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THE MAGAZINE OF THE EUROPEAN PHYSICAL SOCIETY

Materials for the 21st Century

From classical optics to nanophotonics

Scaling without scaling

Artificial intelligence and its limits

Europe's Quantum Flagship is taking off

From particle physics to MedTech

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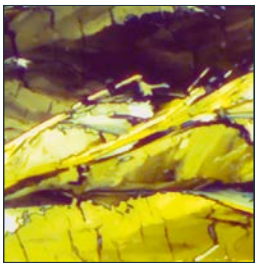
Cover picture: Special issue on Physics and its current and future applications. See p.13 to 38. Image courtesy ©iStockPhoto



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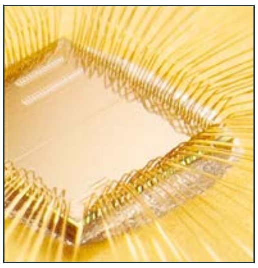
Materials for the 21st Century



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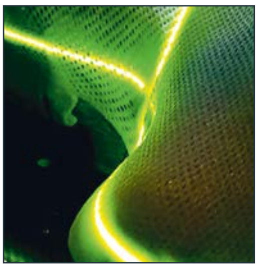
Scaling without scaling, a paradigm shift in the semi-conductor industry



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From particle physics to MedTech and biomedical research

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[EDITORIAL]

Historic Sites

In the EPS jubilee year, the Historic Site Program continues to flourish

As the 50th anniversary year of the European Physical Society comes to a close, we can draw a positive balance: 2018 has been rich in events which have helped to showcase the mission and the action of our Society to the scientific community, and to convey to a broad audience the pivotal role which physics has always played, and continues to play, in addressing the scientific and societal challenges which humankind is facing. The climax of our anniversary celebrations has been a memorable, well-attended ceremony which took place on 28 September in Geneva, the place where the EPS was born in 1968. However, other events throughout the year have highlighted our Society's history and achievements: meetings of our Member Societies, conferences organized by Divisions and Groups, and many others. Let me take this opportunity to thank the many volunteers and contributors who have spared no time and effort to make the EPS jubilee year a success.

A round anniversary is a natural reason to look back, and it does not come as a surprise that 2018 has also been a year rich in inaugurations of EPS Historic Sites. In the wider framework of prizes and distinctions awarded by the EPS, the Historic Sites hold a special place: they do not decorate scientists and their personal (or collective) achievements, but "commemorate places in Europe important for the development and the history of physics". The program was launched in 2011 under the impetus of then EPS President Luisa Cifarelli and, in a few years of existence, has become a remarkable success story. More than 70 proposals for Historic Sites have been received up to now, almost all of them of excellent quality, and more than 40 have been inaugurated. Since the Haldde Observatory, established in 1910 to study the aurora borealis near Alta in northernmost Norway, was added to the list in August of this year, we can proudly say that the EPS Historic Site network spans the entire continent from Coimbra to Moscow and from Sicily to (almost) the North Cape.

Even more impressive than the broad geographical coverage is the historical and thematic diversity of the program. Of course, there are many prestigious universities and research institutions which have been the showplace of fundamental scientific breakthroughs and Nobel Prize winning discoveries: the last Historic Site that we expect to inaugurate in 2018, the Humboldt University in Berlin – workplace of Max Planck, Max von Laue, Gustav Hertz and others – will be just one prominent member in this prestigious line-up. However, visits to all sites add up to a fascinating journey through the history of science, which is rich in surprises. Looking for the oldest, you will discover the picturesque island of Hven, between Sweden and Denmark, where Tycho Brahe built, at the end of the 16th century, the most advanced observatory of its time and revolutionized our understanding of the planetary system. If you are ambitious to visit the most elevated, you will have to climb all the way up to the "Refuge des cosmiques", at 3,613 meters above sea level on the ascent to the Mont Blanc, which has served for many years as a laboratory for important work in cosmic ray physics. The "refuge" is an active alpine hut open to the public, but it can only be reached on foot. If you prefer a more comfortable option to spend a night in an EPS Historic Site: also on the list is the five-star "Hotel Metropole" in Brussels, the venue of the legendary first Solvay Conference in 1911. These are just a few examples – the full list can, of course, be found on the EPS Website.

The Historic Site program has developed into a unique and original instrument to illustrate the rich and prestigious history and the achievements of physics in Europe

When the Historic Site program was launched, it was inspired by a similar initiative of the American Physical Society, and to honour this common tradition, APS and EPS have distinguished two joint Historic Sites, which are both intimately related to the life and work of Albert Einstein: the house in Bern, Switzerland, where Einstein lived during the annus mirabilis 1905; and the Institute for Advanced Study in Princeton.

In a few years, the Historic Site program has developed into a unique and original instrument to illustrate the rich and prestigious history and the achievements of physics in Europe, and to inscribe the diversity of our science, and its omnipresence in our daily life, in our collective memory. Luisa Cifarelli, who has not only initiated the program but has also chaired the Historic Site Committee since its inception, has expressed the wish to retire from this activity in the near future. I am certain that all readers will join me in thanking Luisa, and in congratulating her on a wonderful achievement.

Rüdiger Voss,
EPS President

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Nobel prize in Physics 2018

Following its first demonstration in 1960, after having been initially dubbed "a solution in search of a problem", the laser has become a pervasive tool in science and technology, finding applications that range from fundamental investigations of matter to telecommunications, medical imaging, surgery and materials processing. Several past Nobel prizes in Physics and Chemistry are related to laser science.

The 2018 Nobel Prize in Physics was awarded to Arthur Ashkin, Gérard Mourou and Donna Strickland *"for groundbreaking inventions in the field of laser physics"*. Arthur Ashkin was honored *"for the optical tweezers and their application to biological systems"*, while Gérard Mourou and Donna Strickland were recognized *"for their method of generating high-intensity, ultra-short optical pulses"*.

Radiation pressure has fascinated physicists for a long time, however, in J. H. Poynting's words, radiation pressure forces are characterized by 'extreme minuteness - a minuteness which appears to put them beyond consideration in terrestrial affairs'. It was known from the early history of optics that light carries a linear momentum, thus any object causing a deviation of its direction will receive a slight kick by it. However, tangible effects of these forces could only be observed after the invention of the laser, which, thanks to its brightness, can concentrate many photons on tiny surfaces. In his pioneering work in 1970, Arthur Ashkin showed how focused laser beams were capable of affecting the motion of micrometer sized transparent objects, thanks to radiation pressure forces. He also identified two such forces, scattering and gradient ones. The former occur when photons are reflected from a surface, while the latter are generated when photons are deviated by refraction. Scattering forces are more intuitive and enable pushing small particles in the direction of the incident light (as one can experience in person by standing in the middle of a stream of people exiting the underground), while gradient forces are more subtle and are directed along the intensity gradient of the light beam. Combining two opposite beams, Ashkin could demonstrate a stable three-dimensional optical trap, where scattering forces could confine the particle along the beam axis, while gradient forces gave the transversal confinement. Later on, in 1986, Ashkin and coworkers demonstrated the possibility to achieve three-dimensional optical trapping with a single beam, a technique that soon became known as optical tweezers. In this case, the laser beam needs to be tightly focused in order to create an intensity gradient also along its propagation direction. In this way, a backward gradient force can overcome the forward scattering one and produce a stable three-dimensional trap without the need for the counter-propagating beam.

Application of optical tweezers to biology proved extremely successful, enabling the precise manipulation of living bacteria, viruses and cells. This permitted an unprecedented characterization of their mechanical properties and of their motility mechanisms. An important feature of optical tweezers is that they can be applied to objects down to the nanoscale, opening a new window on the molecular processes that regulate the basic mechanisms of life. Physical properties of DNA strands could be directly probed, as well as for RNA molecules. In addition, optical tweezers enabled the characterization of the kinetics and mechanics of molecular motors. An important achievement was the direct observation of the stepping motion of kinesin along microtubules, with a step size of 8 nm. Ashkin also demonstrated that optical trapping techniques could be applied to neutral atoms, paving the way to laser cooling and trapping of atoms and eventually to Bose-Einstein condensates, achievements which were in turn awarded with Nobel Prizes in Physics.

