Implementations of crypto-biometric and multi-modal biometric systems into trusted hardware-based devices as well as the development of efficient template protection techniques are two challenges to be achieved.

In the case of e-voting, cryptographic protocols are necessary to be developed and improved, at least in security matters. Among other primitives, it is worth mentioning digital signature, homomorphic encryption, sharing of secrets, proofs of zero knowledge, etc. The new proposals in this aspect will improve the democratic aspects of our society and the interaction between citizens and administrations in a context of e-governance (see Chapter 8).

Lightweight cryptography

Lightweightness does not mean less security. The challenge in lightweight cryptography is to keep the same level of security as that of conventional cryptography but to perform it with lower resources. In fact, the topic is to achieve the best trade-off between security protection against attacks (avoiding vulnerabilities), cost (area, memory, energy) and performance (latency, throughput, power). Lightweight cryptography is currently split into ultra-lightweight cryptography (that provides one function with high performance on one platform) and ubiquitous cryptography (that is concerned with more versatile algorithms in terms of functionality or implementation). Low-cost IoT devices are not only characterized by their constraints in processing power, memory, chip size, and energy consumption but also by their minimal or non-existent security. Combining this lack of security with their network dependency, they become the perfect gateway to attack or compromise the whole network. It is thus obvious that developing new and more secure and efficient lightweight cryptoalgorithms is a key challenge regarding the storage of data. This is the reason why 5G technology deployment or specific calls such as that of NIST for lightweight cryptography address the topic of lightweight algorithm design.

Post-quantum cryptography

From a cryptographical point of view, the principal method to avoid the quantum computation threat is the development of the *post-quantum cryptography*, also referred to as quantum-resistant cryptography, i.e., the design and implementation of robust cryptographic primitives, using Mathematics or Computer Science, against the quantum algorithms that threaten the security of cryptography as we know today.

Due to the quantum threat to the protection of information, the NIST has launched an international call to select new quantum-resistant cryptographic algorithms. Their security will be based on specific mathematical problems founded in lattices, error correction codes, quadratic multivariate polynomials, hashes, etc., so that this cryptography be invulnerable to quantum computers, no matter how much computing power they have. The key challenging points of PQC are to develop this type of algorithms and protocols in order to increase the security of the methods to be used for protecting the information in the post-quantum era.

4.2. Quantum-safe communications

Quantum key distribution

Quantum communications consist in the transport of quantum states from one location to another. This can be achieved through quantum communication protocols, such as Quantum Teleportation or QKD. The latter has an interesting application in information security since it enables the exchange of cryptographic keys with unconditional security. Quantum communications will take part in future quantum networks, where different quantum technologies will work in parallel. The end nodes, consisting of quantum processors, will perform certain computational tasks, and will be connected to each other by communication lines. These lines, or physical layer, will consist of optical fiber or free-space channels. In the final stage, quantum repeaters will extend communication over nodes to, in principle, arbitrary long distances.

Although all these technologies are experimenting great progress, the final horizon of a Quantum Internet remains a considerable challenge. Therefore, intermediate steps, outlined by the Quantum Technologies Flagship, are to be taken by European stakeholders to progressively advance towards the final goal. Initial stages of implementation of quantum networks will be through a trusted-node approach that may involve the use of satellites to reach long distances. Communication protocols will implement QKD using Quantum Random Number generators, which, in conjunction with the One Time Pad enable unconditional secure encryption. This approach suits well the protection of critical infrastructures, for instance, whose information is highly sensitive.

A practical case of a quantum communication network will presumably be the QCI, whose agreement was signed by sixteen European Union member states, including Spain, in 2019. The plan is to build a pan-European network with the mission of protecting Europe and its critical infrastructures from global cyber threats. Several European cities will be connected through QKD links by both ground and space-based transmission channels. In later stages, other cryptographic primitives such as authentication, digital signatures, and secret sharing protocols, are planned to be added to the network. These are key challenging points that require a hybrid approach to information security involving a classical and quantum perspective that the groups involved in this challenge can provide.

Other key challenging points remain increasing the range and speed, the robustness, integration, scalability, etc., of QKD systems. In this sense, through our expertise in fast free-space QKD and enabling technologies, we believe we are in position of tackling these challenges successfully. Other open questions in this field, that we are planning to study theoretically and experimentally, are novel protocols capable of closing security loopholes, such as Measurement Device Independent or Twin-Field protocols, novel technologies for polarization tracking in mobile platforms and continuous-variables QKD systems in free-space channels.

Finally, space QKD applications are also driving considerable interest of many research laboratories worldwide. Key challenging points remain inter-satellite quantum communications. Our previous experience and knowledge of experimental QKD protocols place us in a good position to tackle these issues in collaboration with other research institution specialized in space applications such as the National Institute of Aerospatiale Techniques (INTA).

4.3. Hardware devices for secure data processing

The advent of edge computer technology has led to the development of new Internet connected devices to support innovative and important services for citizens and industrial sectors. Most of these embedded systems, usually encompassed in the IoT paradigm, combine specific and general purpose processing elements that were developed without taking security aspects into consideration, which can seriously compromise their functionality and, therefore, their capability to lay the foundations of trust on which the future development of digital administration and electronic commerce should be based. The development of secure devices and secure processing systems will therefore constitute the two main topics that will be considered in this challenge.

Secure devices

Obtaining efficient hardware realizations of the primitives necessary to guarantee the trust and security in the processing and transmission of digital information, and ensuring that these implementations do not present vulnerabilities that can facilitate the execution of attacks by a possible adversary, are, regarding computation on hardware devices, two challenges that should be addressed in the coming years.

The new cryptographic schemes resulting from the standardization processes currently launched by NIST for lightweight and post-quantum cryptography will undoubtedly be the main candidates to attract the attention of cryptographic hardware designers in the short and medium term. In order to combine the high-performance provided by hardware and the flexibility of software implementations, many of these new security primitives will be developed following a Hw/Sw co-design methodology. This kind of hybrid realizations with enhanced security at both hardware and software levels will be also excellent platforms to evaluate possible vulnerabilities, as well as to explore hardware, software and mixed countermeasures during the design phase of a cryptographic system.

The massive use of devices connected to communication networks for the exchange of information among administrations, service providers and citizens, raises a number of open issues related to security. System hardware is the first link in the chain of trust that must be established to provide a secure environment for users. For this purpose, electronic devices must provide a Root of Trust (RoT) based on the confidence on their fabrication and resistant to device impersonation attacks. PUFs and True Random Number Generators (TRNGs) are the key components of a silicon-based RoT. PUFs have been used in recent years as a mechanism to provide unique and non-transferable identities to hardware devices. PUFs should be easily evaluable and repeatable functions so their associated hardware can prove its identity by repeating the function evaluation, whereas another identical device (a possible impostor) is not able to generate the correct output for the same input. PUFs must generate responses with sufficient entropy to not reveal device secret information. On the other hand, Silicon-based TRNGs, which use a source of entropy such as thermal noise to generate unpredictable and statistically uncorrelated sequences of bits that allow generating secure and unreproducible keys and challenges, are a must for trusted and secure implementations.

A reduction of entropy leads to system vulnerabilities. In this regard, a crucial issue is device aging due to different mechanisms (such as BTI-Bias Temperature Instability or HCI-Hot Carrier Injection), which degrade the performances of circuits over their lifetime, and therefore can seriously compromise security in hardware implementations. Furthermore, aging affects not only the PUF but also the other elements of the security chain. It is therefore essential to study and analyze the effects of aging on the whole security chain, paying particular attention to whether these effects are accumulative, and whether and how these effects can be mitigated when the security level is fatally compromised.

Most of the applications mentioned above which use cryptosystems (identification, authentication, digital signatures, etc.) are embedded in smart cards, smartphones, tablets, IoT devices, etc. Hence, many cryptographic devices are physically reachable and might be within adversary's grasp. Regarding this fact, the challenge to be faced is twofold: on the one hand, improving attack techniques (leakage detection, higher-order attacks and protection circuit edition), which will allow improved security evaluations of the devices that citizens will use; on the other, to design new countermeasures capable of guaranteeing that the devices are resilient against increasingly sophisticated attacks. Examples of such countermeasures can be the automatic logic power balancing, the generation of passive and active top metal shielding to prevent focused ion beam circuit edition and microprobing, the integration of light sensors for the detection of die decapsulation, substrate thickness monitoring to identify possible backside attacks, passive layout camouflage based on near-equal layout gate libraries, active hardware obfuscation by means of synthesizing dummy finite-state machines, physical redundancy of protection flags, etc.

Secure processing

As mentioned above, besides secure transmission and storage of information, digital information origin should be authenticated. Avoiding counterfeiting is very important because fake devices do not meet usually the required quality provided by legitimate devices and can be the trapdoor for espionage. In addition, the European technological dependence on companies outside Europe affects many aspects of our digital society as most devices used by citizens every day (smartphones, tablets, smartcards, etc.) employ a technology closed under the control of a few number of non-European companies.

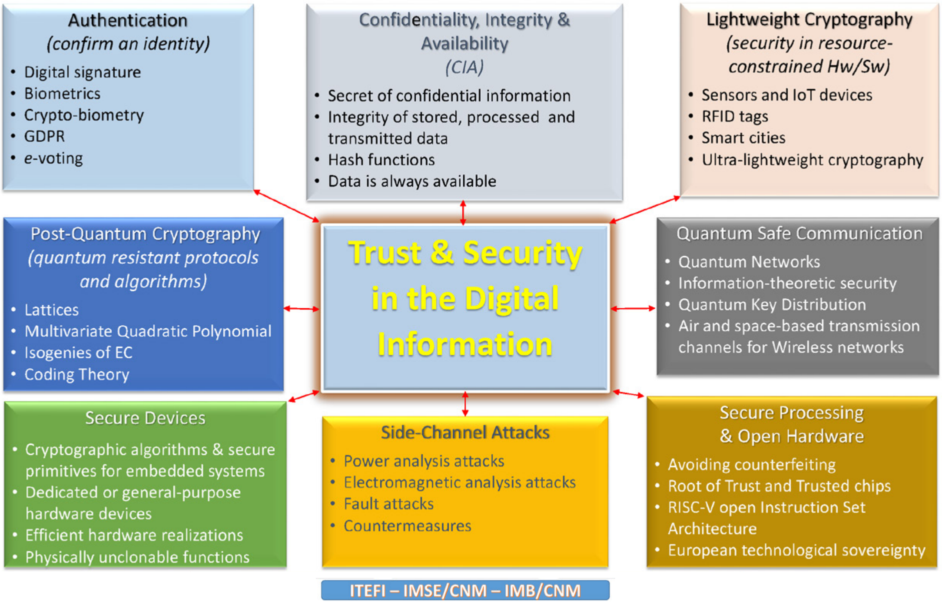
The EU has financed (with around 80M euros), the EPI project within a program that has the heading "H2020-EU.2.1.1.2. – Next generation computing: Advanced and secure computing systems and technologies, including cloud computing". This project has as one of its missions "Developing the first generation of technologies through a co-design approach (IPs for general-purpose High-Power Computation or HPC processors, for accelerators, for trusted chips, software stacks and boards)".

In this sense, "trusted chip" is the keyword and it is evident that Europe, and Spain in particular, need a certain level of technological control that they do not currently have. This challenge is not only the design of a European processor but also includes topics ranging from secure communications protocols that cover the entire range of applications, from broadband to IoT, until the control of manufacturing technologies. However, even in the case of fully European secure computing systems, there is still the need for auditing such a "trusted chip" to detect possible hardware trojans introduced either at the design house or at the semiconductor foundry. Hence, the second challenge here is the automated reverse engineering of full IC designs containing hundreds of thousands of equivalent gates. This hardware trust and assurance verification at chip level requires the physical extraction of the entire mask design and the bottom-up analysis of the resulting layout up to the architectural and functional description levels of the full chip.

Security by obscurity is discouraged and not recommended by standards bodies since the last century. Open technology is preferred. A possible solution to this situation is the RISC-V ISA (Instruction Set Architecture), which is free of royalties for any company and can mimic the path initiated by Linux years ago. In deep, the EU has chosen this architecture as a reference for the future European microprocessors. In fact, it is expected that this RISC-V open ISA will help to start and grow the open-hardware developments and market as happened years ago with Linux open operating system, which ten years later resulted in a large community of open software developers while reducing the costs of software developments. The RISC-V Foundation includes the Security Standing Committee to agree in the best security practices and include them in RISC-V based implementations. Nowadays, academic and industrial sectors are working on developing from cryptographic IP modules to complete Trusted Execution environments based on RISC-V. In addition, in order to have "compliant" RISC-V devices, a complete set of standard compliance test cases, methods and tools have to be provided to the developers allowing the detection of possible errors, security flaws or backdoors.

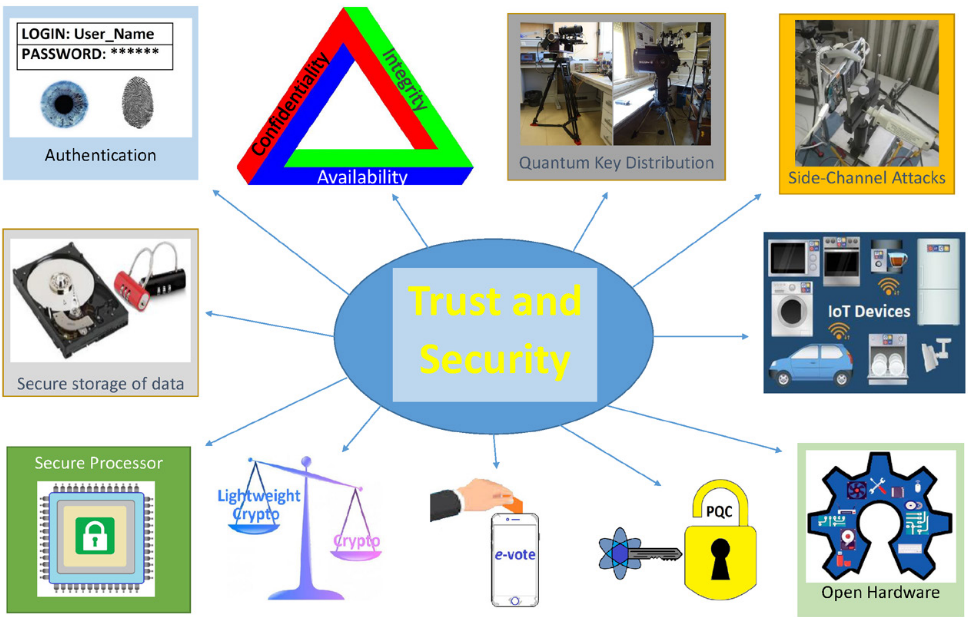
ANNEX: ONE SLIDE SUMMARY FOR EXPERTS

FIGURE 5.3—Trust and Security for experts



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

FIGURE 5.4—Trust and Security for the general public



CHALLENGE 6

ABSTRACT

Open Science is becoming a new paradigm in scientific research and complex changes are being done. This new way in knowledge development requires a great transformation that will allow science to adapt efficiently and effectively to the urgency of the problems to be solved while ensuring the reproducibility, transparency and reliability of scientific results. This chapter analyzes the impact of this change of model, the challenges to be addressed and the expected benefits.

