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

VOLUME 10

DIGITAL & COMPLEX INFORMATION

Catálogo de publicaciones de la Administración General del Estado:
https://cpage.mpr.gob.es

Editorial CSIC:
http://editorial.csic.es (correo: *publ@csic.es*)

ISBN Vol. 10: 978-84-00-10756-7
ISBN O.C.: 978-84-00-10736-9
e-ISBN Vol. 10: 978-84-00-10757-4
e-ISBN O.C.: 978-84-00-10734-5
NIPO: 833-21-140-5
e-NIPO: 833-21-137-1
DL: M-2426-2021

Diseño y maquetación: gráfica futura

VOLUME 10
DIGITAL & COMPLEX INFORMATION

Topic Coordinators
Roberta Zambrini & Gemma Rius

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
Roberta Zambrini (IFISC, CSIC – UIB) and Gemma Rius (IMB-CNM, CSIC)

Challenges Coordinators
Agnès Ponsati (URICI, CSIC), Alberto Corsín Jiménez (ILLA, CSIC), Antonio Lafuente (IH, CSIC), Astrid Wagner (IFS, CSIC), David Zueco (ICMA, CSIC-UNIZAR), Diego Porras (IFF, CSIC), Fernando Aguilar (IFCA, CSIC-UC), Gabriela Cembrano (IRII, CSIC-UPC), Javier Aizpurua Iriazabal (CFM, CSIC), Joan Bausells (IMB-CNM, CSIC), Judith Farré (ILLA, CSIC), Luis Hernández Encinas (ITEFI, CSIC), Miguel Cornelles Soriano (IFISC, CSIC-UIB), Óscar Martínez Graullera (ITEFI, CSIC), Ricardo Martínez Martínez (IMB-CNM, CSIC) and Rodolfo Haber (CAR, CSIC-UPM)

Participant CSIC-Centers
Centro de Astrobiología (CAB, CSIC-INTA)
Centro de Automática y Robótica (CAR, CSIC-UPM)
Centro Nacional de Investigaciones Metalúrgicas (CENIM, CSIC)
Centro de Física de Materiales (CFM, CSIC-UPV/EHU)
Instituto de Instrumentación para Imagen Molecular (I3M, CSIC-UPV)
Instituto de Astrofísica de Andalucía (IAA, CSIC)
Instituto de Análisis Económico (IAE, CSIC)
Instituto de Agricultura Sostenible (IAS, CSIC)
Instituto de Agroquímica y Tecnología de Alimentos (IATA, CSIC)
Instituto de Nanociencia y Materiales de Aragón (INMA, CSIC)
Instituto de Ciencia de Materiales de Barcelona (ICMAB, CSIC)
Instituto de Ciencias Matemáticas (ICMAT, CSIC-UCM-UAM-UC3M)
Instituto de Ciencia de Materiales de Madrid (ICMM, CSIC)
Instituto de Ciencia de Materiales de Sevilla (ICMS, CSIC-US)
Centro de Investigación en Nanociencia y Nanotecnología (ICN2, CSIC-UAB-Generalitat-Fundación)
Instituto de Economía, Geografía y Demografía (IEGD, CSIC)
Instituto de Estructura de la Materia (IEM, CSIC)
Instituto de Física de Cantabria (IFCA, CSIC-UC)
Instituto de Física Fundamental (IFF, CSIC)
Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC, CSIC-UIB)
Instituto de Filosofía (IFS, CSIC)
Instituto de Historia (IH)
Instituto de Investigación en Inteligencia Artificial (IIIA, CSIC)
Instituto de Lenguas y Culturas del Mediterráneo y Oriente Próximo (ILC, CSIC)
Instituto de Lengua, Literatura y Antropología (ILLA, CSIC)
Instituto de Microelectrónica de Barcelona (IMB-CNM, CSIC)
Institución Milá y Fontanals (IMF, CSIC)
Instituto de de Micro y Nanotech de Madrid (IMN-CNM, CSIC)
Instituto de Microelectrónica de Sevilla (IMSE-CNM, CSIC-US)
Instituto de Ciencias del Patrimonio (INCIPIT, CSIC)
Instituto de Gestión de la Innovación y del Conocimiento (INGENIO, CSIC-UPV)
Instituto de Óptica Daza de Valdés (IO, CSIC)
Instituto de Políticas y Bienes Públicos (IPP, CSIC)
Instituto de Química Física Rocasolano (IQFR, CSIC)
Instituto de Robótica e Informática Industrial (IRII, CSIC-UPC)
Instituto de Tecnologías Físicas y de la Información Leonardo Torres Quevedo (ITEFI, CSIC)
Unidad de Recursos de Información Científica para la Investigación (URICI, CSIC)
Unidad de Sistemas de Información Geográfica del Centro de Ciencias Humanas y Sociales (USIG-CCHS, CSIC)

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.

