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".

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.

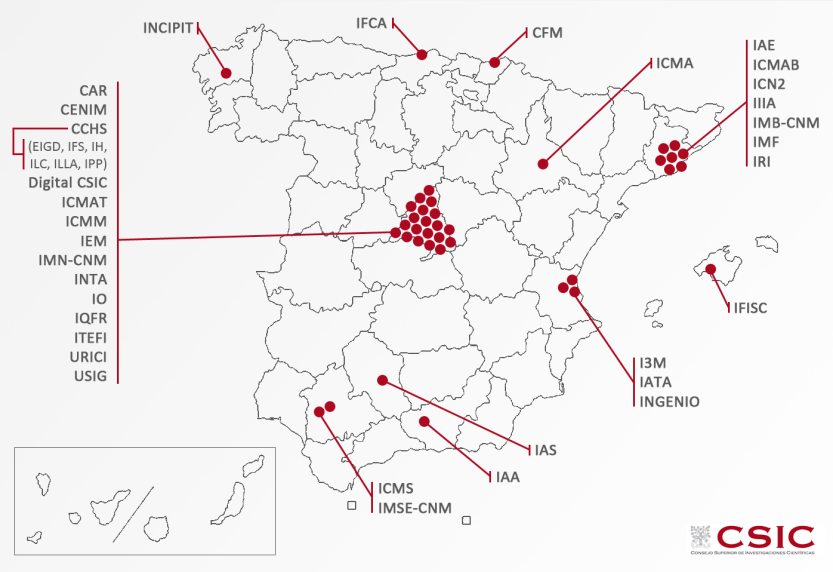
5 OECD (2020), The Digitalisation of Science, Technology and Innovation: Key Developments and Policies, OECD Publishing, Paris, https://doi.org/10.1787/b9e4a2c0en

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

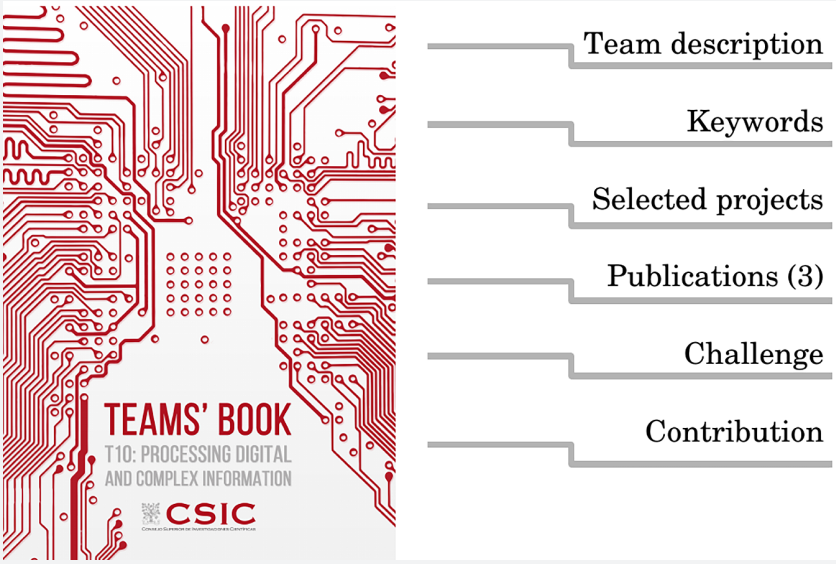
capabilities in mobility, logistics and transportation, manufacturing or healthcare are examples of sectors benefiting from disruptiveness of CPS and IoT.

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.