Gérard Mourou and Donna Strickland invented a revolutionary approach which allowed to solve the problem of increasing the energy, and thus the intensity, of ultrashort light pulses. Mode-locked lasers generate extremely short light pulses, with durations from a few picoseconds down to a few femtoseconds (1 fs = 10^{-15} s); however, their energies are low, of the order of a few nJ. Initial attempts to boost the pulse energy by means of optical amplifiers were frustrated by the problem of optical damage, occurring in the amplifier material when the amplified pulse intensity exceeded a given value. In their groundbreaking 1985 paper, Donna Strickland and Gérard Mourou introduced the "chirped pulse amplification" (CPA) technique, which enabled a sudden increase in the pulse energy by six orders of magnitude, from the nJ to the mJ level. The CPA concept, which is borrowed from radar technology, can be understood by considering that an ultrashort light pulse has, according to the Fourier theorem, a broad spectrum, *i.e.* it contains many different colors. In a CPA system the pulse is first sent to a "stretcher", a dispersive optical system in which the colors travel with different speed, thus acquiring a relative delay, also known as "frequency chirp"; as a result, at the output of the stretcher the colors are temporally separated and the pulse is lengthened by up to 4-5 orders of magnitude. An increase in the duration of the chirped pulse corresponds to a decrease of its intensity, so that it can now be safely amplified by several orders of magnitude without damaging the amplifier material. Following the amplification stage, the last step of the CPA system is the "compressor", an optical system in which the relative delays of the different colors of the pulse are reversed, thus canceling the chirp and restoring the original pulse duration. The CPA concept proved to be very effective and has become a cornerstone of ultrafast laser technology, triggering the race towards the generation of light pulses with unprecedented peak power and intensity. Nowadays lasers with terawatt (1 TW = 10^{12} W) peak power are commercially available and several laboratories host laser systems with peak powers of 1-10 petawatts (1 PW = 10^{15} W). Such incredibly high instantaneous powers exceed by more than two orders of magnitude the combined power of all the world's electrical grids!

▲ Illustration: ©Niklas Elmehed

Besides setting new performance records, these extremely powerful lasers have enabled breakthroughs both in basic science and in applications. Atoms and molecules exposed to such intense light fields enter a completely new regime of light-matter interaction. The electric field of light can become high enough to rip an electron apart from an atom and then drive it back to the parent ion, producing by *bremsstrahlung* coherent bursts of XUV radiation and attosecond (1 as = 10^{-18} s) light pulses. Intense laser pulses can generate in a plasma a wave (the so-called wakefield) resulting in longitudinal electric fields able to accelerate charged particles to high energies (up to GeVs) over short distances (a few cm). At extremely high peak powers, it could also become possible to generate electron-positron pairs from the vacuum – a fundamental test of quantum electrodynamics. High intensity lasers also find important applications in materials processing, as they allow to deposit energy in the irradiated volume in a very short time, avoiding heat diffusion and resulting in clean ablation without collateral damage. High intensity femtosecond lasers are used for drilling holes in metals, such as in the injectors of diesel engines or the stents used in vascular surgery. They find also medical applications in refractive eye surgery, using the laser-assisted in situ keratomileusis (LASIK) procedure to correct myopia and astigmatism.

The inventions by Arthur Ashkin, Gérard Mourou and Donna Strickland are still having a profound impact in science and technology and novel, surprising applications are to be expected in the near future. ■

Giulio Cerullo and Roberto Osellame
IFN-CNR, Dipartimento di Fisica, Politecnico di Milano, Italy

EPJ@20 – Celebrating 20 Years of the European Physical Journal

20 YEARS OF EPJ.org
your physics journal

This year sees the 20th anniversary of the founding of EPJ, the European Physical Journal. Launched in 1998, EPJ brought together the combined strengths of some long-established national European physics journals, starting with the initial merger of *Journal de Physique, Il Nuovo Cimento* and *Zeitschrift für Physik,* and continuing with the adoption and incorporation of *Acta Physica Hungarica, Anales de Fisica, Czechoslovak Journal of Physics, Fizika A,* and *Portugaliae Physica.* The EPJ Scientific Advisory Committee includes now members from 25 European learned societies.

Since those beginnings, EPJ has expanded its geographical reach well beyond Europe and has a much more international and diverse authorship. Its spectrum of journals – 17 by now (www.epj.org) – includes all traditional and emerging fields where the physical sciences contribute significantly to research agendas worldwide. These include, for example the highly successful *EPJ Data Science*, a journal representing a melting pot of physicists, computer scientists and researchers with many other backgrounds in the natural and social sciences, and *EPJ Quantum Technology*, a title launched in response to the huge investment in quantum-related science, technology and engineering in Europe and worldwide.

EPJ still maintains the principle of active editorial board members being in charge of a personalized refereeing process. Equally it is the same editorial boards that provide the crucial input for shaping and adapting the editorial scope and policies of the EPJ journals, in line with the needs and wishes of the scientific communities they serve, in a self-consistent way.

Publishing developments at EPJ over the past years have been fast paced toward enabling the progressive opening of the journal contents, both by giving the option of publishing in Open Access in the traditional journals, turning EPJ C to full Open Access in support of SCOAP3 and offering some new journals as full Open Access outlets. Since 2016, as part of a wider Springer Nature initiative*, the traditional EPJ journals do also feature the *SharedIt* link, a free content sharing tool that allows everyone, anywhere to read the full contents of the journals, whether they have a subscription or not.

The complexity of operations has grown accordingly, involving a publishing team of colleagues spread across Europe and cultivating both European and global networks. Heidelberg, Bologna, Milan, Paris, Dordrecht and London are the hubs from where the majority of the connections emanate. Considerably more focus, investments and expertise will be required for the gradual but steady implementation of an ambitious open science program, better control of research integrity and publishing ethics and development of novel technologies to make the tools and platforms that enable scientists to fulfill their publishing needs.

EPJ's strengths continues thereby to reside in a healthy collaboration and balance between scientific, commercial, and societal aspects, with the shared goal of providing a sustainable publishing infrastructure that plays a crucial part in the research communication and knowledge generation cycles. ■

The EPJ Steering Committee: Barbara Ancarani, Maria Bellantone, Christian Caron, Luisa Cifarelli, Jean Daillant, Agnès Henri

▲ EPJ SAC meeting, Mulhouse 2016

* EPJ is a common brand of EDP Sciences/French Physical Society, Società Italiana di Fisica and Springer Nature.

In memoriam
Gerardo Delgado

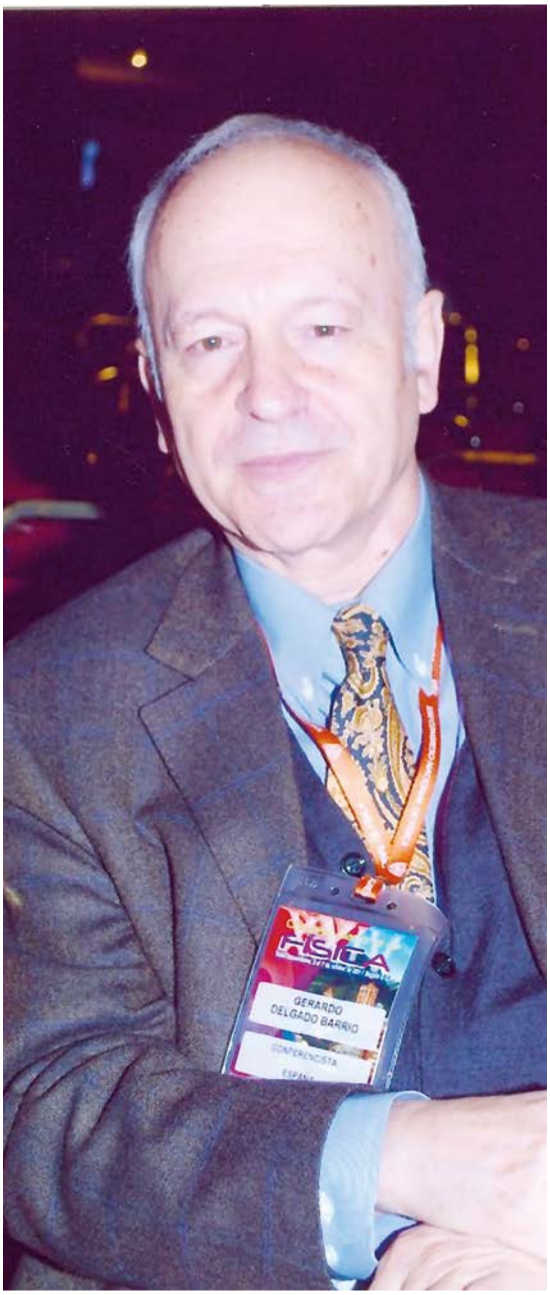
Gerardo Delgado passed away on July 26, 2018. Born on April 9, 1946 in Santiago de Compostela, he studied Physics at the Universidad Complutense (Madrid), where he obtained his PhD in 1973. He specialized in atomic and molecular physics, and got a permanent position in the Consejo Superior de Investigaciones Científicas (CSIC) in 1979. In CSIC he was Director of the Instituto de Física Fundamental, and member of the CSIC Governing Board (2001-2004), among many other commitments. He was member of the CSIC Research Integrity Committee since its creation.

Gerardo was President of the Real Sociedad Española de Física (RSEF) from 1997 until 2006. He was also in charge of international relations of EPS (2004-2006), and President of the Federación Latinoamericana de Sociedades de Física (FeLaSoFi) during the period 2005-2008.