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

Coordinators
Joan Bausells
(IMB-CNM, CSIC, Coordinator)
Óscar Martínez Graullera
(ITEFI, CSIC, Adjunct Coordinator)

Participant researchers and centers
Ramón Aguado (ICMM, CSIC)
Luis Fonseca
(IMB-CNM, CSIC)
Martí Gich (ICMAB, CSIC)
Antonio González
(I3M, CSIC – UPV)
Gervasi Herranz (ICMAB, CSIC)
Carmen Horrillo (ITEFI, CSIC)
Rafael Jiménez (ICMM, CSIC)
Bernabé Linares
(IMSE-CNM, CSIC)
Benjamín Martínez
(ICMAB, CSIC)
Marta Mas (ICMAB; CSIC)
Rafael Molina (IEM, CSIC)
Aurora Nogales (IEM; CSIC)
Anna Palau (ICMAB, CSIC)
Eloi Ramon (IMB-CNM, CSIC)
Gemma Rius (IMB-CNM, CSIC)
Isabel Sayago (ITEFI, CSIC)
Tobias Stauber (ICMM, CSIC)
José Maria de Teresa
(ICMA, CSIC - UNIZAR)

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.

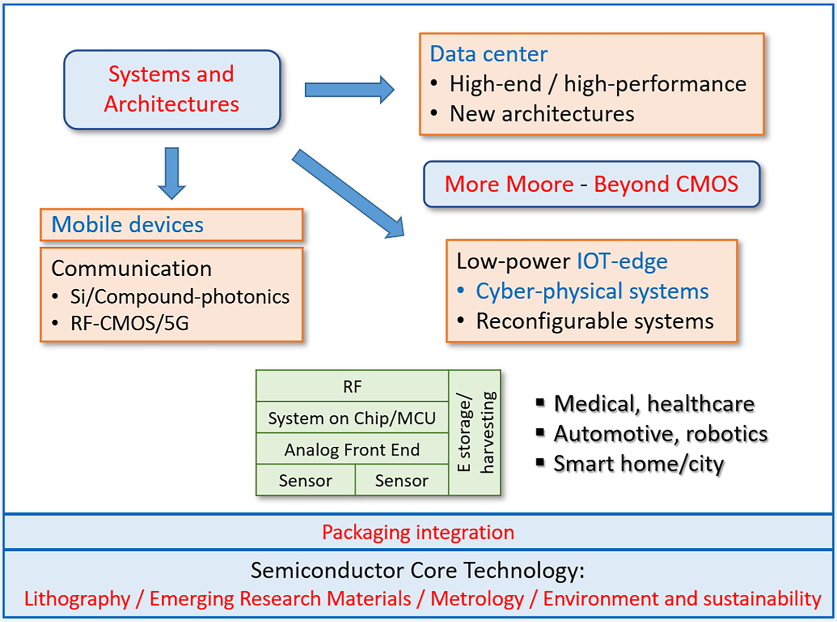
The current structure of the electronics ecosystem is shown in Figure 1.1. It is adapted from the International Roadmap for Devices and Systems (IRDS) [Institute of Electrical and Electronics Engineers, 2020]. The focus technological topics of the IRDS are written in red. The roadmap emphasis is on the 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.

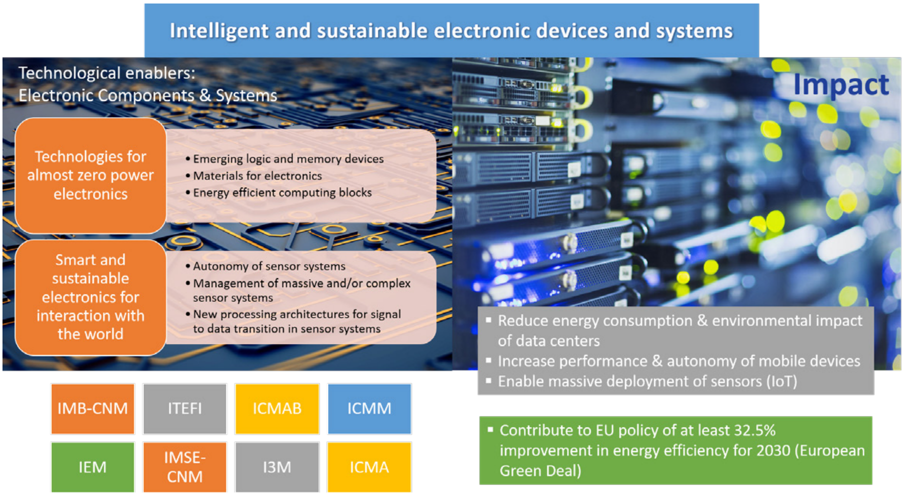
The scenario that is arising is well presented in the IRDS 2018 update (More Moore). *As the global data corpus continues to grow exponentially with a two-year doubling period and with that growth to come disproportionately in distributed CPS and IoT/edge systems, time of flight through wired or wireless 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