KEYWORDS

open science | open knowledge | reproducibility | transparency | FAIR | big data | scholarly communication | outreach | scientific assessment

CHALLENGE 6

OPEN SCIENCE: REPRODUCIBILITY, TRANSPARENCY AND RELIABILITY

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1. EXECUTIVE SUMMARY

Scientific research is a global, collective enterprise, today more than ever collaborative. Its main objective is the production of knowledge that allows society to advance in diverse areas with a strong social, economic, cultural and environmental impact. It is an activity that demands important resources and their long-term sustainability. A very high percentage of it is financed with public money, so society expects in return positive outcomes impacting on health and quality of citizens' life. The current model of scientific research is facing the unquestionable challenge of a great transformation that will allow it to adapt efficiently and effectively to the urgency of the problems it must solve while ensuring the reproducibility, transparency and reliability of scientific results. The CSIC is called upon to move towards this new paradigm, in which it must change the way science is done and, above all, how its results are managed, communicated, used and reused. It should seek ways for a more open, transparent, interdisciplinary, collaborative, sustainable global system of scholarly communication. This chapter analyzes the institutional potential impact of this change of model, the challenges to be addressed and the expected benefits.

2. INTRODUCTION AND GENERAL DESCRIPTION

Research institutions are under a hard pressure of scientific, health and socio-economic challenges. It is time to transform individual research efforts into a more collective effort. Sustainable and innovative solutions must be supported on time by an efficient, transparent and dynamic scientific endeavor, not only from the scientific community, but from other key stakeholders and the entire society. Open Science embodies the need to transform, open and democratize the entire knowledge generation to ensure that every scientific challenge is faced and really drives and allows the achievement of the United Nations Sustainable Development Goals [United Nations, 2020].

Driven by unprecedented advances in our digital world, the transition to Open Science allows scientific information, data and results to be more accessible (Open Access) and be more reliable (Open Data/Open Software) with the active participation of all relevant stakeholders (Open to society/Citizen science). However, in the fragmented scientific and political environment, there is not yet a global understanding of the meaning, opportunities and challenges of Open Science.

Furthermore, academia and scientific institutions need to regain and keep control of its research outputs (publications, data, methods, software, etc.). The control over all scientific results largely due to research funded with public money must be regained because the largest part of the scientific results are under the control of private commercial publishers and access to scholarly outputs is behind paywalls. Open Science is not only about Open Access advocacy and open and foster sharing and reuse of data and software. We must take another step forward and open the validation, use and reproducibility of processes, code, methods and protocols to open the doors. Change the way we do science, following the scientific method (a process established in the 17th century) in the digital era. Open Science is rooted in the tradition of established principles of good scientific practice, but the goal now is to critically reflect traditional scientific culture and to transfer it into the present era of linked-up Open Research.

Digital technologies today allow the setup of working environments for the development of research activity that drives a more trustable, shared, participatory, transparent, optimized and efficient science to meet the aforementioned challenges. In the era of the Big Data infrastructures, the use of artificial intelligence, deep learning technology applied to the analysis of big or long tail data will bring capabilities and results unimaginable a few years ago. But for this to happen, it is necessary a real time exchange of data, which must be organized, properly curated using open and interoperable standards for machines.

Today, because of the huge data production of all kinds of scientific results, to guarantee quality and scientific veracity is paramount. The only way to face this issue and successfully achieve it is through openness, transparency, accessibility and interoperability to reproduce the whole scientific process. The different steps along the research life cycle must be linked and their relationships identified not only to create data, but also to transform into information and, eventually knowledge, technology advance and human progress.

Reproducibility, a cornerstone of the scientific method, is still a challenge. In the era of computational research, reproducing an experiment can be impossible due to the lack of access to data, configuration parameters, software environment, analysis tools, as well as to annotations and provenance information describing all those elements. Therefore, identifying these components is needed, which means that the research life cycle needs to improve its transparency. The reproducibility problem is currently increasing due to the information and data deluge generated by worldwide scientific infrastructures. Solutions are starting to emerge, involving e-science technologies to enhance scientific collaboration and knowledge sharing, ensuring transparency, opening data and methods, and encouraging Open Science methods.

Now more than ever before, due to the planetary challenges we face it is time to foster Open Science practices at CSIC. The institution will thus demonstrate its social accountability, leverage its role in the advancement of worldwide science in the search for solutions to the great problems that today's society is experiencing, as well as the unknown ones that it will have to face in the future to come. This chapter is about defining why, what and how CSIC should adapt to the new paradigm of Open Science already marked by all science agendas worldwide [Netherlands, 2017] [CNRS, 2019], how as one of the most relevant European scientific institutions plans to participate in building a global Open Research infrastructure that improves and adds value to the research workflow by promoting collaboration, sharing of scientific assets and knowledge, avoiding fragmentation and duplication. This is the frame of the European Open Science Cloud (EOSC), a new environment to perform Science and to promote the collaboration among disciplines and researchers in Europe.

The journey through this global cultural change, that means understanding science as a public good, will need efforts and investment in providing capacities (infrastructures), arranging the needed resources, both financial and human, endowed with the necessary qualities and capabilities. Last but not least, the adoption of a new framework for research evaluation and incentive systems that recognizes researchers' commitment in line with the Open Science values and fundamentals of reproducible science.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The expected impact of developing Open Science practices is global and spans across all disciplines within the institution. Benefits of implementing openness along CSIC's community outweigh the potential costs the institution will need to face as takeoff. Among them we can highlight the following classified within main categories:

3.1. Institutional-Science-Society benefits

Promoting Open Science Publishing Publishing in Open Access journals, open publishing platforms or via institutional repositories means that scientific results will be accessible to a wider audience who can read without paywalls, accelerating information and knowledge transfer to society.

Science and social responsibility CSIC's image as a science generator and its social responsibility and commitment will be reinforced for its collaboration in the democratization of the scientific knowledge produced, by improving access to scientific resources; by enabling the participation of a wider community in the research process; and by making science more comprehensible to the society at large as well as more transparent.

Scientific efficiency Among benefits expected as a result of the implementation of an Open Research strategy, and specifically those that have to do with scientific efficiency, it is worth mentioning to ensure accountability: Open Access to scientific research outputs provides greater institutional accountability but also to research funders and taxpayers. Wider availability of knowledge resources will make high quality research faster, cheaper and research success more likely. More fluent collaboration among heterogeneous, multidisciplinary knowledge actors will amplify CSIC's collective intelligence and creativity.

Open Access infrastructures will also increase efficiency because it enables the use of common capacities and facilities that will interconnect knowledge production, reusing online available data to arrive at new findings (data driven intelligence). CSIC research community will be able to interact more fluently, collective intelligence will be amplified by the mere fact of being able to share, validate and quickly rule out different ideas, assumptions, hypotheses or new avenues of inquiry. Accelerating knowledge transfer and reducing delays in the sharing and reuse of CSIC's scientific outputs.

Foster a more open and collaborative scholarly environment @CSIC With the promotion of an Open Science strategy the institution encourages collaboration among all data dependent disciplines, provides infrastructures that facilitates data sharing, analysis to be taken to the next level in order to further scrutinize the data avoiding duplication. The role of the software will be particularly emphasized within the proposed strategy as a key enabler for the production, analysis and visualization of the research data in a scientific study.

3.2. Methodological benefit for the researcher career

Be ready for Open Science Funding CSIC will meet the actual and future requirements established by funding agencies worldwide that promote the Open Science realisation. Thus, CSIC researchers will be better positioned for the upcoming challenges formulated at the international level.

Increase visibility By boosting open practices, CSIC's Open Science strategy practitioners will have the opportunity to get more visibility for their research outputs, through seamless access and reuse (citations), and impact beyond classical bibliometric, media attention, potential collaborators, job opportunities and more recognition.

Tackle the Research Reproducibility problem If researchers release their data, software, and materials into the appropriate repositories with the appropriate metadata curation, then this increases the accessibility, and reproducibility of the findings by other researchers. Ultimately, when researchers share their scientific outputs, they are exposed to further analysis by the scientific community, and thus this fact contributes to increase confidence in their own research. At the same time CSIC research results are preserved and accessible for the future.

Advancement of collaboration Success in research requires collaboration, but, often, it is difficult to identify and connect with the appropriate collaborators. Practicing Open Science within or beyond CSIC will make it easier for researchers to connect with one another because the discoverability and visibility of their work will increase. This in turn will facilitate share, reuse and easy access to novel data and software resources. Researchers will also be in a privileged position with respect to evaluation of their careers in terms of altmetrics.

3.3. Sample of CSIC's use cases

Open Science involves every single discipline represented within CSIC, so this new paradigm emphasizes the intrinsic multi- and inter-disciplinarity of the institution, enabling existing and new ways of collaboration. There are a number of potential new applications thanks to Open Science, both at general and at discipline level, ranging from applications in the fields of health and biotechnology, climate change, management of natural resources and ecosystems, astrophysics, demographic crisis or management of public policies... to mention some. During the last times, this interdisciplinary character of CSIC has been reflected in the creation of the Thematic Interdisciplinary Platforms, which aims to create collaborative groups with CSIC research groups to address complex scientific goals.

Reproducibility review "service" for bio sanitary crisis, the immediate case of COVID-19: During the worldwide challenge to face the bio sanitary crisis produced by the COVID-19 pandemic, an unprecedented volume of scientific information has been released to address the problem from different perspectives: clinical, biomedical, societal, etc. This means that researchers from diverse areas have started to collaborate supported by digital technologies and adopting an Open Science vision. This unexpected problem requires sharing of diverse research results as well as services. Sharing of computational resources and expertise in data science is already happening in CSIC in order to face the COVID-19 pandemic in an interdisciplinary way. Complementary to this, more than ever reproducibility and opening of the scientific methods is key to accelerate research, so that:

1. The results can be more rapidly compared
2. Reuse of methods by different teams in order to analyze different datasets/samples is facilitated
3. Reliability of the results and the exchange of knowledge is reinforced

If papers on COVID-19 can be reproduced, it will be possible to access the code that has been used, identify possible errors or improvements in the data sets, reuse them for new data that becomes available, etc. In practice this would translate in supporting end-to-end reproducibility through a research workflow. Key steps include creation of software environment, access to raw data, steps taken to process them, access to the data, simulations or models, as well as scripts (e.g. in the form of Jupyter notebooks) underlying the results, including making tables and figures in the paper reproducible (data, images, fits and their error bars, simulation models, etc.). Advantages include: faster implementation of peer review (re-running modified notebooks re-generate figures in "a click", cloud access to any other team, validation, re-use, re-purpose, etc.).

Nowadays it is very difficult for the researchers/scientists to do this without support of data stewardships or software engineers, and the investment of time required is often considered to be "not worth it." In the rush to find a solution to the COVID-19 crisis, teams need more than ever support to ensure that their digital research can be easily accessible, shared and reused. Several teams at CSIC have expertise in Open Science and reproducibility applied to different disciplines. In particular, CSIC has released the Global Health thematic interdisciplinary platform, started as a framework to establish relationships among CSIC research groups and also with external entities to develop vaccines and medicines, create new kinds of tests or to propose measurements of social distancing among others. Within this platform, some groups are oriented to facilitate the data management and sharing as well as provide computational resources. This is a clear example of how Science can be more efficient adopting an Open philosophy.

Biodiversity: sharing data, publications or any kind of development will enable the possibility to improve the information we have about not only the distribution of certain species but also how they interact among them. Furthermore, due to the transverse character of Open Science, the interactions between the species and any other process on Earth will be potentially understood thanks to the integration of data sources and knowledge from different disciplines. CSIC coordinates the Spanish node of GBIF (Global Biodiversity Information Facility) and it is actively involved in a few Biodiversity-related ESFRIs like LifeWatch ERIC or DiSSCo.

Earth and Marine Sciences: building a new and innovative infrastructure for mapping seafloor features that may represent potential geological hazard. The initiative will allow defragmenting the geoscience community working at sea through the incorporation and integration of collections, data-archives, services that nowadays remains dispersed through the scientific groups, institutes and services. In fact, today there is a huge volume of data that were initially recovered for specific scientific objectives and that now remain dispersed throughout and stored in research institutes, universities, and exploration and survey companies. These data should be findable, reusable and accessible and thus to ensure that they keep having great value of scientific continuity and also for other end users (industry, public administration). This infrastructure should also ensure their sustainability and offer new methods based on machine learning and artificial intelligence to increase accurate mapping of marine geohazard features, and to build a link with risk assessment; also, it would be transferable to other disciplines.

Astronomy and Astrophysics: Astronomy has a long tradition in Open Science, being a reference for the establishment of standards: the International Virtual Observatory Alliance (IVOA) was created in 2002 to provide standards for data and software interoperability, as well as Open Access to data in Astronomy, with a special emphasis on optical Astronomy. CSIC is leading the Spanish participation in the Square Kilometre Array (SKA), which will constitute the largest scientific infrastructure on Earth and the largest generator of open data.