His presidency of the RSEF spanned a very important period of its recent history. In 2003 the RSEF celebrated its centenary and Gerardo was the President of the Organizing Committee. In 2005 the World Year of Physics took place, coinciding with the 100th anniversary of Albert Einstein's *'annus mirabilis'*. Gerardo was the President of the Spanish Organizing Committee for the World Year of Physics. Both events were important milestones for the RSEF and required tremendous engagement on public relations, agreements with funding agencies and in explaining the important role of physics in our society. I had the privilege to work in close collaboration with him on these occasions. His sense of initiative, leadership and hard work was crucial for the success of both events. He infused his vigour and confidence on his close collaborators. He was a tireless worker, able to communicate with the common citizen, as well as with leaders in different areas of economy and government in Spain and abroad.

He worked hard to establish stronger links between the RSEF and the EPS. Thanks to him RSEF became an important partner of EPS, after a longer period of Spanish low profile within EPS.

▾ Gerardo Delgado, © Fundación BBVA



He was member of the EPS Executive Committee from 2001 until 2006. Through FeLaSoFi he opened up communication channels to Latin America and started new activities in physics for development. Gerardo Delgado was a founding member of the EPS Forum Physics and Society, and organized the 4th FPS Meeting in El Escorial, on improving the dialogue between physics and society.

Gerardo was elected EPS Fellow in 2007 and was awarded the Gero Thomas Medal in 2015 for outstanding contributions to EPS, in particular for his commitment to international scientific cooperation, outreach and education, and physics for development.

He was very aware that the role of a physicist is not only to do good physics, but must include also the human factor by explaining his work to the citizens. The collaboration with different countries reinforces the research groups' success and creates strong links with other cultures. These features of Gerardo's personality were highly appreciated by his colleagues and friends in all the countries where he worked. They will be missed now.

John Donne wrote (Devotions upon Emergent Occasions, Meditation XVII): *"any man's death diminishes me, because I am involved in Mankinde"*.

Gerardo Delgado was an outstanding physicist, as well as a wonderful human being. His death is a great loss for his family, but also for Physics in Spain, Europe and Iberoamerica. Many of us lost a colleague and a close friend. ■

Victor R. Velasco
Research Professor CSIC

Highlights from European journals

RELATIVITY

Is the relation between **mass and energy universal?**

The energy of ordinary particles is related to their mass through the famous relation $E=mc^2$, where m is both the inertial and the gravitational mass of the particle. This energy is minimum when the momentum p of the particle is p=0. Things are completely different if the energy is minimum for a momentum $p=p_o\neq0$. The inertial mass density of a gas of such particles is then $\rho=np_o^2/(3k_BT)$, where n is the density of particles, and T the temperature of the gas. It is not related to the energy density.

Condensed matter gives an example of such particles. Rotons, which are excitations of superfluid ^{4}He, have their energy minimum at a finite momentum. They largely contribute to the inertial mass density of the "normal fluid" in the two fluid model of superfluid ^{4}He. Nothing similar has been evidenced, up to now, within the cosmological particles, but one can raise the question: would the gravitational mass be related to the energy or the inertial mass? Assuming that gravitational and inertial mass densities are the same gives for the gas of such particles properties close to those expected for Dark Energy. This work is a discussion about these questions. ■

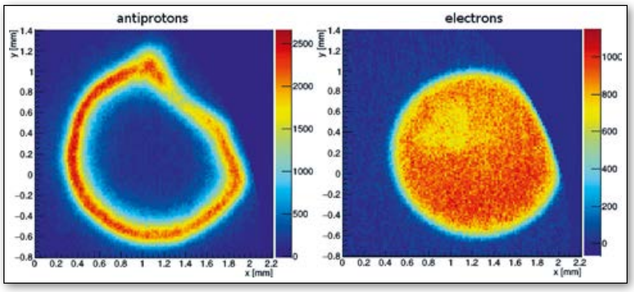
B. Castaing,
'What is the gravitational mass when energy and inertial mass are not equivalent?', *EPL* **123**, 20003 (2018)

PLASMA PHYSICS

Antimatter study to benefit from recipe for ten-fold spatial compression of plasma

Improving the spatial compression of a mixed matter-antimatter trapped plasma brings us one step closer to grasping the acceleration of antimatter due to Earth's gravity

An international team of physicists studying antimatter have now derived an improved way of spatially compressing a state of matter called non-neutral plasma, which is made up of a type of antimatter particles, called antiprotons, trapped together with matter particles, like electrons. The new compression solution, which is based on rotating the plasma in a trapped cavity using centrifugal forces like a salad spinner, is more effective than all previous approaches. In this study published recently, the team shows that — under specific conditions — a ten-fold compression of the size of the antiproton cloud, down to a radius of only 0.17 millimetres, is possible. These findings can be applied in the field of low-energy antimatter research, charged particle traps and plasma physics. Further, this work is part of a larger research project, called AEgIS, which is intended to achieve the first direct measurement of the gravitational effect on an antimatter system. The ultimate goal of the project, which is being pursued at CERN, the Particle Physics Laboratory in Geneva, Switzerland, is to measure the acceleration of antimatter — namely antihydrogen — due to Earth's gravity with a precision of 1%. ■



▲ Example of raw images from the detector for identical particle operations with antiproton detection (left) and electron detection (right).

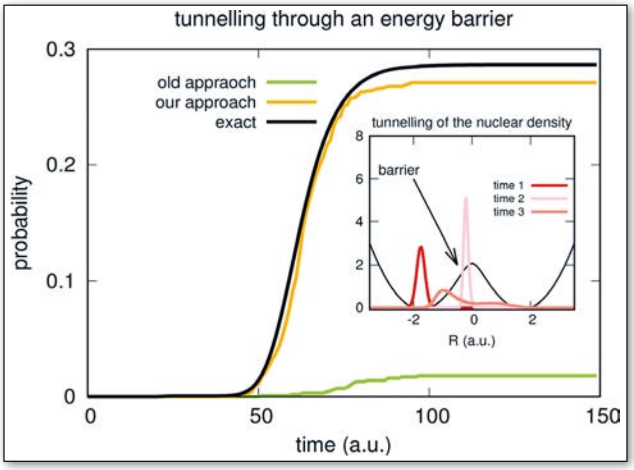
S. Aghion and **61 co-authors**,
'Compression of a mixed antiproton and electron non-neutral plasma to high densities', *Eur. Phys. Jour. D* **72**, 76 (2018)

QUANTUM PHYSICS

Clearer vision **of the biochemical reaction that allows us to see**

Physicists develop improved algorithms for simulating how complex molecules respond to excitation by photons, and explaining what happens when photons hit our eyes

What makes it possible for our eyes to see? It stems from a reaction that occurs when photons come into contact with a protein in our eyes, called rhodopsin, which adsorbs the photons making up light. In a paper published recently the authors propose a refined approximation of the equation that describes the effect of this photo-excitation on the building blocks of molecules. Their findings also have implications for other molecules, such as azobenzene, a chemical used in dyes. The incoming photon triggers certain reactions, which can result, over time, in dramatic changes in the properties of the molecule itself.



▲ Probability of the nuclei crossing the energy barrier over time.

This study was included in a special anniversary issue of EPJB in honour of Hardy Gross. ■

F. Agostini, **I.Tavernelli**, and **G. Ciccotti**,
'Nuclear Quantum Effects in Electronic (Non)Adiabatic Dynamics', *Eur. Phys. Jour. B* **91**, 139 (2018)

NUCLEAR PHYSICS

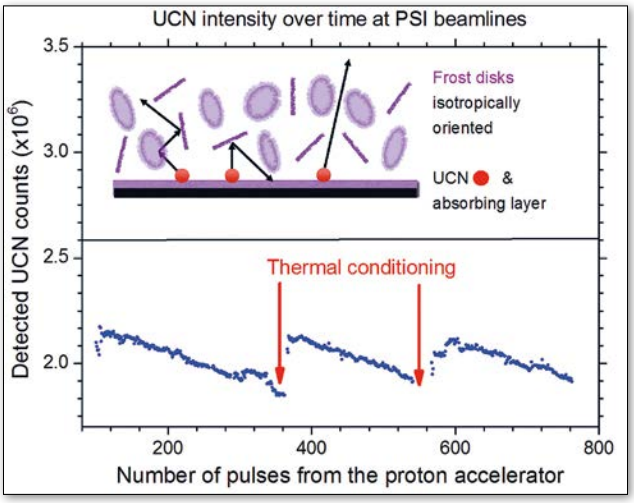
Solid deuterium surface degradation **at ultracold neutron sources**

Highest intensities of ultracold neutrons (UCN) are in worldwide demand for fundamental physics experiments. Tests of the Standard Model of particle physics and searches for physics beyond it are performed with UCN.