VOLUME 10 **REFERENCES**

Aeneas, Artemis-IA and EPoS (2021). Strategic research agenda for electronic components and systems 2021. Technical report. Accessible at: https://ecscollaborationtool.eu/publication/download/2021-01-11-ecs-sria2021-final.pdf

Baker, M. and Penny, D. (2016). Is there a reproducibility crisis?

Baquero-Arribas, M., Dorado, L. and Bernal, I. (2019). Open access routes dichotomy and opportunities: Consolidation, analysis and trends at the Spanish national research council. *Publications*, 7(3):49.

Bechhofer, S., De Roure, D., Gamble, M. et al. (2010). Research Objects: Towards Exchange and Reuse of Digital Knowledge. *Nature Precedings*: 1–1.

Bernal, I. and Román-Molina, J. (2018). Informe de la encuesta sobre evaluación por pares y el módulo "Open Peer Review" de DIGITAL.CSIC. Technical report.

Braun, T. (2010). How to improve the use of metrics. *Nature*. 465, 870–872. Accessible at: https://www.nature.com/articles/465870a

Castaño, F., Strzelczak, S., Villalonga, A., Haber, R. E. and Kossakowska, J. (2019). Sensor reliability in cyber-physical systems using internet-of-things data: A review and case study. *Remote Sensing*, 11(19):2252.

Centre National De La Recherche Scientifique (2019). CNRS roadmap for open science. Accessible at: https://www.science-ouverte.cnrs.fr/wp-content/uploads/2019/11/CNRS_Roadmap_Open_Science_ 18nov2019.pdf

Coalition S. (2020). Plan S. Accessible at: http://https://www.coalition-s.org/

COAR (2020). Building a sustainable, global knowledge commons. Accessible at: https://www.coar-repositories.org/

Coretrustseal (2020). Core Trustworthy Data Repositories. Accessible at: http://https://www.coretrustseal.org/

CSIC Divulgación (2020). Webs de Divulgación | Consejo Superior de Investigaciones Científicas – CSIC. Accessible at: csic.es.

ECSEL JTI. (2020). From IoT to system of systems: Market analysis, achievements, positioning and future vision of the ECS community on IoT and SoS. Technical report, ARTEMIS Industry Association.

ESFRI (2020). European Strategy Forum on Research Infrastructures. Accessible at: https://www.esfri.eu/

European Commission (2013). Cybersecurity strategy of the European Union: An open, safe and secure cyberspace. Accessible at: http://eeas.europa.eu/archives/docs/policies/eu-cyber-security/cybsec_comm_en.pdf

European Commission (2020). European Commission awards contract for setting up an open access publishing platform. Accessible at: https://ec.europa.eu/info/news/european-commission-awards-contract-setting-open-access-publishing-platform-2020-mar-20_en#:~:text=The%20European%20Commission%20has%20awarded,is%20planned%20for%20early%202021.

European Commission (2020). Horizon Europe. Accessible at: http://https://ec.europa.eu/info/horizon-europe_en

European Commission (2019). Orientations towards the first Strategic Plan for Horizon Europe. Accessible at: https://ec.europa.eu/research/pdf/horizon-europe/ec_rtd_orientations-towards-the-strategic-planning.pdf

European Council (2009). European security strategy – a secure Europe in a better world. Accessible at: https://www.consilium. europa.eu/en/documents-publications/publications/european-security-strategy-secure-europe-better-world/

European Parliament and Council (2019). Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on Open Data and the re-use of public sector information.