This brings the challenge of providing access to SKA (Big) data products, tools and processing power to international distributed teams. Creation of new standards for radio astronomy is crucial to enable bringing the new facilities in construction into the Virtual Observatory ecosystem, facilitating multimessenger science to a wider community. The construction of the new mega science projects and infrastructures are moving the field into a new era in which large international alliances of scientists will be required to analyse the data deluge. We are hence in a race to exploit ever larger datasets, and in our quest for "efficiency" we risk forgetting about reproducibility. In this challenging new era in which Big Data will be analysed by teams largely distributed along the globe, only if we are ready to change the way in which we work, we will be able to increase the degree of reproducibility of our research, and consequently improve the quality of Science. A new kind of infrastructure and platform to share knowledge, big/complex data, and methods, will be required to follow the FAIR principles [Wilkinson, 2016] (Findable, Accessible, Interoperable, Reusable) and achieve reproducibility.

4. KEY CHALLENGING POINTS

4.1. Ensure reproducibility: standards and interoperability building capabilities

Ensuring full openness and reproducibility will take time and major efforts to operate with interoperable and reproducible data. A questionnaire on reproducibility published in Nature (2016 [Baker and Penny, 2016]) found that 70% of researchers cannot reproduce another's experiment while > 50% their own ones. Furthermore, the academic paper represents just a small part of the research if it doesn't come together with input data, configuration parameters, software environment and analysis tools, as well as annotations and provenance information describing all those elements. The actual standard formats for publications come with a loss of at least 40% of the knowledge [Bechhofe et al., 2010].

Open and reproducible science often consumes time, mostly in the early phase of implementation of a new system. Archiving, documenting, and quality controlling of source code and data takes time, but the resultant benefits are manifold for the creators, their institutions and the broader user community. Just as the quality practices in the software development life-cycle shall be enforced from the very early stages, curation activities must start as close to data creation as possible in order to ensure reproducibility and replicability. Different types of additional practices will be needed, for instance: enough time to learn and implement emerging tools, methods and standards; time and incentives for researchers to change habits and an experienced dedicated staff should be engaged in the process of data management and curation according to such standards and best practices. Further, CSIC multidisciplinary poses an extra challenge in this regard, as the adoption of Open Science tools, standards and good practices should meet specific discipline requirements and foster at the same time high degrees of interoperability across all institutional infrastructures and associated contents. DIGITAL.CSIC compliance with several standard metadata schemes and various data management best practices move towards greater interoperability within the institution and in the global Open Science ecosystem.

Because the cost of not FAIR data for research is high, strict adherence to FAIR principles to ensure sustainability (research data and software) alike data preservation are other major challenges. Applying FAIR criteria will guarantee discovery, access and reuse of research outputs by humans and machines, while long term sustainability and preservation will depend on the adoption of Core and Trust Seal principles [CoreTrustSeal, 2020] by CSIC repositories. Also a robust institutional preservation policy is needed behind, such as repositories, with a clear mission, budget, priorities and strategy and based on the OAIS preservation model. This institutional infrastructure should cover the maximum level of compliance of NSDA recommendations. Ensuring digital preservation will contribute to eliminating science's blackout tomorrow.

FAIR principles do not just apply to data, but also to other research objects. In particular, research software sustainability shall be given a high level of importance and visibility in order to develop Open Science, since it is an undeniable key piece. It will be necessary to establish comprehensive quality criteria for software production and delivery, including documentation, code management and accessibility, as well as validation and verification processes. The challenge is not only to manage new research outputs from an Open Science perspective but also to fully identify, document and safeguard software heritage produced by CSIC in past years. Documenting, managing and making workflows accessible will also be a requirement to enable computational reproducibility.

Good data management is critical for ensuring validation, transparency of research findings, as well as to maximize impact and value of publicly-funded research through data reuse. CSIC repositories and other Open Science infrastructures would need to provide crucial services and tools that manage and enable full description, date and provenance registration, access, versioning of data and software, publications, software quality assessment and a wide array of other types of scholarly content, as well as value added tools for the community to ensure the good management of the research results.

CSIC must contemplate a strong investment in training and development of knowledge and skills. Groups exist in CSIC that are a reference at international level in these aspects applied to their domain, but this should be expanded, and not only must the scientific community be trained, but also the technical staff, and that will need a major skills upgrade in order to assist it in adopting practices and guidelines for the development of an Open Science environment ("Metadata curators", "Knowledge Commons Specialists" "Research Software Engineer", "User support staff", "Data scientists").

4.2. Providing capacities by implementing Open Research infrastructures

CSIC would need to be able to deploy a set of reliable and open infrastructures (European Open Science Cloud driven) that covers the needs of a multidisciplinary institution with a huge diversity of requirements. To cover all scientific and technical communities, assuring none of them is left behind. The infrastructures must cover the complete research workflow, tailored for big and long-tail data environments. These infrastructures shall provide an open environment with sufficient computing capacity for managing the research process, including added-value services and tools that allow the scientific collaboration, FAIR data and software quality assessment, setting the path for the reusability and exploitation of the scientific results and digital research objects (Text Data Mining, Deep and Machine Learning, Extracting, Visualization, etc.) The challenge of setting up a distributed, powerful, granular and scalable infrastructure must also be considered.

Best practices akin to FAIR principles can be adopted by Open Research infrastructures aiming at properly providing the required functionalities. Some of the resources already available for the researchers are not always well-known or they cannot easily be found (Findability). Furthermore, the set of services provided need to be seen as a common daily basis tool, just like a teleconference room or an E-mail client. In that case, the learning curve needs to be reduced and some training needs to be provided, making the use of research infrastructures and e-infrastructures more accessible. Some of the required components to compose the Open Research infrastructure environment are already available. For example, repositories providing Open Publications/Data and metadata, computing infrastructures enabling technologies for data analytic or data preservation services storing long term data. The future infrastructures will not need to reinvent the wheel but adopt an interoperable practice of the already available facilities. This can be done thanks to the federation of resources, implementing machine-actionable features to allow services to interact among them or promoting the sharing of research products, not only papers but open-source software or data.

One of the main critical challenges to be addressed by new research infrastructures is the capability to support the growing volume of scientific data being gathered. The high data rate and volume as well as the complexity of data produced by disciplines like those above mentioned (see Sample of CSIC's use cases) will necessarily transform how scientists access, share and analyse information. Furthermore, to address complex and global challenges and problems to be faced, an interdisciplinary way to do science needs to be implemented. The future research infrastructure needs to be able to manage Big Data from different perspectives (Volume, Variety, Velocity, Veracity, and Value [Ishwarappa and Anuradha, 2015]) in a FAIR manner and it needs to facilitate the data sharing and collaboration among researchers.

4.3. Open Science as the norm in research practice: meet the agendas of the funding agencies

Managing an Open Science environment in the CSIC will involve facing a change in the scientific culture of the organization and its members. Conceive how to generate science and produce knowledge based on the values of Open Science. Understand knowledge as a common good, defend a cognitive justice that promotes plurality and diversity, be inclusive and foster equity to the fullest. Respect the right to make research, fulfill collaboration in terms of equality between partners and advocate for sustainable and inclusive infrastructures for all. It is relevant to take into account that the idea of Open Science started as a bottom-up initiative, directly from the community (Declaration on Research Assessment (DORA), Metric Tide, Leiden Manifesto, Altmetrics, etc.) and just recently became top-down with initiatives like "cOALition S" or through the implementation of different working groups at the European Commission.

Open Science is one of the European framework pillars, and will become the modus operandi of Horizon Europe [Horizon Europe, 2020], requiring Open Access to publications and data. CSIC, as a research institution that manages numerous national and international projects and especially those under the umbrella of the European Commission, has to harmonize the protocols necessary for researchers to comply with the requirements of regulations and guidelines that affect open publication and data management. It must provide the tools and infrastructure that allow access and interoperability between the different systems of the ecology of scientific communication, and foster the implementation of monitoring processes to measure compliance, compatible with similar procedures in other countries, regarding variables and processes for its calculation.

A challenge that CSIC must face in the near future will be how to adapt our infrastructure and protocols to comply in the next future with the Directive (EU) 2019/1024 of the European Parliament and of the Council on Open Data and the re-use of public sector information [European Parliament and Council, 2019]. The Directive extends its coverage to research data resulting from scientific research activities subsidized by public funding or co-funded by public and private-sector entities, according to the principle "as open as possible, as closed as necessary". This will require that the ethics committees take into account all those cases in which the investigation deals with individuals. CSIC should provide tools, resources, and training for the good management especially of those personal and sensitive data to comply with the data protection regulations, as well as the implementation of protocols and software applicable to data anonymization.

On the other hand, Plan S [Plan S, 2020] endorsed by the European Commission and the ERC, and supported by more than 20 European research funders, considers both the golden route and the green route to Open Access scholarly outputs. To comply with the requirements for Open Access repositories (H2020, ERC, CSIC), technological and standard requirements must be implemented along with the mandatory criteria. In this regard, Confederation of Open Access Repositories [COAR, 2020] (COAR), of which CSIC is a member, is working on the recommendations to adapt the repositories to those requirements, based on among others in the FAIR principles (Findable, Accessible, Interoperable, Reusable). Regarding publications, the European Commission has recently awarded the development of a platform [European Commission, 2020] for open scientific publications that meets the requirements of its calls and that will be launched early in 2021.

4.4. Research Evaluation

Current CSIC indicators of performance (Strategic plan 2018-2021) are based on global figures as number of papers (I1, I2), books (I3), PhDs (I4), protected technologies (I5), created companies/spin-offs (I6), or economical value in terms of budget of signed research contracts (I7) or return of licensed technologies (I8). There is wide bibliography (including e.g. a Nature special on Open Science in 2010 [Braun, 2010]), stating that science is killed by numerical ranking. Open Science denotes new ways of generating and using scientific knowledge that facilitate collaborative modes of research. Such collaboration connects individuals from many different contexts thus dissolving the sharp institutional boundaries that had so far segmented the processes of knowledge generation and use. Technicians, scientists, and citizens can get involved, through large teams and informational platforms for sharing in a seam-less manner in complex processes of knowledge generation and use.

The consequences of this shift for research evaluation are nothing short of momentous. Current evaluation practices typically assume a strict division of tasks. Separate organisations are assumed to produce specific types of outputs (publications, patents, etc.), which are used in incentives schemes that revolve around the individual as the central evaluand. Given the focus in Open Science on the facilitation of knowledge flows across diverse stakeholders, research evaluation has to shift from the current focus on journal outputs and visibility, to a focus on communication and collaboration processes. This means that the traditional evaluation approaches that reward individuals based on performance, and assess such performance through the analysis of narrow sets of indicators (like publications and citations) are not fit for use in a context of Open Science.

Therefore, the challenge goes beyond the definition of new sets of "Open Science" indicators, but requires the design of a different research governance system. It needs to shift to forms of evaluation of labs, teams or institutes that value not only the knowledge but crucially also how this knowledge is made available and the collaboration with a variety of social stakeholders. Given the great diversity of communication and collaborative practices across disciplines, Open Science evaluation cannot rely on a fixed new set of indicators, which replaces the 'late 20th century' bibliometric indicators. Instead, the evaluation of Open Science requires contextualized evaluation methods in accordance with principles put forward in the DORA or the Leiden Manifesto. In some disciplines and contexts sharing 'software', well-curated 'data' or training local experts may be as or more important than publishing. Evaluation of Open Science needs the flexibility to capture the varying values of these activities in different research environments. This is why they cannot rely on universal indicators, as reported by the EC Expert Group on Open Science evaluation [Wouters et al., 2019].

While Open Science is a challenge for research evaluation it is also a great opportunity to put the value of scientific learning, collaboration and communication at the center of the evaluation effort – and to move away from top-down, one size fits all, evaluation practices that may have harmed research in the last two decades.

4.5. Sustainable scholarly communication system (Authors rights management, OA licenses and GDPR)

A system based on Open Science by design contemplates that all products of the research process will be available as soon as possible at no charge. This view conflicts with the current CSIC scientific communication system that relies on the *modus operandi* imposed by the third-party content subscription system. It is thus necessary to look for alternative models (e.g. Publish and Read agreements). All this, complemented with other options of promoting Open Access publication (Gold route), through repositories (Green route) or through an Open Access institutional publishing platform (Red way).

In the current scholarly publication system there is another doubtful component, the actual peer-review system. Its opacity can jeopardize the truth or scientific integrity, thus opening the door to scientific fraud, data manipulation, poor quality peer review and conflicts of interests. Alternative models supporting wider transparency and accountability have been put in practice over the last years by several publishers and repositories. Opening up identities of reviewers and/or associated reviews is contributing to create a new scientific validation environment that is more participatory, transparent and informative. However, major challenges and reticence remain within the scientific community. For instance, DIGITAL.CSIC survey [Bernal and Román-Molina, 2018] to CSIC researchers about peer review practices and opinion about the repository's Open Peer Review Module shed light about current lack of incentives to embrace new peer review practices, and other factors such as fear of retaliation and time consuming-ness.

There is an urgent need to establish an institutional system whereby CSIC centrally manages the intellectual property rights derived from the works produced by institutional researchers. According to national legislation, exploitation rights of intellectual outputs by employers in the public sector belong to their institutions however there is a high degree of confusion amongst researchers as to the proper management of such rights. An institutional copyright management that avoids the transfer of exploitation rights of CSIC intellectual works to third parties is a must in a system based on Open Science. By signing copyright transfer agreements and exclusive licenses to publishers use and reuse of CSIC outputs (even by CSIC itself, for instance when it comes to self-archiving into DIGITAL.CSIC) are highly compromised and this widespread practice contributes to the permanence of the current system of scholarly communication. On the contrary, a CSIC policy is needed so as to enable Open Access and reuse of its research outputs through the appropriate Open Access licenses ("as open as possible, as close as necessary"). This policy should include considerations for CSIC publications, research data and software as all these types of research outputs fall under copyright legislation.

There are more legal concerns around. CSIC must monitor the current landscape around the national transposition [FESABID] of the European Copyright Directive in order to make sure that it does not harm the interests of research, does not prevent certain types of Text and Data Mining actions or does not impose additional management workload on content sites. Last but not the least, the correct application of the new EU General Data Protection Regulation (GDPR) requires an extra effort of awareness raising, training and allocation of resources. From May 2018 collecting and processing personal data is regulated by the GDPR for all EU citizens. Personal data, and in particular sensitive data, are at the core of some research fields. However, there are research exemptions in the Regulation; it is crucial that CSIC includes GDPR considerations in the technical design and operational policies of its research repositories and infrastructures to avoid major legal breaches. At the same, a full understanding of GDPR amongst CSIC researchers and technical staff is needed considering the implications on the planning of data management plans and recommended data curation throughout the whole research cycle. In this regard, clear institutional guidance on best practices to safely store, process, anonymize and pseudononymize and share personal data will need to go accompanied with resources that enable the lawful management of this type of data while supporting Open Science.