Two of the leading UCN sources, at Paul Scherrer Institute (PSI) and at Los Alamos National Laboratory (LANL), are based on solid deuterium (sD_2) at temperatures around 5 K. Here, together with NCSU they joined forces to understand UCN intensity decreases observed during pulsed neutron production. The study shows that the decrease can be completely explained by the build-up of frost on the sD_2 surface during operation. Pulsed proton beams hitting the spallation targets generate heat pulses causing cycles of D_2 sublimation and subsequent resublimation on the sD_2 surface. Even very small frost flakes can act as total reflectors for UCN and cause an intensity decrease.

Optical observation of the sD_2 surface at NCSU – not possible at the operating spallation neutron sources – confirmed a severe surface degradation due to heat pulsing with an external heater in strong support of the frost model. ■

▼ As shown in the figure for the PSI UCN source, the intensity decrease can be fully recovered by a conditioning process, removing the frost from the sD_2 and restoring good surface quality.

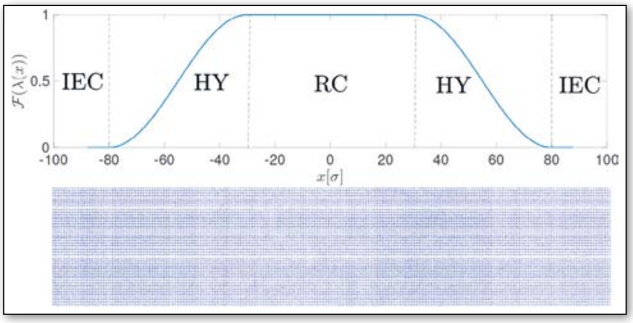


A. Anghel and **29 co-authors**,
'Acoustically-driven surface and hyperbolic plasmon-phonon polaritons in graphene/h-BN heterostructures on piezoelectric substrates', *J. Phys. D: Appl. Phys.* **51**, 204004 (2018)

COMPLEX SYSTEMS

Physical properties of solids elucidated by zooming in and out of high resolution

A new study shows how to couple highly accurate and simplified models of the same system to extract thermodynamics information using simulations



▲ Setup of an adaptive resolution simulation for solids.

Computer simulations are used to understand the properties of soft matter—such as liquids, polymers and biomolecules like DNA –which are too complicated to be described by equations. They are often too expensive to simulate in full, given the intensive computational power required. Instead, a helpful strategy is to couple an accurate model—applied in the areas of the system that require greater attention—with a simpler, idealised model. In a paper published recently, the authors make the accurate model in high-resolution coincide seamlessly with an exactly solvable representation at lower resolution. ■

M. Heidari, **R. Cortes-Huerto**, **K. Kremer**, and **R. Potestio**
'Concurrent coupling of realistic and ideal models of liquids and solids in Hamiltonian adaptive resolution simulations', *Eur. Phys. J. E* **41**, 64 (2018)

MATERIAL SCIENCE

Turning graphene **into light nanosensors**

Tuning the graphene embedded in a photonic crystal by varying the external temperature can transform it into a light-sensitive sensor

▲ Adsorption of water molecules on the surface of copper nanoparticles could produce hydrogen faster and more efficiently.

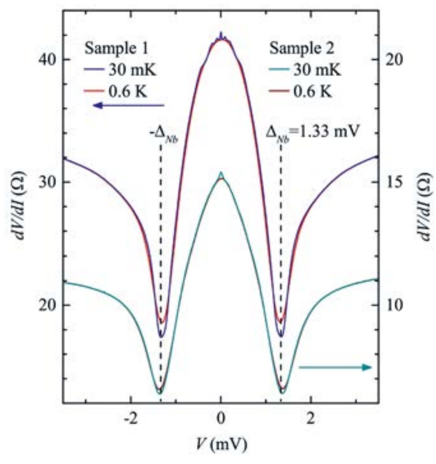
Graphene has many properties; it is *e.g.* an extremely good conductor. But it does not absorb light very well. To remedy this limiting aspect of what is an otherwise amazing material, physicists resort to embedding a sheet of graphene in a flat photonic crystal, which is excellent for controlling the flow of light. The combination endows graphene with substantially enhanced light-absorbing capabilities. In a new study published recently, the authors demonstrate that, by altering the temperature in such a hybrid cavity structure, they can tune its capacity for optical absorption. They explain that it is the thermal expansion and thermo-optical effects which give the graphene these optical characteristics. Potential applications include light sensors, ultra-fast lasers, and systems capable of modulating incoming optical beams. ■

▮ **A. Rashidi** and **A. Namdar,**
'Tunability of temperature-dependent absorption in a graphene-based hybrid nanostructure cavity', *Eur. Phys. J. B* **91**, 68 (2018)

CONDENSED MATTER

Signature of Fermi arc surface states in Andreev reflection

Weyl semimetals are conductors which are characterized by topologically protected conducting surface states. In contrast to three-dimensional topological insulators described by Z_2 invariant, Weyl surface states inherit the chiral property of the Chern insulator edge states, similarly to the quantum Hall effect regime. To observe this difference in symmetry, we experimentally investigate charge transport through the junction between a niobium superconductor and a three-dimensional WTe_2 Weyl semimetal. In addition to classical Andreev reflection, we observe sharp non-periodic subgap resistance resonances. From an analysis of their positions, magnetic field and temperature dependencies, we can interpret them as an analog of Tomasch geometrical oscillations for transport along the topological surface state across the region of proximity-induced superconductivity at the Nb-WTe_2 interface. The crucial point is that observation of distinct geometrical resonances implies a specific transmission direction for carriers, which is impossible for trivial two-dimensional surface states in planar junctions without strict axial symmetry. In contrast, for Weyl chiral surface states the preferable direction is present, forming a specific transmission direction for surface carriers. Thus, observation of distinct geometrical resonances is a hallmark of the Fermi arc Weyl surface states. ■



▲ Examples of dV/dI(V) characteristics with subgap resonances for two Nb-WTe_2 junctions.

▮ **A. Kononov**, **O. O. Shvetsov**, **S. V. Egorov**, **A. V. Timonina**, **N.N.Kolesnikov** and **E. V. Deviatov**, 'Signature of Fermi arc surface states in Andreev reflection at the WTe_2 Weyl semimetal surface', *EPL* **122**, 27004 (2018)

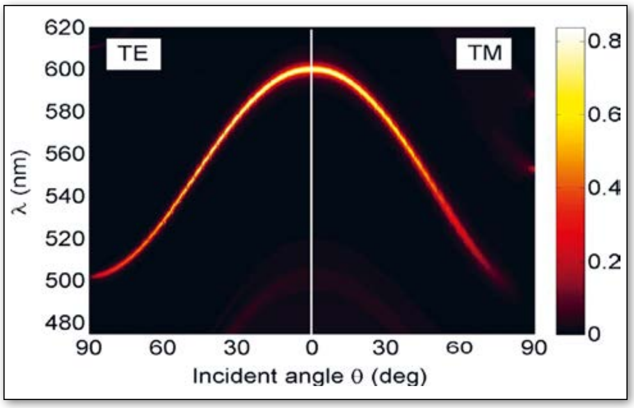
CHEMICAL PHYSICS

Producing hydrogen from splitting water without splitting hairs

New model explains interactions between small copper clusters used as low-cost catalysts in the production of hydrogen by breaking down water molecules

Copper nanoparticles dispersed in water or in the form of coatings have a range of promising applications, including

▾ Absorption on the plane of incident angle and wavelength.



lubrication, ink jet printing, as luminescent probes, exploiting their antimicrobial and antifungal activity, and in fuel cells. Another promising application is using copper as a catalyst to split water molecules and form molecular hydrogen in gaseous form. At the heart of the reaction, copper-water complexes are synthesised in ultra-cold helium nanodroplets as part of the hydrogen production process, according to a recent paper published recently. For its authors, splitting water like this is a good way of avoiding splitting hairs. In their study, they synthesised neutral copper-water complexes by successively doping helium nanodroplets with copper atoms and water molecules. These droplets are then ionised by electrons. The authors show that the composition of the most prominent ions depends on the partial copper and water pressures in the cell where the reaction occurs. They observe ions containing several copper atoms and several dozen water molecules. ■

■ **S. Raggl**, **N. Gitzl**, **P. Martini**, **P. Scheier**, and **O. Echt**
'Helium nanodroplets doped with copper and water', *Eur. Phys. Jour. D* **72**, 130 (2018)

APPLIED PHYSICS

Image-guided restricted drug release in friendly implanted therapeutics

This review exposes a possible therapeutics scheme of using active implants for restricted drug release, accounting for friendly wellbeing and security of patient. Friendly therapeutics ought to use controlled drug release with minimally-invasive and non-ionizing techniques. The review of different issues elucidates that the strategy sought may use non-ionizing image-guided drug release embedded implant, which is powered and controlled wirelessly by an external source. The analysis of the principal biomedical imagers indicates the MR (magnetic resonance) imager as the most adequate non-ionizing solution.