European Parliament, European Council, Council, European Economic and Social Committee and Committee Of The Regions (2020). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A New Industrial Strategy for Europe. COM/2020/102. Accessible at: https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en. pdf

European Technology Platform Photonics 21 (2019). Multiannual Strategic Roadmap 2021–2027. Accessible at: https://www.photonics21.org/download/ppp-services/photonics-downloads/Europes-age-of-light-Photonics-Roadmap-C1.pdf

European Union (2020). Network and Information Systems Directive. Accessible at: https://ec.europa.eu/digital-single-market/en/network-and-information-security-nis-directive

European Union (b). Cybersecurity Act, 2020. https://ec.europa.eu/digital-single-market/en/eu-cybersecurity-act.

Fesabid (2020). Grupo de Trabajo Copyright. Accessible at: http://www.fesabid.org/bpi/grupo-bpi-bibliotecas-y-propiedad-intelectual

Fundación Acción Pro Derechos Humanos (2020). ARTÍCULO 44 de la Constitución Española - Acceso a la cultura y promoción de la ciencia. Accessible at: https://www.derechoshumanos.net/constitucion/articulo44CE.htm

Gobierno De España (2017). Estrategia de Seguridad Nacional. Accessible at: https://www.dsn.gob.es/es/estrategias-publicaciones/estrategias/estrategia-seguridad-nacional-2017.

Greer, C., Burns, M., Wollman, D. and Griffor, E. (2019). Cyber-physical systems and internet of things. *NIST Special Publication*, 202:52.

Griffor, E. R., Greer, C., Wollman, D. A. and Burns, M. J. (2017). Framework for cyber-physical systems: Volume 1, overview. Technical report.

IEA (2020). Data Centres and Data Transmission Networks, International Energy Agency, Paris. Accessible at: https://www.iea.org/reports/data-centres-and-data-transmission-networks

Institute Of Electrical and Electronics Engineers (2020). International roadmap for devices and systems 2020. Technical report. Accessible at: https://irds.ieee.org

Ishwarappa and Anuradha, J. (2015). A brief introduction on big data 5Vs characteristics and hadoop technology. In *Procedia Computer Science*, 48: 319–324. Elsevier B. V.

IX EPSCYT (2018). Informe De Resultados. Technical report. v261118. Accessible at: https://icono.fecyt.es/sites/default/files/filepublicaciones/20/epscyt2018_informe.pdf

Mckinsey Digital (2020). A game plan for quantum computing. Accessible at: https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/a-game-plan-for-quantum-computing

Netherlands (2017). National plan open science. Accessible at: https:// www.openscience.nl/en/national-platform-open-science/ national-plan-open-science

Open Access 2020 (2020). Open Access 2020 Initiative. Accessible at: http://https://oa2020.org/

Preskill, J. (2018). Quantum Computing in the NISQ era and beyond. *Quantum*, 2:79.

Quantum Flagship Initiative (2020). Strategic Research Agenda. Accessible at: https://qt.eu//app/uploads/2020/04/Strategic_Research-_Agenda_d_FINAL.pdf

Quantum Flagship Initiative, Mishina Et al. (2019). Strategic Agenda Summary: Education for QT. Accessible at: https://qt.eu/app/uploads/2019/03/Strategic-Agenda-Summary-Education-for-QT_19.03.19.pdf

Raymer, M. G. and Monroe, C. (2019). The US national quantum initiative. *Quantum Science and Technology*, 4(2):020504.

Red De Bibliotecas Y Archivos Del CSIC (2020). Apoyo para la publicación en acceso abierto para los investigadores CSIC. Accessible at: http://http://bibliotecas.csic.es/publicacion-en-acceso-abierto

Riedel, M. F., Binosi, D., Thew, R. and Calarco, T. (2017). The European quantum technologies flagship programme. *Quantum Science and Technology*, 2(3):030501.

UN General Assembly (2015). Transforming our world: the 2030 agenda for sustainable development. Resolution A/RES/70/1. Accessible at: https://www.refworld.org/docid/57b6e3e44

United Nations (2020). About the Sustainable Development Goals - United Nations Sustainable Development. Accessible at: https://www.un.org/sustainabledevelopment/development-agenda/

Van Lier, B. (2018). Cyber-physical systems of systems and complexity science: The whole is more than the sum of individual and autonomous cyber-physical systems. *Cybernetics and Systems*, 49(7-8):538–565.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J. et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3:160018.

Wouters, et al. P (2019). Indicator frameworks for fostering open knowledge practices in science and scholarship. Accessible at: https://op.europa.eu/en/publication-detail/-/publication/b69944d4-01f3-11ea-8c1f-01aa75ed71a1

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.

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

EDITORIAL CSIC