4.6. Outreach and dissemination

Access to culture (including scientific culture) is a right enshrined in the Spanish Constitution [Fundación Acción Pro-Derechos Humanos] in which scientific centers are actively working. The number of initiatives to promote scientific culture is very wide in formats: from initiatives outside the centers such as the international “Pint of Science” festival in which scientists give outreach talks in bars, to science fairs promoted by universities, to television programs whose central theme is science. But just as new technologies have revolutionized all aspects of society, the distribution of scientific culture is no exception.

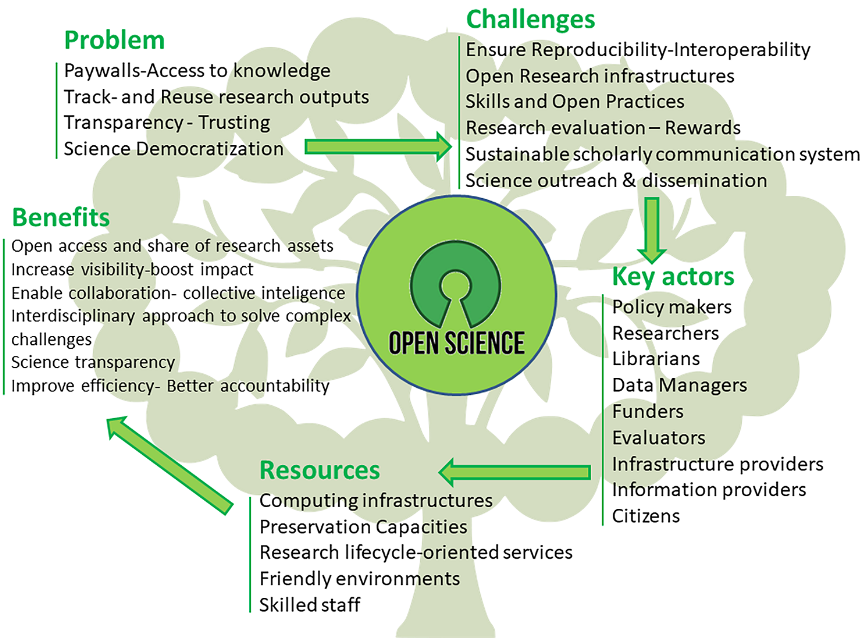
The digitalization of everyday life has led to a change in the consumption of information. The latest report on the social perception of science and technology in Spain [FECYT, 2018] by the Spanish Foundation for Science and Technology (FECyT) highlights the fact that 63.4 % of those surveyed report on science and technology issues through the Internet, the digital press, social networks and other websites. In the 15-44 age range, the preference for this medium is always above 70%. In this context, it is clear that an effective strategy to digitize scientific culture is necessary.

Since scientific communication is a field with so many possibilities, there are many digital formats in which to carry it out. However, there are common strategies among most CSIC centers, such as the management of their own self-managed dissemination websites to collect these materials, which are listed in the Dissemination section of the CSIC website [CSIC Divulgación]. On these platforms, digital material such as videos or blogs produced by the center’s own research and/or technical staff can be found. These materials not only have value in themselves, but are often used by the traditional media as support when they echo related research. Having the capacity to generate this type of audiovisual format has gained importance in the digital era.

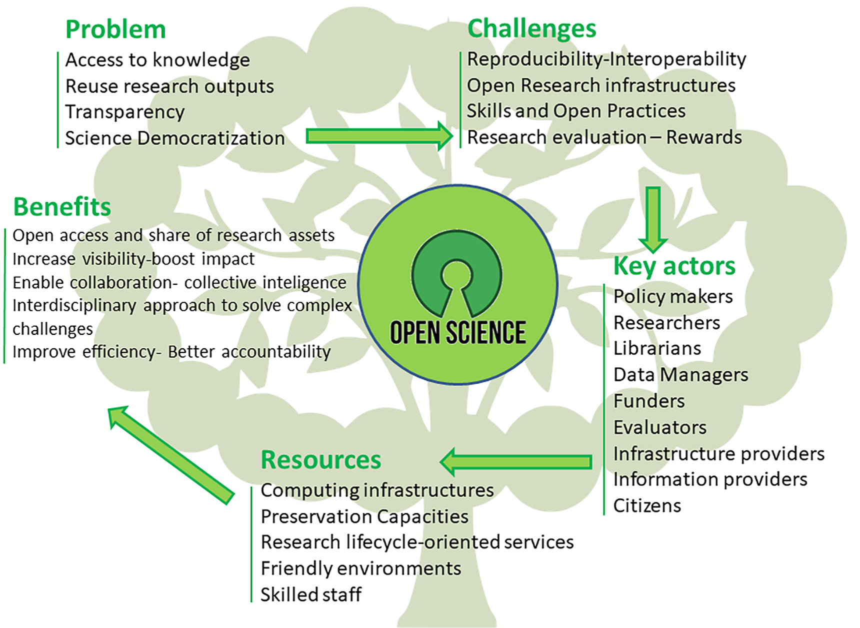
However, in current times, the amount of information that digital communication channels are bombarded with, much of it fake or malicious, can make efforts to digitize scientific culture go to waste and become diluted in the midst of so much noise. It is key to design strategies that not only tell the story of science in a rigorous way, but also do so in an aesthetically attractive way. In this scenario, one of the biggest challenges in the field of scientific communication is to adapt to these new realities; this requires dedicated staff and training, as well as providing centers with sufficient funding to be able to subcontract professionals from the sector who are capable of generating and distributing digital content for scientific communication.

However, this does not mean that face-to-face dissemination activities can be neglected. Close and face-to-face scientific communication remains very important, especially for those groups that may be more distant from the digital world, such as the elderly or children.

ANNEX: ONE SLIDE SUMMARY FOR EXPERTS



ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC



CHALLENGE 7

ABSTRACT

We hold three fundamental ideas regarding the role of Digital Humanities today: (i) Digital Humanities speak from technology rather than about it; (ii) Digital Humanities are a new attempt at understanding the problems that we humans face through the production and standardization of meaningful and interoperable computationally processed data; and (iii) Digital Humanities bridge the gap between engineering and art, science and literature, academic culture and urban culture, scholarship and design.

KEYWORDS

interdisciplinarity | interoperability | ontological turn | platform culture | citizen science | data visualisation | thick data

CHALLENGE 7

DIGITAL HUMANITIES

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1. EXECUTIVE SUMMARY

There is consensus in seeing Digital Humanities as a big tent that shelters the most diverse initiatives. We do not need a definition to argue that they are not limited to the task of digitizing cultural heritage.

Digital Humanities offer an opportunity to open up objects to interdisciplinarity and to provide them with novel layers such that each vision becomes also a version. Digital Humanities represent the opportunity to interweave scholarly, critical and design cultures, as well as bringing Humanities knowledge closer to technicians and argumentative practices to artistic ones. The scope of action of the Digital Humanities is broad and goes beyond traditional faculty and discipline based definitions of human knowledge. Its vastness does not prevent us from identifying some urgent challenges:

- Digital Humanities will be key for the optimal understanding of what data is and how it should be processed for scholarly purposes. Without Digital Humanities the process of digitization may well be blind.
- Digital Humanities represent an opportunity to open up knowledge regarding the creations of the human mind to new actors and conversations, both inside and outside the Academia.

- Digital Humanities build digital objects that incorporate multiple viewpoints, different methodologies. They promote novel forms of collaboration, beyond disciplinary and institutional culture.
- Digital Humanities are fundamental to understanding how human and social behavior is embedded in thick webs of interactions and relationships with other humans as well as with natural and human-built environments.
- The Humanities are moving from a traditional individualistic approach to a team effort, embracing standards, methodologies, structured data, processes, and documentation, that is discoverable, openly accessible and reusable.

Digital Humanities are not a new phenomenon in the CSIC. Currently, there are over 60 initiatives in progress involving over a hundred researchers. The case of the CSIC is particularly worth considering. Given its place as Spain's largest research organization (and this is also true for the Humanities), it is uniquely positioned to lead forthcoming transformations in higher education and scientific organization, as well as help build a decentralized infrastructure for Digital Humanities in Spain. As the country's premier scientific organization, in the next 5-10 years CSIC should lead efforts to:

- Create hybrid profiles and hybrid research groups, including a scientific computation unit to facilitate the use and development of open source software applications.
- Create Digital Humanities Laboratories to provide PIs and researchers technical support on project design and implementation, select adequate technologies and standards, choose the right digital tools at different stages of a project, and help in its dissemination from its first
- Develop and apply analytical tools (e.g. spatial and geostatistical analysis, network analysis, image analysis, 3D analysis, textual analysis through computational linguistics, modeling, simulation, artificial intelligence, machine learning, etc.)
- Create information systems for managing and distributing research data (compliant with an Open Science policy), such as spatial data infrastructures (SDI) or documentary repositories (for text, image, sound, etc.). Linked to this, the creation of metadata catalogs locating and identifying data sources is important too.

- Create dissemination platforms for the general public (through different multimedia resources such as cartographic displays, virtual reconstructions, etc.) and collaborative platforms to promote communication between the scientific community and citizens.

2. INTRODUCTION AND GENERAL DESCRIPTION

As computer machines became more affordable and user friendly around the mid 80s, humanists began to incorporate digital tools into their everyday research; first in text related sciences (Linguistics, Literature and Philology), then elsewhere. It is not as if no other attempts to measure and modelize their object of study were not aimed for before: mathematical calculation of simple stylistic patterns in literature works, information retrieval techniques and bibliometric studies for Library Science (i.e. Zipf Law from 1940s) or measurement of linguistic frequencies in closed written corpora had started already during the 19th century, and measuring and modelling the object of research have always been a characteristic to some Humanistic disciplines such as Archaeology and History. Several large-scale projects to apply computer-based methods of research to text data were already in development during the 1950s (the best known of them being the Index Thomisticus of Roberto Busa).

However, it was not until personal computers became a staple of universities and research centers, and gigantic improvements were made to computer interfaces and high-level programming that humanists adopted computer tools as a *sine qua non* of their research. Immediately after that, humanists all over the world started using IT tools not just to improve the quality of their work, but to manage data in a completely new way.

In those early years, humanists practiced just "computing humanities" i.e., they explored ways to use computing power to broaden their field of research. By the start of the new millennium, it was clear that such a huge collection of new efforts (to a large extent carried out by a small number of teams or even individuals) and practices had transformed the ways in which many Humanists worked and conceived their disciplines, and the Humanities at large. Hence the tag Digital Humanities (and translations thereof) was swiftly adopted worldwide.

At the core of Digital Humanities lies the concept of modelling. The scientific study of the basic elements of the world (Physics) has been modelling its field of study for centuries. Because the products of the human mind are the most complex of all structures we are given to study, Humanities was the last domain of scientific study where modelization was put at the center of scientific research or even considered as hermeneutically desirable. And it was only after computers were accessible to Humanists that modelling became possible in most such fields. Because language is maybe the most complex, encoded product of the human mind, and written text is relatively open to digital encoding, digitization started with texts and, from this core, it expanded in all directions.

Together with modelling, a new set of principles and methods started to take shape. Not last among them was the clear realization for the need to define broad, shared, extended standards in a consensual way among scholars for different tasks, like text annotation. This led to the conclusion that the ability to share data and knowledge among teams and disciplines relied heavily in the development of ontologies to define and describe their objects of study.

It is not by chance that the creation and development of the Digital Humanities runs almost in parallel with that of the World Wide Web. This highly standardized protocol to share data of many origins in a way that matches the needs of Human sciences researchers is not only the most favored way to disseminate results: it is also one of the main venues to collect data for in many Social Sciences and Humanities.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The massive, collective task that we call Digital Humanities is an international effort. It is probably just our luck that as the Digital Humanities grew in parallel with the Web, they inherited the best part of the open ethos of the early times of the Web and even the Internet before the adoption of hypertext. Digital Humanities technologies do not just benefit enormously from the emergence of the semantic web: they have also enabled this process in many ways, not least through the development of named entity recognition. Digital Humanities hubs all over the world do their best to adopt open software, as well as to release the results of their research online. Serious commitment to FAIR Data Principles and Linked Open Data are a given among the Digital Humanities communities.

The technical part of this endeavor has its specific requirements: it demands specially trained researchers; the adoption of new methods and approaches to face new challenges; a much stronger collective organization (Humanities have been for the best part of their history a mostly personal endeavor); new work habits, tools, and facilities and specific local and international infrastructures. Institutions like the Department of Digital Humanities at King's College London, the UCL Centre for Digital Humanities, the Humboldt Chair of Digital Humanities at the Universität Leipzig, the Digital Humanities departments at the Italian universities of Pisa and Università Ca' Foscari in Venezia; the EPFL's Digital Humanities Laboratory (Switzerland) and the Digital Humanities departments in several universities in Paris, just to mention a few of the main European hubs of Digital Humanities have developed their own local infrastructures, and their pioneering work has been pivotal to the development of tools, standards and the creation of specific research lines so far.

It must be noted that this process has been hugely uneven from place to place, and not every country or organization has evolved at the same speed. The case of Spain is particularly grievous, since the current state of its Digital Humanities infrastructures lags well behind any comparable country by almost any indicator of human development. Very few universities in Spain have Digital Humanities laboratories; Digital Humanities master's degrees were non-existent just three years ago, very few researchers can rely on support from Digital Humanities specialists, etc. In addition to the CSIC, there are currently several institutions seriously engaged in the promotion of Digital Humanities in Spain, notably among them the Biblioteca Nacional de España, LINHD (UNED), Grupo IXA (UPV), Grupo TALG (USC), or the PRHLT research center (UPV).

3.1. How does Digital Humanities change the understanding of society and the human mind

In Natural and Life Sciences the digital modelling of complex natural systems, or the virtual recreation of one or another species' behavior exposed the shortcomings of previous models and conceptions. In a similar vein, digital modelling in the Humanities forces us to make explicit many unspoken assumptions, and this, in turn is provoking a massive change in almost every field of research. The fact that this process took place in parallel with a complex evolution of modern large urban societies, only compounds the magnitude of the challenge.