The review of MRI (magnetic resonance imaging) technology suggests an optimization of performance versus biological effects, as well as of compatibility with hosting materials in its environment. For the sake of such compatibility, an EMC (electromagnetic compatibility) analysis has been performed considering the nature of different MRI fields and their conventional protections and corrections.

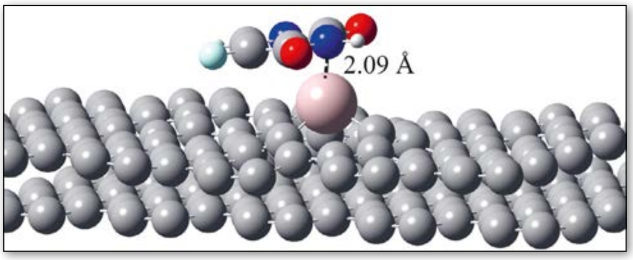
A possible future strategy would consist of an interactive system operating autonomously. Such a system is composed of the imager, the implant and its external wireless powering/control device. It integrates an AI (artificial intelligence) algorithm and has to operate under the supervision of the health-care team. ■

■ **A. Razek,**
'Towards an image-guided restricted drug release in friendly implanted therapeutics', *Eur. Phys. J. Appl. Phys.* **82**, 31401 (2018)

BIOLOGICAL PHYSICS

Better chemo drug adsorption **onto targeted delivery capsules**

New study demonstrates adsorption of chemotherapy drugs onto active carbon delivery capsule can be enhanced with aluminium atom inclusions



▲ Adsorption of chemo drug onto active carbon with aluminium inclusion.

The efficacy of chemotherapy treatment depends on how effectively it reaches cancerous cells. Increasing targeted delivery could mean decreasing side effects. Scientists are enhancing methods of selectively transmitting active chemotherapy agents and reducing their toxicity by encapsulating chemo drugs into active carbon used as the targeted delivery device. In a new study published recently, the authors have demonstrated that adding minute amounts of aluminium atoms onto activated carbon atoms helps increase the adsorption onto the delivery carbon capsule of a standard chemotherapy drug, called 5-Fluorouracil (5-FU). This drug is typically used for stomach, colorectal, neck and head cancer treatments. This model could lead to more effective and convenient cancer treatments with fewer side effects by encapsulating the chemo drug into the active carbon, so that it can be taken orally. ■

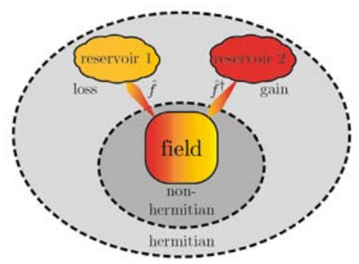
■ **G. Román, E. Noseda Grau, A. Diaz Compañy, G. Brizuela, A. Juan,** and **S. Simonetti,**
'A first-principles study of pristine and Al-doped activated carbon interacting with 5-Fluorouracil anticancer drug', *Eur. Phys. J. E* **41**, 107 (2018)

QUANTUM PHYSICS

Nonexistence of PT-symmetric gain-loss photonic quantum systems

Our common understanding of quantum mechanics relies on the Hamiltonian operator describing any quantum mechanical system to be Hermitian. This has been challenged 20 years ago by the discovery that, for an operator to possess real eigenvalues, it only needs to be invariant under combined parity-time (PT) symmetry operations. This had profound impact on photonics where potential landscapes with tailored gain and loss for electromagnetic waves can easily be implemented.

However, this is as far as the analogy to quantum mechanics can be taken. A straightforward implementation of gain-loss structures for quantum states of light - even for the most classical ones, coherent states - fails. As the authors show in this article, concatenating lossy and amplifying media turn coherent states into thermally broadened quantum states, whose first moments (*i.e.* their amplitudes) are retained, but whose variances are increased proportional to the amount of gain.



▲ Realizing non-Hermitian systems by coupling to a reservoir.

This shows that PT-symmetric quantum optics cannot be implemented within the prevailing paradigm of using distributed gain and loss. The wider consequence of this simple result hints at the limits of simulating quantum physics beyond wave mechanics using photonic quantum systems. ■

▌ **S. Scheel** and **A. Szameit,**
'PT-symmetric photonic quantum systems with gain and loss do not exist', *EPL* **122**, 34001 (2018)

APPLIED PHYSICS

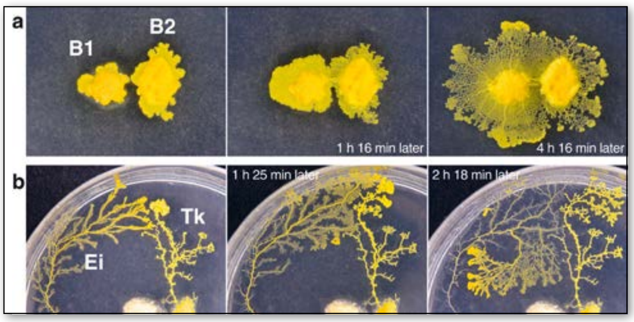
Self-extension model of slime mold's allorecognition behaviour

When slime molds encounter an allogeneic individual, they judge whether to fuse or avoid it. This decision can be made without coming in contact with each other.

Slime molds move, feed, and grow during single-celled amoeboid stage—plasmodium. They can divide into multiple individuals and fuse.

In this study on *Physarum rigidum*, an interesting behaviour was observed when they encountered an allogeneic individual. The plasmodia stopped their movement, came in contact with each other at the cell membrane surface, and then decided their actions. If they judge the encounter can become "self", they fused, and if they recognize it as "non-self", they avoided each other. This allorecognition behaviour can sometimes take several hours. More importantly, this behaviour can occur without contact between cell membranes. It is impressive to observe plasmodia stay apart from each other and decide their behaviour.

▼ Two typical encounter cases of Physarum rigidum (plasmodium). They can recognize an encounter as self or non-self and decide to fuse (a) or avoid (b) allogeneic individuals.



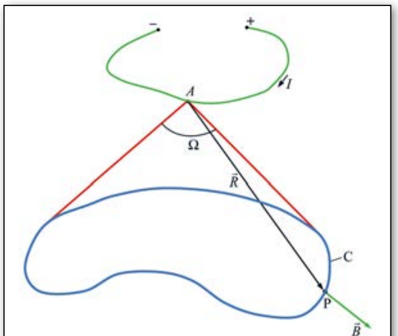
In our study, we clarified that this behaviour, *i.e.*, non-contact allorecognition, occurs with the spread of slime sheath, which is hyaline mucus secreted by plasmodium. Plasmodium diffuses slime sheath as an information substance of "self" to the environment, and it can be called "self-extension". ■

▌ **M. Masui, S. Satoh** and **K. Seto,**
'Allorecognition behaviour of slime mold plasmodium—Physarum rigidum slime sheath-mediated self-extension model', *J. Phys. D: Appl. Phys.* **51**, 284001 (2018)

MATHEMATICAL PHYSICS

Scoping magnetic fields out for prevention

A new study reveals how to best evaluate the circulation of magnetic fields around closed loops



▲ Magnetic field generated by a current (I) through a finite wire.

Concerns about the effects of magnetic fields on human health require careful monitoring of our exposure to them. Mandatory exposure limits have been defined for electric and hybrid vehicle architectures, in domestic and work environments, or simply to shelter sensitive devices from unintended sources of magnetic disturbance. In a new study published recently, the authors develop a method for deriving an approximate value of the circulation around a loop of the magnetic field generated by the flow of electric current in an arbitrarily-shaped wire of a given length. In this study, the authors set out to adapt Biot-Savart's law, which describes the magnetic field generated by finite wires, to evaluate the circulation of such fields around a closed path or loop. This led the authors to a mathematical formula that, as the finite wire thickness decreases to zero, becomes identical to one of their recent research results expressing the magnetic field circulation as a function of the wire current and of the solid angles between the circulation path and each of the conducting wire's endpoints. ■

▌ **J. M. Ferreira** and **J. Anacleto,**
'The magnetic field circulation counterpart to Biot-Savart's law', *Eur. Phys. J. Plus* **133**, 234 (2018)

SPECIAL ISSUE
PHYSICS AND ITS CURRENT AND FUTURE APPLICATIONS

Christophe Rossel and Markus Nordberg, Guest Co-editors – DOI: https://doi.org/10.1051/epn/2018501

The importance of scientific research and innovation to the development of our economy is a well-established fact. A study made in 2013 for the EPS by the Centre for Economics and Business Research (Cebr) assessed the value generated by physics-based industries to the economic prosperity of Europe. A new report will update this study with a more recent analysis over the 2011-2016 period for the 28 EU countries including also Iceland, Norway and Switzerland.