As an example of the above, taken from Linguistics, in the 1960s many professional linguists believed that automatic translation was just around the corner. More than three decades of immense work in machine translation made clear just how complex human language is, how dependent on context and shared preconceptions among the community of speakers, and how interrelated it is with other cognitive functions. Of course, standardized modelling, shared ontologies, and open tools and data make it possible to compare the products of the human mind at a scale that was unthinkable just four decades ago.

This conceptual evolution should not obscure the fact that the material available to researchers has grown so much in most fields that it can only be handled by using complex digital tools. In this regard, the impact of Digital Humanities has been massive. Moreover, the present ability to deal with a large part of all the known material that is relevant to a given field makes it is possible to conceive multi-team projects that were inconceivable in the past.

Digital Humanities and Computer Vision walk together, but they do not necessarily overlap most of the time, nor is either of them redundant. Digital humanists should use Artificial Intelligence, learn from their methods and follow its progress, but approaches to similar problems from either field often take us to very different places. For instance, pattern recognition based advances in stylometry (the measure and study of the "style" of an author or a text) have been enormous in the last two decades, and instrumental to the growth of forensic stylometric analyses. Such advances, however, had virtually zero impact on our understanding of what makes an author's style different from others, which is what Digital Humanities are genuinely interested in.

A different situation that may exemplify the fruitful collaboration of Digital Humanities and Artificial Intelligence is Stemmatics (the branch of textual criticism concerned with analyzing the relationship of surviving variant versions of a text to each other, especially so as to reconstruct a lost original). This is a particularly complex subfield of Philology where advances in Artificial Intelligence and genetic algorithms methods may prove indispensable. The reading of carbonized papyri is another example of collaboration between traditional and Digital Humanities and Artificial Intelligence specialists working together with scholars from different fields like Physics and Computer Science (mainly digital imagery processing).

3.2. New digital tools: visualization, graph theory, and digital markup

Digital Humanities suggest new challenges in the forms and spaces of representation. By its very nature, the digital environment fosters new interpretations of complex genealogy and paves the path for new communication dynamics. Data visualization is a paramount challenge for the Digital Humanities. Much more than just a tool, visualization largely determines how data and corpora are defined, it shapes data processing and, not unfrequently, it even steers preliminary interpretations. Take network analysis. Human worldviews are made up of innumerable relational layers. Representing links and flow between social actors and their connected knowledge is inevitably governed by strategic choices about what is and what is not worth representing. The often neglected politics of mapping (or unmapping), of visualizing (or making invisible), experiment a major overturn when IT tools allow to expand the number of possible representations to suit multiple actors' interests and/or expectations. The digital ecosystem favors the shared and expanded culture which necessarily intertwines data and incorporates infrastructures, to make knowledge progress beyond data. Databases enable data access and modelling very much like system design. Linked Open Data has dramatically modified the scale and visualization strategies of many projects, in the same way that the georeferencing introduced by GIS and other infographic tools allows set a new paradigm not only for data visualization but also for designing new strategies of study.

The usage of AI derived computational techniques has steadily increased in recent years. An efficient exploitation of linguistic corpora greatly benefits from techniques such as machine and deep learning, which can detect hidden patterns or predict novel features. In any case, it is crucial to correctly label the set of training data for a good categorization of the employed algorithm.

Another tool that has transformed the field of Humanities is the theory and analysis of social networks. The creation of complex webs of connections between actors is inherent to human societies. Network theory and analysis was created from graph theory, in order to understand the relationships among the individual members, with two main goals. First, it aims to investigate the structure of a specific networks; second, it explores the centrality and connectivity of its members, based on their position. The result is a form of visualization that presents related nodes through edges or links that offer a global overview of the network being studied. This type of visualization shows relationship patterns or communities that usually go unnoticed when the texts are studied individually.

3.3. Multiple Ontologies and Multiple Technologies

In the Semantic Web the notion of 'ontology' is borrowed from philosophy to designate the mechanisms, techniques and languages for the representation of knowledge in a digital framework. Thus, an ontology is a specific conceptualization embodying a common framework for storing, searching and retrieving information. An ontology incorporates the concepts and relationships essential to understanding of a given field of knowledge. It also sets the rules by which these concepts are combined to express complex statements and descriptions. One of the ontologies that have transformed the traditional practice of the Humanities into Digital Humanities is the text TEI/XML digital markup. Thus, it could be worth asking what the purpose of carrying out a digital edition is. Is it just a matter of preservation and disclosure? There are many answers, but it is undeniable that a digital edition allows different annotation layers with different levels of complexity and intention. It allows us to visualize several types of annotations that lead to a global understanding of its genesis, opening new and necessary fields of study

Digital Humanities give new dignity to qualitative practices as opposed to quantitative ones, since both produce data, model the environment and demand algorithms for their treatment. While quantitative approaches are strongly established, advances in qualitative methodologies are needed to address the difficulty of working with multimodal data and, above all, with the type of sources that produces them, since these, when embedded in interactive processes, are dynamic. Digital mediation itself can make the repeated practice of certain processes condition both the production of data and the sources that, in turn, can be digitally mediated.

This may be especially relevant for Digital Humanities in the analysis of affective production through social-digital media, in which more and more people participate who are articulating increasing levels of multimodality. This requires the primacy of qualitative frameworks that are capable to interpret meanings that are beyond quantitative.

4. KEY CHALLENGING POINTS

The digital age raises complex questions of responsibility, identity, privacy, and data security that need to be addressed. Engineers, computer scientists, and developers are providing the infrastructures for these changes but innovation within the Arts, Humanities and Social Sciences will be essential to exploiting their potential to transform our methods of organizing, interpreting, and using knowledge. The arguments developed in this section are based on five basic points that we detail below:

- Ontological turn. The discourse of Digital Humanities speaks not about technology, but from technology. It is also, simultaneously, an investigation of human processes and a component there of and, as such, it modifies its object in the course of trying to understand it. Digital Humanities represent a crucial opportunity to comprehend the world we inhabit from the perspective of those who have managed to get hold of new technologies and use them on objects as heterogeneous as unforeseen by their designers. This fact explains why the Digital Humanities are not only a space for skilled users, but also for real co-producers of the upcoming world.
- Interoperability. Digital Humanities are not the simple addition of Humanities plus digital tools, but a new attempt to understand the problems that we humans face through the production and standardization of meaningful and interoperable data processed computationally processed data. While a significant part of Digital Humanities research is carried out with minimal computing, many projects draw on AI or machine learning. It is nevertheless important to bear in mind that the kind of problems that the Humanities deal with realities much more complex than the tools being used for their study, and are not easily translated into meaningful digital format. Turning the data into machine-intelligible demands an effort to keep rethinking the relationship between datum and fact and the path that must be followed in order to find out the traits to be preserved in order to make data interoperable. Digital humanists, for example, must figure out how to transfer the condition of blackness to a table of values, since it is never an easy task to turn a prejudice into a piece of data that can be interchanged with other data derived from different historical researches or interoperable modeling.
- Interdisciplinarity. The Digital Humanities have the potential to bridge the gap between Engineering and Art, Science and Literature, academic culture and urban culture, scholarship and design. The objects used in Digital Humanities can incorporate the layered standpoints and mixed sensitivities of scholars from different areas of knowledge. Such a situation represents a challenge that designers have to make visible and that programmers will have to make possible. Furthermore, the fact that these objects do not go from one department to another but need to be designed jointly is quite innovative. And, of course, we refer here to a type of work that can easily incorporate the experience or points of view of the actors concerned by the problem under study, including dimensions linked to

oral culture or to traditionally excluded population sectors. The Digital Humanities can be a tool for overcoming the division of the world by disciplines, faculties, knowledge, degrees, genres, classes or tools.

- Transdisciplinarity. Digital Humanities also address ongoing challenges to individual and collective identities. In fact, digital activity constitutes a major new identity variable. The Digital Humanities must embrace the new relational models between individuals, collectives, access and use of technology and their limits. The application of new technologies to old historiographical, archaeological, anthropological, linguistic, political, esthetical or sociological objects transforms them by inducing new questions, different connections or different sensitivities and actors. It also transforms researchers themselves, in as much as they leave a trail that broadens the scope of their relationships, connections and situations, as well as have their identity enriched, infected or deformed by the support they get or the criticism to which they are exposed.

4.1. Dense data, complex data, hybrid data

Digital Humanities will be key for the optimal understanding of what data is and how it should be processed. Without Digital Humanities the process of digitization would be blind. Data in the Humanities and Social Sciences are remarkably complex, dirty, blurred and ill-bounded. Far from being predetermined or unproblematic, they are multifaceted constructs that need to be approached in a critical way. Their very complexity, though, turns them into the best possible arena for an optimal understanding of what data are and how they should be processed. Data have a twofold genealogy that must be incorporated into their metadata. On the one hand, data on human phenomena are generated within a sociocultural context and make sense within a web of biased, socially determined meanings. On the second hand, it is for the observer (researcher) to process them according to a certain logic, based on a series of postulates and serving a given research purpose. Digitization helps to make explicit the nature of the data and provides new ways to conceptualize, elaborate and organize them. Conceptual modeling becomes, thus, a crucial technique for dealing with highly complex and diverse objects. By modelling, non-essential details are removed, leaving those that are essential to investigate in a simplified, yet manageable, version of the world.

Aspects such as temporality, subjectivity, vagueness or multilingualism that are often left out in traditional scientific research, become crucial "soft" issues when dealing with the Humanities. Standards in Digital Humanities must be able to bring all these into their modelling. In this sense, data interconnection is essential. There is an increasing trend to relate and combine different datasets (linked data) and to collect and analyze huge amounts of information (Big Data). Searching and linking datasets is strengthened thanks to the Semantic Web and the creation of large metadata catalogs. An example are corpora built from microblogging platforms such as Twitter. In addition to the mixed character of the generated texts (different registers, different varieties), we have at our disposal an unprecedented amount of data that includes, e.g., user connectivity, location, topic, or automatic language detection, which provides us with rich information on the more social aspects of language, a field of research which is at the forefront of current computational linguistics. In conclusion, it can be said that Digitization has promoted a methodological revolution in exploring and analyzing data, with advanced technologies (e.g. computational linguistics, image computing, virtual reality, data mining). Also, it has favored the formulation of new questions and problems, unapproachable with conventional methods.

4.2. New actors, new audiences, new knowledge

Digital Humanities represent the opportunity to open up knowledge to new actors and new conversations, both inside and outside the academy. They allow us to explore new ways of producing and validating knowledge that hybridizes the experimental with the experiential, what machines know and what bodies know. In other words, Digital Humanities have enabled the rise of hybrid forms of knowledge production and validation. More recent approaches not only have taken into account a great variety of sociocultural variables, they have also argued for the importance to involving citizens in the decision making processes as a way to democratize science and increase the acceptance of technological developments.

Public engagement in science studies have encouraged scientific and regulatory organizations to become more reflective to the point that public assessment of science has come to include not only include scientific and technological contents but also the actual practices, processes and regulatory organizations of the scientific endeavor. As a consequence, the worldwide scientific community has increasingly embraced dialogue and engagement with the lay public, civil society organizations and other stakeholders, as part of its "license to operate". Most recent perspectives in public engagement in science have, thus, accepted that the public(s) may contribute not only with values and concerns but also with lay knowledge.

In recent years, increased attention has thus been paid to two promising forms of hybrid knowledge generation. One of them is the variety of citizens initiatives to discuss and shape the implementation of digital technologies and data gathering practices, such as those associated with privacy activism, or with the quantified self-movement. The other one emerges from the collaborative work of different collective groups, some of them scientific or academic actors, others being patient groups, professional actors, communities of concern, social movements or even artisans and amateurs scientists. For this groups, the digital media and digitalization in general not only plays a key role in their emergence and consolidation; they also define their culture and operation, as well as their specific identity as in the case of hackerspaces and virtual communities.

4.3. Platform culture and laboratory culture

Digital Humanities build objects that incorporate multiple viewpoints, different methodologies, different epistemes. They promote novel forms of collaboration, beyond disciplinary and institutional culture. Somehow, they are not identified by the tools they share, but by the transgressions they inaugurate. Digital Humanities are not only experimental, but are themselves an ontological experiment.

The so-called industrial revolution 4.0 has as one of its bases in massive access to data, its storage, custody, analysis and use based on criteria that are not always transparent and public. The Internet of Things (IoT), which turns personal ubiquitous devices into data producers, loses control of part of their individuality to the private/corporate owners of social networking platforms, commerce and communication.

Information extracted from individual and collective data is being used to modify social behaviors to the point of becoming decisive in electoral processes even in the most consolidated democracies.

New digital objects / assets have a dynamic and mixed nature. We face a new scenario where users' interaction on multiple platforms modifies nature of the original asset by adding layers and attributes. Likewise, the concept of individual or collective authorship goes from static to dynamic. How can Science be opened to society while recognizing authorship and preserving the very notion of 'author'? How can Open Science accommodate the currently established methods for evaluating and assessing Science (and scientists)? Can the new capabilities such as block chain help democratize access to digital assets in a safe, monitored and traceable way? Who should then bear the cost of a broad spectrum public network granting such capabilities? How will the ecological footprint of such an infrastructure like the one described be addressed?

4.4. Modeling and Simulation in the Humanities

Recent European Research Area (ERA) programs have been favored to problem oriented research, targeting specific societal challenges. Policy making driven research programs deal with different topics such as innovation, or the social attitudes on heritage, identities, climate change, etc. In this context, there is a growing need to incorporate massive data management and analysis tools to reduce uncertainty in our results and increase our research's predictive capacity. Therefore, one of the challenges of current research to which the contribution from the Social Sciences and the Humanities is fundamental, is the understanding of human and social behavior. Humans are embedded within thick webs of interactions and relationships with each other as well as with natural and built environments and specific methodologies such as Network Analysis help us understand the structure and dynamics of such social nets (detecting and interpreting them). Despite this, social network research has been criticized for lacking proper theoretical development, and for playing a merely role that is merely instrumental and descriptive role. The confluence of experts from Science, Technology, Engineering, and Mathematics (STEM) and Social Sciences and Humanities within a transdisciplinary approach will allow going beyond these limitations.