The aim of this EPN focus issue is to present a few topics where physics has and will continue to contribute to the development of new technologies and applications. The choice of the 6 articles is somewhat subjective and certainly doesn't cover the whole spectrum of scientific research but it should give the reader a good flavour of the actual important trends.

The first contribution addresses the role of materials science in our modern society confronted with grand challenges such as the global population growth or climate change. The authors discuss how scientists and urban planners need to work together to design materials for smarter and more energy efficient homes, and how research on new materials can provide low-carbon, low-consumption solutions in energy, transportation, consumer electronics, or healthcare issues. The second article entitled 'from classical optics to nanophotonics' shows how the development on micro- and nanoelectronics makes it possible to control both spectral and spatial properties of light by using materials with well-defined 2D or 3D structures. Some recent advances in nanophotonics applications are presented, demonstrating the impressive impact of this field on novel information and communication techniques. The semiconductor industry is experiencing a paradigm shift. For years microelectronics has become more and more performant thanks to the progress in the design and fabrication of basic components such as the transistor. But today scaling alone cannot feed the growing needs for mobile and power electronics, automotive and healthcare applications. Further innovation will be needed, including new device concepts, new materials and system-level architectures with integrated functionalities. The authors of the third paper describe also the emergence of new disruptive neuromorphic computing architectures where memory and processing units are co-located, and working in a similar way to the synaptic and neuronal functions in the brain. This work introduces us directly to another topic, namely Artificial Intelligence with its spectacular breakthroughs in the last ten years and its future impact on various sectors of human activities. The author discusses how AI technologies are likely to reshape completely many aspects of our society and presents a few examples. But, as he claims, AI will affect our lives for the better and the worse, with machines being able to make decisions, but still being far from our human intelligence. Other emerging fields of interest in science are quantum computing, quantum communication, quantum simulation and quantum sensing and metrology. The European Quantum Flagship, which is a 10-year, 1 billion Euro initiative, is expected to bring quantum technologies from the lab to the market. In this fifth article, the authors describe the history of this initiative, the implementation of its governance and the start of the first funded research projects. Finally, last but not least, the sixth contribution explains how particle physics has played an important role in healthcare since the advent of radiation-based medicine after the discovery of X-rays and radioactivity. Today, state-of-the-art techniques derived from particle accelerators, detectors and computing tools are routinely used in clinical practice and for far-reaching medical and biomedical research.

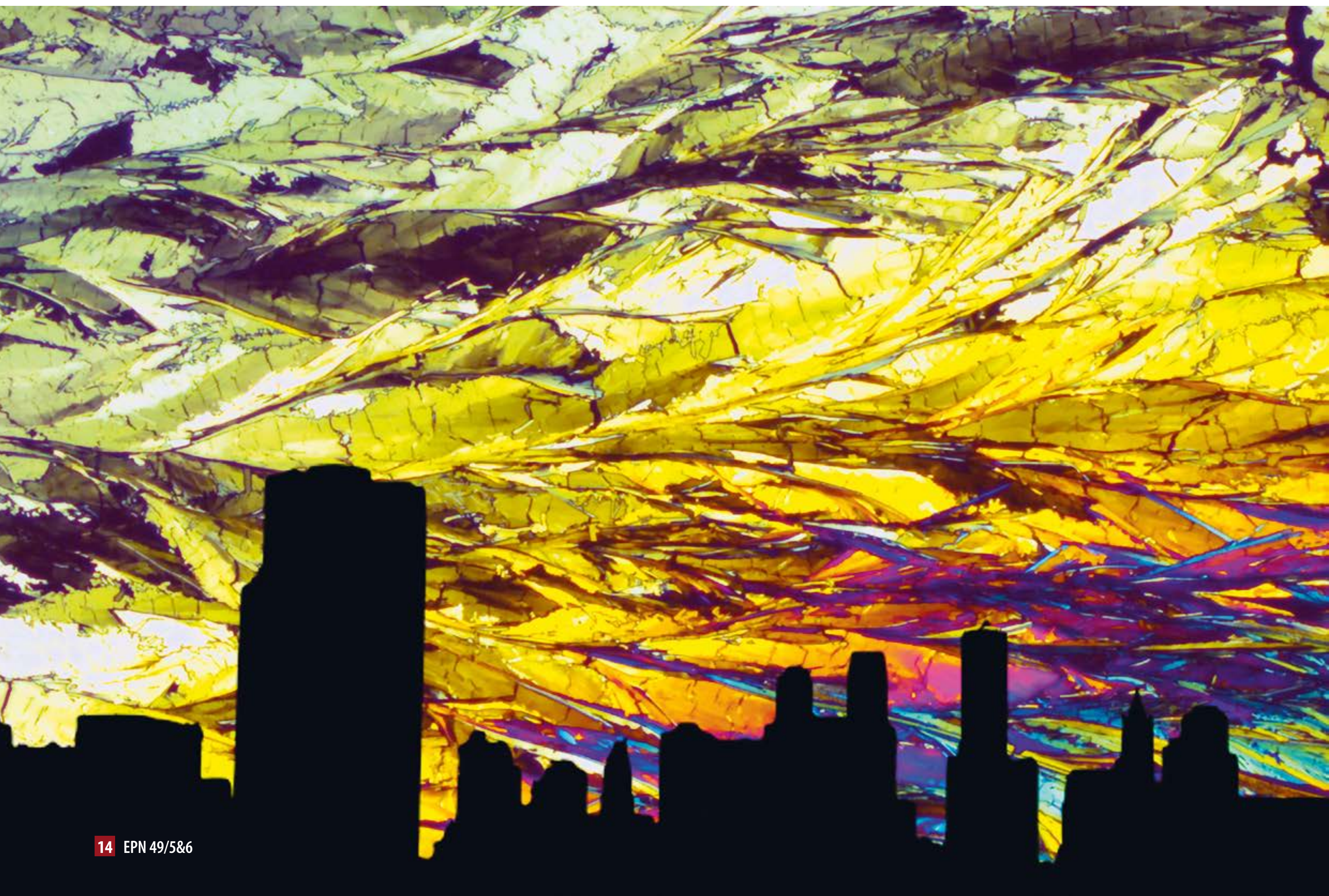
We wish you an enjoyable and interesting reading.

MATERIALS FOR THE 21ST CENTURY

Jessica Wade, Sebastian Wood – DOI: https://doi.org/10.1051/epn/2018502
Department of Physics, Imperial College London, Prince Consort Road, SW7 2BW

The combined challenges of growing populations, climate change and increasing scarcity of raw materials is driving innovation in materials and design. The motivation to innovate comes from the economic impact of not doing so, as well as consumer demand, with mature customers actively seeking out more environmentally sustainable solutions.

Materials science is at the centre of modern society; essential for scientific and industrial advancement. This article considers the impact of a growing (and developing) global population and climate change on materials design and manufacture. The global population is expected to reach 9.6 billion by 2050, with an estimated 90 % of people living in cities. It is essential that scientists and urban planners work together to design and protect materials, or this urban growth will result in increased pollution, infrastructural congestion and socioeconomic inequality. In October 2018, the UN Intergovernmental Panel on Climate Change warned we must make 'unprecedented changes' to reach the target of less than 2 °C of warming. Alongside constructing smarter and more energy efficient homes, new materials will also be required for transportation and healthcare.



Climate change is poised to become the ultimate design challenge for civil engineers and architects. It will test the way we design, construct, inhabit and maintain the built environment. Not only will the cities of the future have to be less energy and carbon intensive, but they will also need to handle hotter summers, warmer winters, and an increasing occurrence of 'freak' weather conditions, whilst also catering for rapidly growing populations. As well as considering a changing climate in the design of new materials for construction, there is also increasing pressure to reconsider contemporary building materials – many of which perform poorly even today. At the same time, scientists are developing materials for sustainable and renewable energy production, efficient transmission, and storage. Research into new materials can provide low-carbon, low-consumption development solutions. The challenge is providing better performance than existing technologies, with lower environmental costs, at an affordable price.