While documents and archaeological material show snapshots of different historical moments, modelling allows recreating social and historical processes within a virtual environment, offering the possibility to evaluate the roles played by different agents. Modelling allows disentangling the complexity inherent to the social domain and deal with otherwise unmanageable problems in a more tractable way. Producing a model consists in building a formalized representation of the reality under study. All models, by definition, simplify the world. But, thanks to this simplification, we can deal with extremely complex phenomena that would be unmanageable otherwise, and apply whatever conclusions we obtain from our models back to the world. In this manner, modelling allows us to remove complexity and tackle very difficult problems.

Modelling is also a crucial component of computer simulation. In order to simulate a social process, we need a model of that process so that a computer can act on it and simulate what would happen in the "real world". However, and despite the steep increase of the application of computer simulation in many fields over the last 40 years, including archaeological science, its impact in the Humanities has been scarce yet. A simulation is a tool that not only allows understanding the dynamics of the object or process under study or that can be used to produce new experimental scenarios, but can also be a heuristic tool to develop hypotheses and theories. The complexity inherent to human societies, cultural manifestations and their historical development can be approached through the application of modelling and simulation, thus complementing more traditional and developed approaches.

4.5. Diversity of objects and tools

Digital Humanities have grown and changed over the years. Probably we no longer look at technology as a tool for our purposes but as part of a collaboration between equals, where research becomes interdisciplinary in a humanistic and technological sense, moving from its traditional individualistic approach into a team effort, assuming standards, reusable methodologies, structured data and processes, documented and discoverable, openly accessible and reusable. This open and interoperable character yields innovative scientific and technological results, altering research methods and helping develop new digital tools to advance knowledge generation in those disciplines.

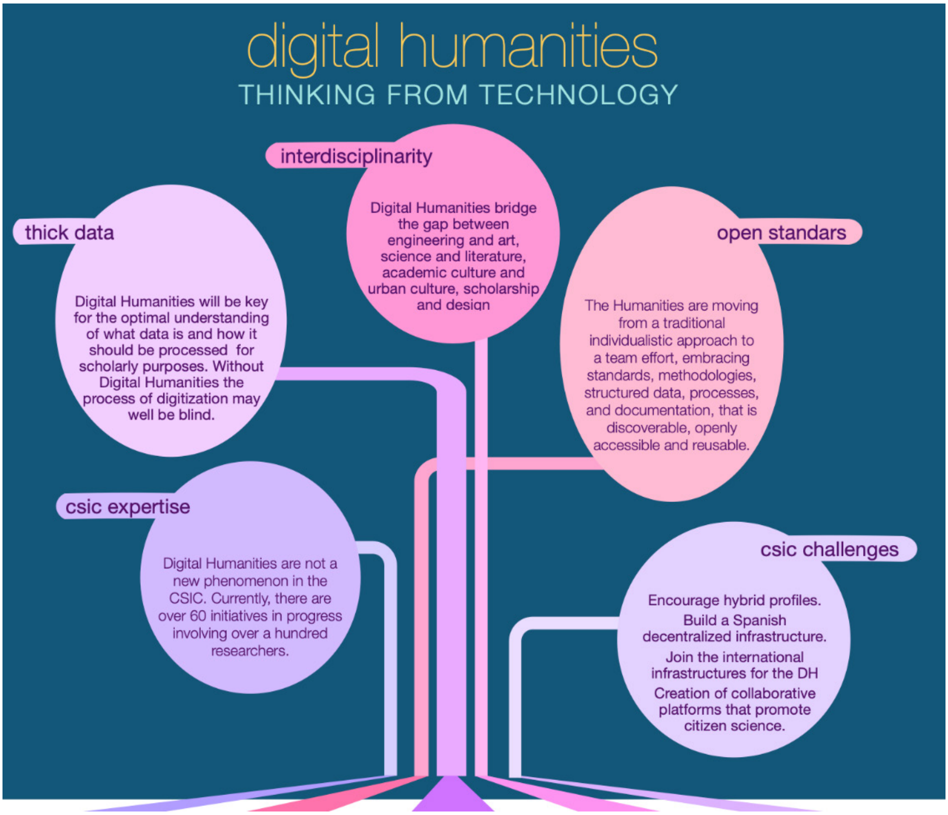
- New objects. Digital Humanities foster technological innovations in fields such as: data modelling and conceptual modelling; texts technologies and computational linguistic; Big data, data mining, and block chain; spatial and textual analysis; information visualization; semantic web and Linked Open Data in Humanities
- New objects as a source for digital assets. People's digital activity generates new digital assets. An important part of these assets are intrinsic to their personal identity. Therefore, third-party access and management of those assets has direct consequences on the attributes and defining elements of individual identity. Digital assets provide new exchanges between the public and private spheres. Digital identity as an inherent and unequivocal part of "private property" must be protected and recognized by public authorities. But at the same time the digital world implies new dynamics between individuals, groups and business entities. All of them consume, build and permanently modify multiple digital assets from individual or mixed origin. Therefore, digital assets as a part of digital identities are inherently dynamic (they are not static as a

property title to use, e.g. a home, a vehicle, bonds or shares). The ownership, access to and rights over digital assets have fuzzy boundaries. Digital Humanities must provide the models and scenarios on which to articulate new rules for these new realities.

- New objects as a part of the Digital identity. The generation of digital assets has a strong dependence on technologies controlled by transnational corporation technologies that hold exclusive ownership and use rights over digital asset creation. Their position of dominance threatens present and future individual freedom, by bringing individual and collective liberties into private hands, regardless of democratic control and representation. Therefore, it is necessary to rethink the public-private relationship and reconsider responsibility of the Public Administrations in putting limits to the commercialization and privatization of individuals and civil groups through the appropriation of their digital assets by private players. Current and ongoing technological capabilities and developments open new scenarios for the management of digital assets. New assets often involve rethinking and redefining traditionally used instruments such as Intellectual Property Rights (IPR). Even accepting that the current IPR system may not provide a correct response to future needs, it is the available instrument to address the transition in the short term. Already reasonably mature technologies such as block chain can support a mixed path for democratization in the management of authorships and rights, while ensuring the integrity of assets and providing transparency to interactions with users.

ANNEX: ONE SLIDE SUMMARY FOR EXPERTS

ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC



CHALLENGE 8

ABSTRACT

Digital relations are deeply transforming our lives: from the nature of political participation to the relationship between digital and non-digital environments; from the reorganization of the public sphere to the ethics of responsibility, transparency or inclusiveness. We are witnessing fundamental changes in the infrastructures of democracy and the emergence of new forms of digital citizenship.

KEYWORDS

digital democracy | e-participation | group decision support models | fake news | explainable artificial intelligence | big data | data justice | digital ethics | surveillance | privacy | digital activism | digital grassroots innovation | citizen science | cybersecurity | digital economics

CHALLENGE 8

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1. EXECUTIVE SUMMARY

Digital relations are deeply transforming our lives: from the nature of political participation to the relationship between digital and non-digital environments; from the reorganization of the public spher e to the ethics of responsibility, transparency or inclusiveness. We are witnessing fundamental changes in the infrastructures of democracy and the emergence of new forms of digital citizenship. These developments open up a new field of study that brings together research groups in artificial intelligence, mathematics, anthropology, philosophy, economics, sociology, political science and geographical information technology to address the nature of these fundamental shifts under three research hubs:

1. *Digital democracy*: Governments are increasingly resorting to digital platforms to expand citizens' democratic agency. However, these systems often reproduce structural inequalities in their target audiences and design algorithms. Digital technologies are also transforming economic markets. Whereas liberal and social-democratic polities once hinged on a balance of powers between state and market forces, digital technologies are transforming the relationship between society, economy, and democracy.

2. *Big data and human rights*: Big data analytics raise fundamental questions about the collection, ownership or analysis of data, as well as the nature of surveillance, privacy, anonymity and memory. Data-based prediction tools are increasingly in use by law enforcement agencies and corporations, making pre-emptive assumptions about people's behaviour. With regard to data profiling and social sorting, these uses are under suspicion of violating fundamental human rights. Our self-understanding as knowing, autonomous, moral and vulnerable subjects is also under tremendous pressure from systems of behavioural and cognitive predictability that standardize cultural expectations regarding social comportment. The ethics of the digital human person remains one of the greatest challenges of the 21st century.
3. *Digital activism*: Around the world grassroots collectives have rushed to organize community-based alternatives to our digital futures, challenging narratives of state sovereignty or corporate supremacy. The study of how social movements and citizen science networks design and recast digital technologies has become essential for understanding the shifting nature of digital citizenship today.

2. INTRODUCTION AND GENERAL DESCRIPTION

The world we live in is as much a digital as a material reality. Our daily choices and chores are inflected by digital relations: we self-track our daily workouts using biometric data collected by wearable technology; we choose to take public or private transport on the basis of traffic data provided by integrated public-and-commercial digital platforms; the quality of the air we breathe is monitored by digital sensors controlled by municipal authorities and, sometimes, contested by alternative citizen science projects; we order food from digital platforms that is home-delivered by precariously employed couriers. Our bodies, movements, environments and economies are bundled into, mediated by, and reorganized into digital relations. As such, the data worlds we inhabit and the digital relations we establish set the terms of our liberties, rights, and obligations: Where does our privacy start and end? Who gets to say what is intimate and what is public? What values, behaviours, and expectations get inscribed into the designs of algorithms, databases, user interfaces or legal licenses organizing our digital life? And who has stakes over these definitions? Who owns, controls and archives such data relations? These questions go to the heart of what it means to be a citizen today. The classic conception of citizenship, where civil rights and obligations are defined vis-à-vis state hegemony, is under stress. We design, use, consume and produce data and digital relations through infrastructures that fly under the radar of state sovereignty, yet modulate and organize, sometimes in novel and unpredictable ways, how we relate to others and think of ourselves. We are rightly concerned when digital corporations invade our privacy or register our genetic identities into proprietary databases. We are proudly surprised when hacktivists expose a state's massive surveillance operations, demonstrating thus what the shape of our digital public sphere should be. Social media and citizen science projects, hacktivist initiatives or participatory platforms, mobile apps or bitcoin block chains are shaping our cultural experiences of proximity and difference, indignity and pride, vulnerability and empowerment, outrage and fear, precarity and hope. Whatever future awaits us, it will be our digital citizenship that we will have to reckon with.

The Digital Citizenship challenge brings together research groups from artificial intelligence, mathematics, anthropology, philosophy, economics, sociology, political science, and geographical information technology in identifying three areas for research synergies and conceptual breakthroughs: (1) digital democracy, (2) big data and human rights, and (3) digital activism. The interdisciplinary approach touches on a number of issues transversal to these fields: fundamental transformations in the nature of citizenship, political participation and democracy; the relationship between digital and non-digital environments, including economic markets, cities, and natural ecosystems; the reorganization of the public sphere; the ethics of responsibility, transparency, inclusiveness and distributive justice; and the relation between data security, protection and fundamental rights and liberties (privacy, anonymity, etc.). One crucial point here is to reflect on ethics by design, i.e. on embedding ethics in the design and development of technologies.

3. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The study of digital citizenship opens up a unique scenario for original collaboration across a diversity of fields, in anthropology, philosophy, artificial intelligence, mathematics or sociology, to name but a few of the disciplines represented here. In particular, the interdisciplinary study of digital citizenship will have a profound impact on two domains of fundamental scientific research: (1) on the nature of experimental modelling, and (2) on the opening of scientific inquiry to citizen participation.

3.1. Experimental Modelling

The rise of digital technologies has brought along an increase in various forms of citizen participation. Whilst certainly not all forms of participation amount to political agency, the role of the 'participant' (and concomitant participatory structures) is one that now merits specific forms of modelling and theorization across disciplines, especially in mathematics and economics.

First of all, participation inevitably refers to a group decision-making context. Participatory democracy brings to standard group decision support issues like: (a) scalability, (b) capability, as group decision is adapted to the analytical inclinations of participants, (c) the availability of time, (d) the willingness to use it for a democratic good, as there is a clear underlying assumption that citizens will contribute in substantial ways to deliberations, and (e) communication and coordination issues. An open question is how decision analyses should be communicated to the general public. Moreover, no coordination approaches are yet available for potentially large groups.

Modelling must take into account cybersecurity, too. To build trust and legitimacy on e-participatory systems their security has to be enhanced. Facing the possibility to delegate decision-making and negotiation to agents, advances in the development of agent systems are to be expected. In turn, the development of methods for policy analytics and fake news detection would lead to advancements in machine learning, statistics and operations research.

From an applied perspective, four issues are emphasized: (a) the development of large scale group decision support systems with a wide spectrum of applications, from the support of political processes to business decisions; (b) the incorporation of such decision support capabilities to social networks so as to make them more useful; (c) driven by the fight against fake news, the improvement of content filter systems; finally, (d) the enormous potential of policy analytics in problems like examining the distribution and patterns of health events, developing rational infrastructure plans, developing personalized government services, building smart grids and cities, and many more.

The impact of Big Data on the use of targeted advertising and personalized prices requires a new approach to market regulation. It is crucial to understand when personalized pricing benefits or harms consumers. Crowdfunding facilitates access to funds for small entrepreneurs, affecting innovation, growth and employment. Equity crowdfunding enables citizens to become investors with a potential to reduce inequality and improve financial inclusion. The underlying mechanism of crowdfunding has much wider applications. For instance, when social coordination is inhibited by risks of reprisal when individuals participate, digital platforms can guarantee them anonymity in the event that they lack sufficient safety in numbers. Blockchain technologies have potentially extensive implications for transparency, trust and democratic participation.

3.2. Citizen Science

Digital technologies are enabling citizens to carry out low-cost, do-it-yourself research projects. Whilst some of these projects lack sufficient computational or metrological capabilities to produce standardized and robust results, they are nevertheless opening up spaces for new research subjectivities, methods and collectives. Some activist projects, for example in environmental science, do manage to scale-up. These cases open up fascinating scenarios where research objectives and methodologies are mutually constituted by the leading agency and interests of grassroots collectives. Such projects are questioning anew classic dichotomies such as those between tacit and explicit knowledge, experts and amateurs, pure and applied science, etc.