Energy production

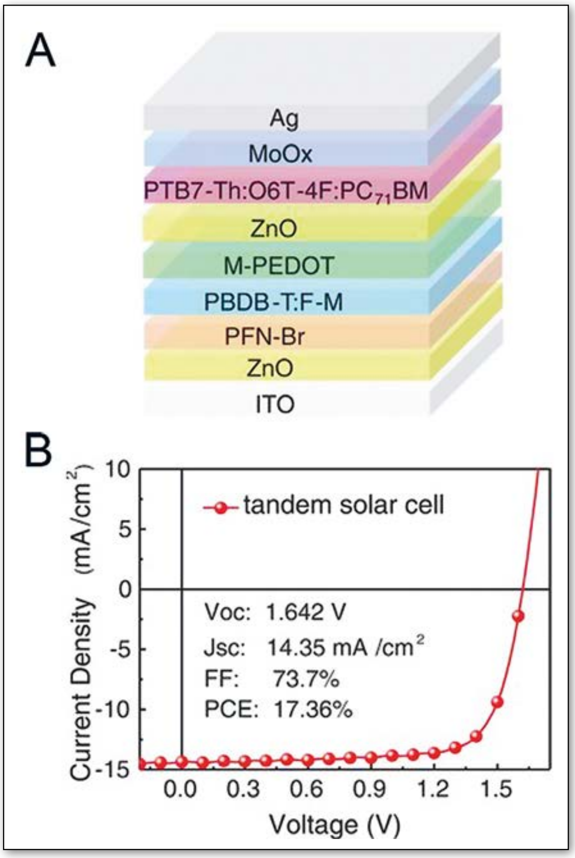
The stretchability, softness and low-cost processing of organic (carbon-based) materials have attracted considerable attention from researchers across the world. In particular, the class of electrically conducting and semiconducting conjugated polymers offers great promise for a wide range of electronic materials. In contrast to conventional (inorganic) electronic materials, the weak intermolecular bonding results in organic materials being soluble, meaning that they can be printed with relative ease. For almost four decades, they have been used in organic light emitting diodes (OLEDs), photovoltaic cells (OPVs) and transistors. OLEDs were the first organic devices to go to market, and can today be found in high-end mobile phones, digital cameras, laptops, televisions and lighting panels. Whilst conventional LEDs still use liquid crystalline filters with backlighting, individual pixels of organic materials emit their own light, resulting in higher energy efficiency, wide viewing angles, vivid colours and exceptional contrast. As of 2018, organic photovoltaics have achieved a remarkable efficiency of 17 % (Figure 1), thanks to the development of new materials and better control over heterojunction structure. This was achieved by combining low and high band-gap materials in a tandem structure.[1] Energy-efficient electrochromic windows demonstrated by the University of Princeton reduce the transmission of sunlight on hot days to keep the rooms inside cool and let heat (near-IR radiation) in on cold days.[2] The smart windows contain transparent solar cells that absorb near-UV light, generating electricity to change the windows colour. Hybrid organic-inorganic perovskite based materials boast extraordinary light absorption and charge-carrier lifetime, and have received significant academic and industry interest. In just a few years, perovskite based solar cell efficiencies have increased from 4 % to 23 %, making them competitive with silicon in terms of performance. The design space for next generation materials is enormous, and chemical synthesis is costly and time-consuming. Chemists are now partnering with computer scientists to combine quantum chemistry and artificial intelligence. The virtual molecules are evaluated for their potential as new materials, with the results being fed back into the platform to inform the next generation.

Construction

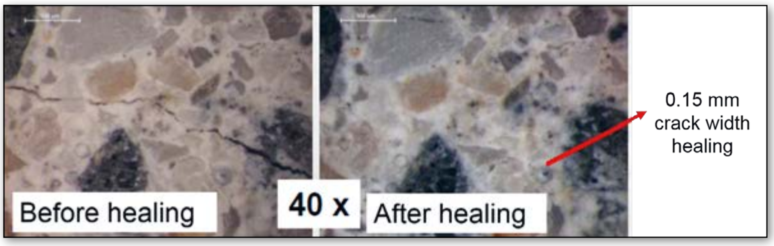
Concrete is the most commonly produced and consumed material on earth and makes up 70 % of Europe's infrastructure. It isn't very durable and so maintenance is expensive – an estimated € 6 billion per year – and producing concrete results in up to 12 % of the world's carbon dioxide emissions. In 2015, Jonkers *et al.* at Delft University, demonstrated Basilisk, a self-healing concrete using limestone-producing bacteria and calcium lactate.[3] The bacteria lie dormant for many years, waking up when the concrete is damaged and water starts to seep through the cracks (Figure 2). When this happens, the bacteria start to feed on calcium lactate, which converts it to insoluble limestone that seals cracks.

Infrastructure

Air-conditioning units account for 10 % of the global energy consumption and often involve coolants that deplete the ozone layer or contribute to the greenhouse effect. The need for air-conditioning can be reduced by simply painting buildings with white reflective paint to



◂ **FIG. 1:** A: Device architecture of record-breaking tandem solar cell comprising multiple layers of organic and inorganic materials. B: Current-voltage characteristic of solar cell under 1 Sun illumination showing power conversion efficiency (PCE) of 17.36 %. From [1]



▲FIG. 2: Optical micrograph images of self-healing bacterial concrete sample showing a crack with width 0.15 mm, before (left) and after (right) healing. From https://www.raeng.org.uk/publications/other/bioconcrete-a-novel-bio-based-material

keep them cool, however this strategy is limited by the poor broadband reflectiveness of the paint. Researchers at Columbia University have combined a transparent polymer paint with nanoscale air pores, in order to give a white surface that strongly scatters all wavelengths of light (Figure 3).[4] Thin films of a polymer, poly(vinylidene fluoride-co-hexafluoropropene), are prepared from a blend of acetone and water, which creates a series of droplets and microdroplets. As the droplets evaporate, a coating forms that can result in a 6 °C cooling compared to room temperature. Advances like this seem small in the wider context of global energy use, so it's important to also consider the energy efficiency of whole buildings. The University of Swansea has developed the view of 'buildings as power stations', through their SPECIFIC initiative (Figure 4), combining full-scale technologies such as photovoltaics, thermoelectric generation, low-cost batteries and heat storage. This comprehensive view of building efficiency also encompasses the use of waste heat, which they convert back into useful electricity through tin selenide themoelectric generators.[5]

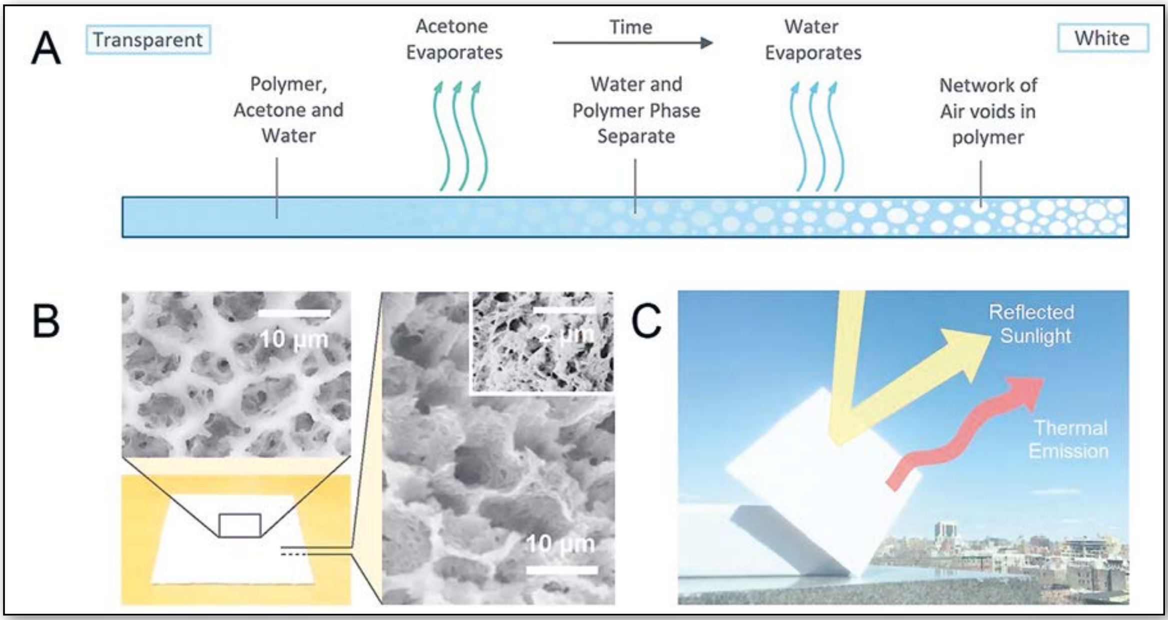
Transport infrastructure also has a key role to play in sustainable development, and the aerospace sector continues to explore significant advances in materials design. Whilst aluminium once made up 70 % of aeroplanes, titanium, carbon fibre, ceramic-matrix composites and heat-resistant alloys are offering improved efficiency and fuel economy. Ceramic-matrix composites that are reinforced with silicon carbide are low weight and hard, as well as being incredibly thermally and chemically stable. They are one of the fastest growing trends in the aviation industry, with their use in aircraft engines projected to double in the next five years. Carbon fibre is already the main material in the fuselages of the Airbus A350 and the Boeing 787.

Supply and demand

As globalisation improves living standards around the world, we are at risk of running out of the raw materials that modern life relies on. Rare-earth metals, much coveted for their specific properties, enable high-performance electronic devices with greater energy efficiency. This demand is resulting in the politicisation of mining rare-earths, with prices dependent on trade agreements, scarcity, and political maneuverings, but there is also a high environmental cost to these activities.