Whilst some well-known citizen science projects in astronomy and archaeology have received substantial press coverage, it is the use of citizen science networks in disciplines related to the observation and conservation of the natural environment (zoology, botany, and geography) that stands out. In particular, to address the challenges of conservation of natural heritage in relation to climate change it is necessary that governments, non-governmental organizations and scientists take advantage of all available sources of information, including those provided by citizens.

Last, attention has to be drawn on the extent to which digital corporations such as Facebook or Microsoft are themselves engaged in massive data research operations. Their computational capabilities, as well as sheer access to raw data, has no equal in the academic world. This has led some sociologists to announce the death of quantitative empirical sociology in universities, whose expert claims are now allegedly better served by corporate social scientists. By contrast, ethnographic and qualitative social science approaches, with their distinctive long-term and trust-based methodologies, will be uniquely positioned to tackle the challenges of a citizen science paradigm.

4. KEY CHALLENGING POINTS

4.1. Digital Democracy

Governments are increasingly resorting to the use of digital platforms in a variety of policy and governance contexts. In Spain, many city councils have deployed digital participatory infrastructures to enable citizens (or more precisely, registered users) to vote in participatory budget allocations and public consultations, to launch calls and enlist support for grassroots initiatives or to take part in the drafting of municipal legislation. It would appear that we are in the midst of an expansion of democracy, inasmuch as citizens are now invested with decision-making powers that were previously the prerogative of an elected minority, enabling direct democracy that complements representative structures. Yet the challenges of a new era of digital democracy extend beyond citizens' enlistment in government-sponsored participatory mechanisms. New digital and automation technologies have deeply transformed the logics and logistics of economic markets, for example by reducing the costs of information-processing, promoting new contractual innovations based on trust-enforcing technologies or encouraging the rise of micro-financing and crowdfunding platforms. Whereas liberal and social-democratic polities once hinged on a balance of powers between state and market forces, digital technologies are transforming the relationship between society, economy, and democracy. *We need to understand how to embed democratic principles and values in the design of digital infrastructures.* One crucial point to be taken into account consists in avoiding three kinds of digital gaps: (a) the generational gap, (b) the social and economic gap, and (c) the gap between urban and rural spaces.

The promises of digital direct democracy

Research on participatory digital platforms casts light on some of the ambiguous promises of digital democracy. In a context of enduring disenchantment about the state of democracy and suggestions that civic culture is in decline, hope has been placed in e-participation and digital civic engagement. However, questions must be asked about the increasing individualisation of democratic participation enabled by digital media, about what could be called 'slackpolitics', a politics that involves little commitment or effort. Citizens may use participatory budgeting in the same way as they use Amazon, voting proposals as they would add items to a shopping cart, only superficially engaging with democratic issues. There is the added issue of the atomization of voters and voting preferences, such that problems of governance that have traditionally involved discussions between local authorities and civil society organizations (trade unions, neighbourhood associations, NGOs) are now reframed in terms of individual voting preferences. On the other hand, new spaces for democratic debates are taking shape within as well as outside digital democracy platforms, creating new communal spaces of deliberation.

There are also fears of co-optation: the hijacking of participation by institutional powers to legitimise their actions. Questions posed to citizens may be deliberately framed to prompt particular answers, or ad campaigns with bots could be run in networks where issues are discussed to guide participation in specific ways. The hopes that rest on digital democracy will likely change roles, but they may also reinforce behaviours that were present in traditional, representative, 'analogue' politics.

In sum, digital democracy forces us to rethink traditional normative sociological scales and roles. If digital participation becomes prevalent, what would a politician be? A concerned citizen who makes proposals and spends time pushing them forward? At the same time, in a context of retreating public services and the dismantlement of the idea of the welfare state, digital participation has been seen as a way to contest the increasing privatisation of social life. New relations between neighbours, spaces and communities are sprouting. Libraries, for example, have been put forward as spaces of digital literacy and critical-making, fostering the coming together of novel communities of practices and learning.

E-participation and policy analytics

Participatory budgets are emerging as one paradigm for participation, especially at a local level. They constitute an attempt to allow citizens to have a word on deciding how part of a public budget is spent. They constitute a budget allocation approach based on dialogue and citizen participation, transforming thus the idea of a representative democracy, in which the citizens' input is considered just at the moment of elections, to move closer to participatory democracy. The political imperatives towards e-government and public participation, together with pressures from the Information and Communication Technologies (ICT) industries to sell their wares, indicate that e-participation and e-democracy are coming, and coming fast, whether or not the processes involved are meaningful and valid. Nevertheless, except for the numerous experiences which use discussion forums to collect suggestions for project proposals as well as votes, there is little use of ICT. Up to now, the formal modelling of citizen preferences is undertaken and the use of negotiation or group decision support tools is still outstanding although most of the benefits traditionally attributed to citizen participation could be enhanced through the use of ICT. However, there is a lack of unified methodology in the fields of participation and e-participation, no clear design methodologies for choosing which instruments to include and sequence in a participation process.

Within such an environment, we should recall the issue of fake news, even though this phenomenon is actually far from new. The well-known and perverse Goebbelsian paradigm has recently found new strategic allies in technology and social networks: massiveness, virality and redundancy in deception, focused in a brief but intense period of time. The current problem with geopolitical fake news is that there are not yet real time mechanisms to deal with such challenges. This is aggravated by the recent interest in text-generating artificial intelligence systems.

With respect to the issue of e-participation and policy analytics we identify the following key challenges:

a. The first challenge refers to how we might transform democratic processes using web-based decision and negotiation support to structure and articulate participatory deliberations. This is in contrast with the bulk of research in the field, which mainly concentrates on technologies to facilitate or automate standard democratic instruments. This requires the development of improved and encompassing group decision support methods; the development of a generic system that supports general group interactions (with modules to control participatory processes, structure the decision problem, model preferences, support voting under various schemes, support negotiations, manage arbitration, manage debates, manage information resources and finally explain the decisions made) as well as the development of security mechanisms for such types of systems. Moreover, we should cover the experimentation with such systems to check how the heuristics, instincts and thought patterns which govern our behaviour evolve with such systems; as well as the development of methodologies to design the best participatory methodology for the problem at hand so as to avoid agenda rigging and manipulability. We should also perform a political, behavioural and legal assessment of the platform. This would focus on case studies, for example in participatory budgeting.

b. With respect to fake news, the aim would be to develop a framework for automatic and real time fake news detection, favouring a hybrid approach which takes into account the contents, demographics and propagation of the news. Given the novelty of the problem, methods have to be developed for both determining features, extracting the relevant ones and adopting the adversarial classification decision.

c. As mentioned, a key difference between analytics for business and for policy-making relies on the need to take preference over multiple consequences into account. A key topic would be to provide analytic methods for preferences, based on political surveys and consumer choices. At a deeper level, analytics may also be able to be used for understanding public policy related cultures and value systems across and between countries in order to develop more acceptable policies in a broad range of governance systems. Future research may investigate the importance of interpretation, interpellation, intuition, ground-trusting in policy analytic work and the translation of analytic outputs into action, thus determining relevant roles for machines, their owners and impacted parties in different processes of policy making and governance systems. Finally, we wish to mention the possibility of combining the recent class of adversarial risk analysis models, focused on competitive decision-making, with analytics methods applied over Internet and social network data to drive competitive intelligence in security and defence contexts.

d. The design of digital systems is a matter of critical importance too. There are important sociological biases in how users interact with these platforms, in terms of their age, socioeconomic level, educational background, etc. Scholars of digital democracy have long debated whether e-participation widens the digital divide. Moreover, information systems tend to induce or reinforce biases, a common occurrence in algorithm design which worsens discrimination and inequality. However, it is not just sociological variables that one needs to pay attention to. Frequently, the design aesthetics of these digital systems carry preconceived ideas about their future users, such as the decision trees that chart how and when people can vote or express a preference, or the infographics of interaction and legibility employed in user interfaces. There are also important risks and dangers to the use of gamification design techniques for organizing and promoting specific voting preferences.

e. In order to cope with the current limitations of interfaces, progress has been made in the development of advanced artificial intelligence techniques, like intelligent virtual assistants, aimed at easing citizens' participation. The objective is to develop explanatory functionalities that can explain citizens how collective decisions have been reached. This is the subject and target of an emerging AI field: explainable artificial intelligence. Developments in explainable AI must reckon with advances in text and voice recognition as well as functionalities for "hearing" citizens' values, interests and preferences.

Digital economics
Digital technologies have greatly reduced the costs of storing, processing and transferring information, and have given rise to new patterns of social, political and economic interaction. The rise of the Internet and World Wide Web sparked hopes of levelling the playing-field between concentrated political and business actors on one side and ordinary citizens on the other. Many of these hopes have not been fulfilled and the trinary combination of very small marginal costs, significant fixed costs and large network effects have led to a small number of digital giants (Amazon, Apple, Facebook, Google, Microsoft, etc.) posing new challenges to traditional regulatory policy. Economists can complement other disciplines by studying changing economic incentives, contractual innovations and new opportunities for citizen participation. In this task, special attention will be drawn to: (1) search and advertising in a digital context and (2) novel digital platforms.

1. Search and advertising. Search engines such as Google permit ready access to an enormous amount of information and products. However, a monopolistic search engine may distort its search results, when advertising is its dominant source of revenue. Those financial incentives to distort, and the fact that search engines are not omniscient, require people to consider multiple search recommendations and search options. The ability to assemble, harness and analyse large and complex datasets (Big Data) makes targeted advertising and personalized pricing possible. Standard economic theories suggest that targeting and price-discrimination by firms will favour consumers (lower prices, better matches), with a reasonable amount of competition. Unfortunately, there is a serious risk that increasing the information of firms about consumers may weaken the position and welfare of consumers enough to justify new forms of public intervention on the legitimate use of Big Data. Like firms, political parties and interest groups can exploit digital algorithms to identify who is likely to respond to well-targeted

advertising. In fact, the analogies between interfirm competition in a market and political competition abound. Another area of interest is the impact of online media outlets and their ability to provide good content when advertising revenues are vital. In particular, the study of how journalists' organizational response to the reduced fixed costs in digital publishing affects consumers' ability to find good content has become of great interest.

2. Innovative digital platforms. Crowdfunding enables citizens to play an active role in determining which innovations get funded. Crowdfunding platforms allow entrepreneurs to prove the value of their ideas by soliciting fully credible pledges as signals of consumer demand. This saves them paying fixed costs of production when demand is too low. Despite strong tendencies towards concentration driven by network effects, fast and secure communication between actors on a network has enabled an impressive degree of decentralization in one arena: that of digital currencies, with bitcoin leading the pack and a follower called etherium expanding into the further-reaching area of smart contracts. Block chain technologies can already provide essentially-immutable recordings of what people agree on. Individuals interact through different online social networks such as Facebook, Instagram and Twitter, and online communications are affected by their design. The most visible aspect of their evaluations is usually highly reductive ("likes" or upvotes and downvotes) but influential because readily amenable to aggregation and used to motivate people to "post" content.

In summary, the four main challenges in the field of Digital Economics are: (a) Targeted advertising and personalized prices generate conflicting effects. A crucial challenge is to provide a theoretical framework for data collection, aggregation and trade, from which empirically-based policy recommendations can be derived. (b) We need to understand better how online social networks affect people's beliefs and behaviour in environments with extensive information overlap. How does information spread? Can fake news be usefully flagged or filtered out? (c) Reward-based crowdfunding has already been analysed, but equity-based crowdfunding is harder (because of "common values") and important for upscaling. Timing and dynamics of contributions and inspections must be analysed to evaluate free-riding efficient sorting. A further challenge is to assess whether individuals will understand and trust online mechanisms. Crowdfunding is a proof of concept, but great caution and careful design should accompany attempts to extend its use to contexts where money transfers are inappropriate and emotional factors loom large. Experimental investigation will be an important tool. (d) Energy costs associated with bitcoin mining are a significant concern. Thus, game-theoretic challenges associated with assigning power of authority to network nodes based on "proof of stake" instead of the "proof of work" concept underlying bitcoin and the other major decentralized ledgers have to be studied.

4.2. Big Data and Human Rights

Big data has been hailed as inaugurating a new social and political era. Increased computer processing capabilities can now draw comparisons and analyses between more datasets, of a larger and more variegated kind (visual, text, audio, numeric), more quickly. One can scale-up, enrich, and verify datasets whose information has rarely before been placed side-by-side. Data sciences and analytics, it has been argued, can help governments and corporations uncover previously unidentified correlations or statistical patterns, in crucial matters of public health, urban governance, market preferences, even criminological dispositions. Notwithstanding the very exciting and novel applications opening up for big data analytics, there remain fundamental questions to be asked about the designs, uses and abuses of such data politics; about the nature of the relations between citizens, states, and corporations, and how these relations are reconfigured in an age of data exuberance; about the collection, ownership, storage or analysis of data, which throw into relief in turn concomitant questions about the nature and extent of surveillance, proprietorship, privacy, anonymity or memory. Moreover, data-based prediction tools are increasingly in use by law enforcement agencies and corporations, often making pre-emptive assumptions about people's behaviour in public and private spaces. These uses raise problematic issues of data-profiling and social sorting that could be in violation of fundamental human rights. Big data analytics are also bringing about profound changes in human subjectivity and ethical reason. Our self-understanding as knowing but also vulnerable subjects is under tremendous pressure from systems of behavioural and cognitive predictability that standardize and homogenize cultural expectations regarding social comportment and exchange. Collective and personal identities are trafficked and negotiated through algorithmic backchannels that artificially manipulate projections of self-esteem, appreciation or solidarity. *The main challenge lies in outlining the fundamental data conditions and limits for an ethics of the digital person in the 21st century.*

Dataselves and algorithmic governmentality

Datafication—the conversion into data objects of different aspects of our human and environmental relations—is reshaping human bodies and social bonding, and influencing the way we form our identities and intimate relationships. Because of the sensitivity of health data, sexual preferences, genetic, ethnic or biometric information, in the EU this type of information is considered a special category of personal data, whose processing requires additional technical and organisational safeguards. Other aspects, such as the societal implications of the digitalisation of this type of data, are still evolving and uncertain. We know for sure that our life is increasingly visible to corporate eyes, even those most private and intimate aspects of it. When we search online for the symptoms of a disease, for a medical drug, or for a nearby clinic, we leave traces of our vulnerabilities. When we use a dating app to meet a lover, we leave traces of our sexual preferences. When we share our genetic information to know more about our ancestors, we leave traces of our racial characteristics. Some of this data is just about us. Something else is about our family, friends, lovers, colleagues, and other groups we interact with or belong to. Direct-to-consumer genetic testing is a classic example of the fascination for bodily data as a source of self-awareness, catering to people's curiosity about their ethnic origins or predisposition to common diseases. Genetic data can be used in medical clinics to accelerate the diagnostic process as well as to monitor chronic patients, or to find relatives.

These days we let a wide range of devices enter our life to help us learn about our wellbeing, the appropriateness of our lifestyle (nutrition habits, physical exercise, sleep patterns, mood variation, etc.) and our health conditions (cardiac rhythm, glucose, blood pressure, risk of epilepsy seizures, etc.). The processing of this data can be very intrusive, and risky if it generates therapeutic imperatives, a sense of unease, or new forms of dataveillance (surveillance through data) and algorithmic governmentality (governance through algorithms) meant to orient people's habits, minds or behaviours. Sensitive information comes from a variety of sources. Sensors connected through the Internet of Things collect all kinds of information, from our physical states, to our movements in bed or our house's temperature. These same digital tools are also used to assist physicians (e.g. analysis of radiological images) and facilitate their work. A wide range of private and public entities play a role in the collection and processing of our intimate data. Some hospitals have begun storing their patients' data in the cloud or in data warehouses. Insurance companies complement data they collect with other external data to adjust the prices of insurance products.

Digital enterprises contribute to offer the capability and build the IT big data infrastructure necessary to process the data. Each actor has different interests and fiduciary obligations toward data donors or prosumers. Mapping the politics of data is a necessary step toward the development of transparent, inclusive and fair forms of data governance.

The integration of this information in big data lakes improves our knowledge of patients' health conditions in relation with the environment, and facilitates the development of new forms of personalized medicine, meant to generate therapies tailored to specific groups or even subjects. Since the 1990s, advances in the sequencing of the human genome enabled the prediction of the risk of developing certain diseases, such as cancer. Today, it is possible to monitor the progression of a chronic disease, or to detect risk factors, the determinants of a pathology, or the link between a pathology and specific behaviours (e.g. very low displacements and depression).

The following points are key challenges in this area: (a) The impact of digitalization on people's intimacy and identity formation especially amongst young people. (b) Policy and legal implications of the effects of digitalization on the fiduciary relationship between patients and doctors (depersonalization, lack of empathy). (c) Risks of increasing social control through dataveillance, while reproducing cumulative disadvantage dynamics and socio-economic inequalities. (d) Benefits and drawbacks of alternative data governance solutions at the crossroad between public and private entities. (e) The protection of individual and group privacy and the analysis of potential privacy harms in view of data monetization and group solidarity.

Cognitive vulnerability and epistemic responsibility

We live in a digitalized environment in which technology increasingly determines who we are, how we think and act, how we perceive and feel. We are surrounded by artificial intelligence. The Internet has invaded our lives in an unavoidable way, and the virtual world has become an integral part of our lifeworld. The changes in communication culture driven by the Internet are quite complex. On the one hand, social networks tend to make us all equal. On the other hand, they give way to populism and opinion manipulation via falsified data, exaggeration, conspiracy theories and fake news.

New criteria of rationality are being established, and along with them changes in our common sense and the standards of credibility. The boundaries between real and virtual, between fact and its interpretation, between truth and lie, are being blurred. And by losing belief in the power of argumentation, confidence in our critical capacity is disappearing. New rules of discourse are emerging, a rhetoric that draws back on sceptic and relativist strategies and that measures everything in quantitative terms. Playing on latent fears and prejudices, these strategies undermine the foundation of our knowledge. In a culture where public opinion is dominated by social influencers that depend on fast clicks and likes, the gates to populism and manipulation are wide open. Are we on the way to a post-factual, post-truth society, one that is permeated by hate and fear, by scepticism and mistrust, in such a way that careful, critical and balanced debate becomes impossible?

Deliberative democracy needs autonomous, well-informed, critical and responsible citizens, but the digital citizen is on the way to lose just these features. Social networks have contributed to a hyper-ideologization, identitary fragmentation and affective polarization of the public sphere. Parallel political universes are being created such that voters of different political parties are actually perceiving different realities. Parties act more and more like companies, following marketing strategies. The logic of advertising increasingly enters into political strategies, taking benefit from typical fallacies and psychological mechanisms that produce a biased perspective. Confirmation bias, group polarization, priming, repetition effects, affective excitation and other similar cognitive biases thus feed a series of informal fallacies that inhibit critical reasoning.

Furthermore, the social relations that constitute the construction of identity, the consolidation of self-esteem and the formation of the moral subject have been displaced to a space that permits us to distance ourselves from the affection that characterizes the interaction between physical persons. The alarming loss of affectivity in the field of social relations finds its counterpart in an abuse of emotion under the pretext of authenticity. Here we are faced with the challenge of establishing a new sentimental education, of an amplification of ethics to the technological sphere that implies a redefinition of the concept of responsibility that differs from the classical concepts especially on two points: (a) In a systemic and highly interconnected environment, responsibility has to be conceived also as structural responsibility, i.e. it can no longer be reduced to a bipolar relationship that presupposes direct causality and intentionality. (b) In order to counteract the culture of mistrust caused by fake news, business with personal data and loss of control over privacy, a clear concept of epistemic responsibility is required, which has not been established so far.

4.3. Digital Activism

Air Quality Egg is an open source platform that uses low cost, do-it-yourself sensors to collect high resolution readings of NO and CO2 concentrations. The technology has been amply used by activist organizations around the world to monitor and contrast readings of atmospheric pollution in their cities, often disputing the official readings produced by local authorities. At once a project in citizen science and in digital activism, Air Quality Egg exemplifies how the politics of technological sovereignty impinges on the politics of urban ecology. The story of Air Quality Egg exemplifies how activists around the world have rushed to organize community-based alternatives to our digital futures. It demonstrates the extent to which the shaping of citizenship in the digital age is no longer a matter of state sovereignty, nor simply of technological advancement, but hinges, too, on the capacities for collective action of social movements. *The study of the socio-technical regimes of grassroots alliances and commitments that are constitutive of emancipatory political projects in a digital society is essential for a better understanding of the shifting and emerging nature of digital citizenship today.*

Urban digital rights and environmental data justice

Much of the data that is harvested today has an urban dimension. From air pollution to the geolocation of rent defaults or mortgage evictions, from the geographic distribution of sexual assaults or school dropouts to income distributions along ethnic or racial axes: data analytics on these various datasets has an effect on house prices and school applications, on local rates of child respiratory diseases or the appearance of informal subsistence economies. Such data is never abstract, never impartial. It has specific effects on specific populations. It sorts out and categorizes people along lines of race, age, income, postal code or credit ratings. Sorted into such urban data categorisations, we may say that people no longer live in this street or that neighbourhood. We inhabit geolocational bundles of data analytics instead. Without noticing, our rights and liberties have become someone else's database.

Importantly, these databases are located in energy intensive data centres. The eco-logics of data extraction and analysis are often in direct contradiction with the eco-logics of urban sustainability. The decarbonization of urban societies demands our addressing their de-computerization. The politics of a new green deal in cities is only realisable as a political project in environmental data justice too. It is therefore hardly an overstatement to note that the shape of our future digital citizenship will be largely defined by the shape of the rights to the city. Whatever our future digital rights and liberties look like, they will be drawn out and staked over specific urban struggles and reclamations. In this larger context, the meaning of urban democracy in the 21st century will therefore largely hinge on the rise of new activist alliances between urban social movements and data hacktivists: for example, regarding urban atmospheric pollution; real estate speculation and the right to housing; racial and ethnic forms of urban segregation; or the value and financing of public utility infrastructures (water, gas, electricity, etc.). Our capacities to remain in control and bring justice to the data environments of our cities will largely determine our urban digital rights therein.

More specifically, there are three dimensions to the nature of urban digital rights that we believe will drive fundamental research in these areas in the future: (a) The nature of the *legal infrastructures* (intellectual property licenses and codes) underpinning the right to access, use, edit, and redistribute the original designs and datasets of every public urban infrastructure; (b) The design of *technical infrastructures* in accordance with systems, standards and protocols that are open, inter-operable, and sustainable, such that they cannot be sequestered by commercial or proprietary interests; These two requirements for legal and technical openness make-up what is known as *technological sovereignty*; (c) Just as importantly, we must heed also to the organization of *social infrastructures*, the rich tapestry of alliances, synergies and commitments through which civil society collectives own up to the challenges of our digital futures.

The different ways in which the legal, technical, and social dimensions of digital infrastructure are taken up, negotiated, and contested by different social actors, from government administrations to social movements and corporations, will shape the nature of urban democracy in the future.

Digital grassroots innovation

The concept of the smart city has offered municipal administrations a point of entry into the digitalization of urban environments. Such discourses have been largely founded on a corporate-driven view of digital technologies as "primary drivers of change", where these have often become pseudonyms for capital accumulation, land grabbing and dispossession. As such, the nature of the smart city is haunted by a democratic deficit. Digital Grassroots Innovation can contribute to address this deficit. Digital grassroots innovation encompasses a varied repertoire of initiatives where the purpose of digital innovation is not only to solve problems that affect citizens, but to make spaces for the creation and empowerment of critical persons that are vigilant of the actions of public and private powers. The innovations brought about by these projects may be described therefore as "transformative" of the democratic sphere.

Whilst digital grassroots innovation projects inevitably overlap with other projects in digital democracy, we wish to focus here on the contribution that they make to the expansion of human capabilities. In political philosophy and development studies, the capability approach defines a normative space of evaluation by focusing on people's freedoms to achieve the life they value. Conversion factors and goods and services available are also central issues, in order to understand and contextualise how capabilities are shaped. Thus, digital grassroots innovations may be valuable for different reasons: they contribute to multi-dimensional human flourishing; they improve public reasoning processes by creating counter-narratives, democratic spaces and new capabilities for reasoning and mobilisation; they create better structural conditions for human flourishing through the creation of more diversified, decentralised and democratic systems. These processes take place in complex and dynamic ways, modelled by existing structures that limit but also present opportunities for change. We identify two scientific challenges in particular: (a) the study of how digital grassroots innovations contribute towards the expansion of human capabilities and the creation of better conditions for human flourishing; (b) research on how transformative innovation can be understood in term of the expansion of human capabilities.

Citizen Science

Citizen Science describes the involvement of the population in scientific activities where volunteers do not need to have specific scientific knowledge or skills. There are different models and degrees of involvement. One of the most common is the contributory model, in which public volunteers follow protocols designed by scientists to collect data on variables of interest in large geographical areas and/or over a long time. The current use of ICTs offers the opportunity to collect new data by volunteers in a simple and efficient way employing widely used low-cost mobile tools (smartphones/tablets). Information can be transmitted in real time to open access repositories. The data collected by volunteers helps scientists to address unfeasible research questions with traditional data acquisition techniques. Moreover, these participatory research experiences allow volunteers to connect with each other, reduce the science-society gap by contributing to research as direct providers of information, influencing management decisions and increasing sensitivity to environmental conditions in their communities and, therefore, participate more actively in their protection and conservation.

Another model involves the creation of science advisory bodies within parliament. Current scholarship largely circumscribes the role of science in politics to aiding in the design of evidence-based policies. A recent project which has received the backing of the Spanish Parliament is an initiative called Science in Parliament (CEEP), which attempts to bridge the distance between scientific research and parliamentary debate by institutionalising an independent scientific advisory body with citizen participation. The attempt to incorporate citizens within scientific advisory processes is something unique in the world and provides an exceptional opportunity to challenge utilitarian assumptions embedded in the literature.

We identify five main key challenges in the field of Citizen Science: (a) *Building the bridge to truly connect science and society*. This implies: raising new scientific questions and co-creating a new scientific culture; improving science-society-policy interactions and promoting democratic research based on evidence and informed decision making; taking into consideration inclusion and equality parameters in every science engagement initiative; achieving 'Science with and for Society' Research and Innovation DG European program objectives. (b) *Optimize exchange, reusability, and comparability of citizen science information*. Open Geospatial Consortium standards need to be followed to make the geospatial location information and services FAIR (Findable, Accessible, Interoperable, and Reusable). (c) *Validation*: The collection of data by scientific volunteers should always be preceded by adequate training and followed by scientific validation. It is necessary to apply additional functions and statistical analysis to guarantee the quality of the data collected by volunteers and to minimize thematic and spatial errors. Assessing statistical bias when non-scientific personnel collect data is difficult. Although previous experiences suggest that the quality of voluntary geographic information is not significantly different from that collected by scientists, data validation is a challenge that must be addressed. (d) *Integration with other data sources*: Methodologically, it is feasible and advisable to integrate voluntary geographic information with other data sources. Remote sensing, for example, is a key source to promote the information scaling-up, from the local to the global (spatial scale), and the variables monitoring, in the short and long term (time scale). (e) *Emerging Institutionalizations of Science*: Initiatives such as CEEP open up a novel field of inquiry into the empirical designs of parliamentary policy-making as a participatory process.

ANNEX: ONE SLIDE SUMMARY FOR EXPERTS

ANNEX: ONE SLIDE SUMMARY FOR THE GENERAL PUBLIC

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Information, gathered, stored, processed and transmitted, is the cornerstone of the present era and shapes every aspect our daily life, thus permeating cultural and social deep changes. A multi- and cross-disciplinary approach is needed to cover all present challenges of the Information age, ranging from both the more technological aspects to the social ones. This duality is reflected in the title of this volume, Digital and Complex Information. The current Digital Transformation is enabled by developments in physics and engineering and entails several fields including electronics, optics, material science, and quantum technologies. Nowadays challenges include sustainable and energy efficient electronics, integrated photonics with new functionalities, quantum computing and machine learning, and operation within the Internet of Things. Nonetheless the Digital world generates an ever-increasing amount of data in which security and trust play a critical role. The advances in digital technologies call for a new scientific research approach: an Open Science, reproducible, interoperable and accessible. New avenues are open in how we deal with Humanities and with individual/social security and rights, within digital citizenship. This is the broad spectrum of challenges that drives research across about the 40 CSIC institutes in line with the latest developments in digitalization worldwide.

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