Storage

Lithium-ion (Li-ion) batteries have powered the start of the 21st century, however, we're reaching the limit of their efficiency and they don't age well. Supercapacitors, the energy storage sensation that powers Serbia's e-buses, store their energy in an electric field - free from chemical reactions, they do not suffer from the degradation that plagues Li-ion batteries. On their own, supercapacitors can't store energy for very long. Several energy storage startups have turned to the wonder material of the 21st century: graphene. Carbon-based supercapacitors offer high capacity energy storage and short charging times in battery technology, with researchers trying to identify the perfect nanostructures. Whilst it is hard not to get carried away with all of the promises of lightweight electric supercars, it is important to remember that the production of graphene still requires harsh chemicals or expensive



▸FIG. 3: A: Formation of hierarchically porous polymer coating through phase inversion process. B: Micrographs of top surface and cross-section of porous polymer coating. C: Schematic showing high reflectance and thermal emission from coating resulting in cooling effect. From [4]

▲ **FIG. 4:** Schematic illustrating the 'buildings as power stations' concept where a residential building generates, stores, and releases energy. From specific.eu.com

processes, and there are still quality control challenges. The Graphene Flagship project is Europe's largest ever research initiative, which indicates both the perceived benefit of graphene in industry, but also the enormous challenges that must first be addressed.

Future healthcare

Thanks to the inherent softness of the materials they are made from, organic electronic devices can conform to human tissue or even provide conducting scaffolds between cells. They can transport electrons, holes and ions – which makes them compatible with conventional solid-state electronics as well as biological systems, as a result they are well-suited for applications in biological sensors, implanted electrodes, drug delivery systems and artificial muscles. One of the most versatile conjugated materials for bioelectronics is poly(3,4-ethylenedioxythiophene) (PEDOT), which can be printed from an aqueous dispersion making it compatible with low-cost, stretchable large area devices.

As additive printing becomes more commonplace in manufacture it will revolutionise manufacturing, reducing materials waste and increasing the scope for personalisation. It will shorten supply chains, make work more collaborative and improve repair and maintenance. Manufactures can create innovative structures using layer-by-layer growth, as well as recycling plastic waste for new applications.[6]

Plastics

We manufacture over 300 million tonnes of plastic a year. Only 14 % of plastic bottles being recycled and, as consumers become more environmentally aware, there is increased concern about the long-term impact of plastic on wildlife. Plastic bans have been announced in Chile, Botswana, Peru and India. In 2018 LEGO partnered with the World Wildlife Foundation to create a range of sustainable bricks made from plant-based materials. But these plant-based plastics are not biodegradable, and their production is still environmentally intensive. Serendipity has played a key role in a number of great scientific breakthroughs, and the accidental discovery, this year, of enzymes that can break down plastic might yet prove to be the key to unlocking the problem of plastic recycling.[7]

Conclusion

At a recent symposium on printed electronics, a speaker from a large, far-eastern manufacturer of consumer electronics was asked whether they considered recyclability in the development of new products – their answer was an un-nuanced 'no'. Whilst that attitude is by no means universal, one can't help feeling that those organisations which are most sustainability aware are generally smaller and will struggle in a global market with less environmentally-driven competitors. This serves as an important reminder that sustainable development is a global issue, and so requires a global solution. ■

About the Authors

Jessica Wade is a postdoctoral research associate in the Department of Physics and Centre for Plastic Electronics at Imperial College London, creating chiral molecular structures as the active layer for electronic devices. She is involved with several projects to improve diversity within science, working closely with the Institute of Physics and Women's Engineering Society.

Sebastian Wood is a Visiting Researcher at Imperial College London and a Senior Research Scientist based at the National Physical Laboratory (NPL) working in the field of printed and emerging electronic technologies. NPL is positioned at the interface between government, academia, and industry with the role of supporting UK industry and quality of life through measurement science and standardisation.

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FROM CLASSICAL OPTICS TO NANOPHOTONICS

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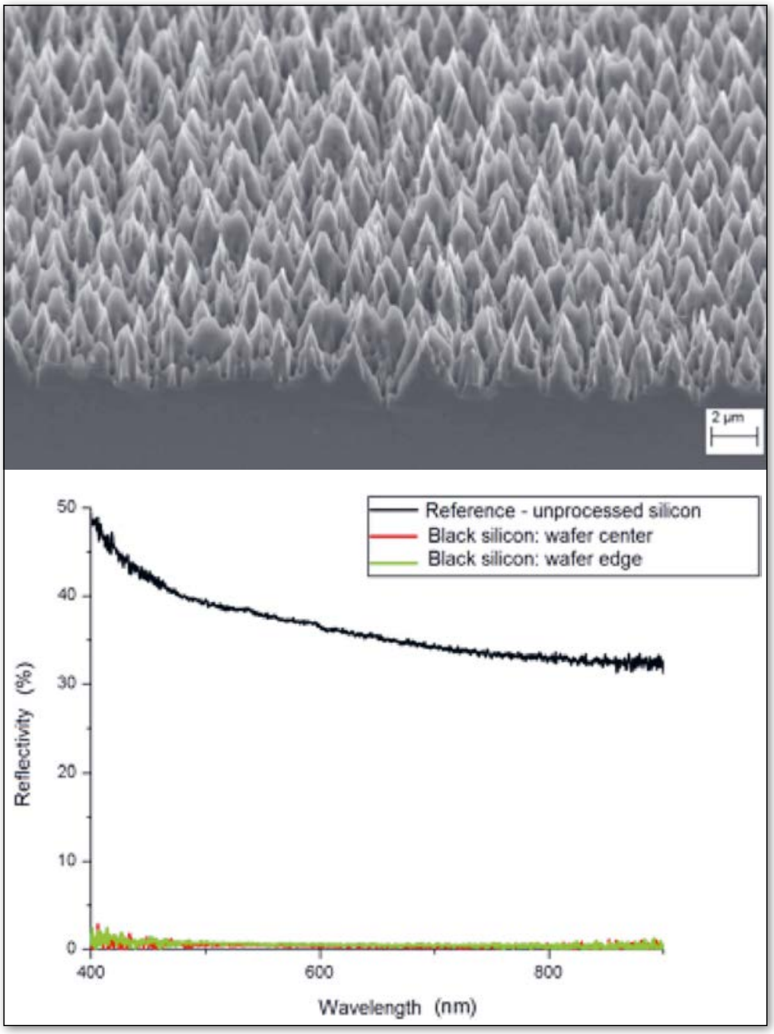
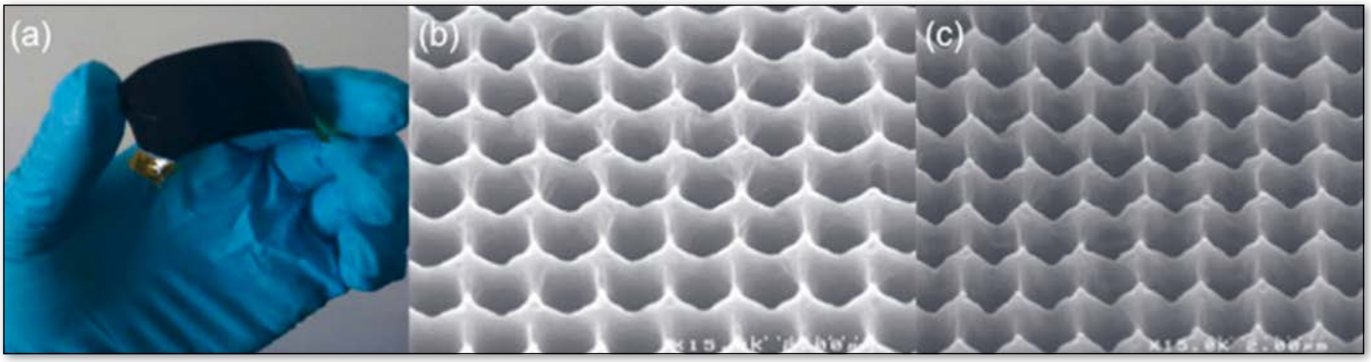
Nanophotonics is a very large and rich young field experienting a very rapid development worldwide. It is based on the study of light/matter interaction at low dimension. Several books are dedicated to different aspects of nanophotonics [1].

A long list of philosophers/scientists allowed understanding the nature of light and of its interaction with matter, the development of optical instruments and of lasers. We can briefly cited some of them who are known to bring important steps in these progresses. By trying to explain vision, Greek like Euclid (300 B.C.), Hero (60 A.D.), Ptolemy (120 A. D.) and then the Arab scientist Alhazen (1000 A.D.) described light propagation, till 13th century Italian glassworkers made lenses that were used for spectacles. Kepler (1604) decribed the propagation of light through lenses with geometrical optics, and he applied his studies to the eye. Lippershey invented the telescope soon before Galileo (1609) produced his own telescope and started to study planets and moons. Snell, Descartes(~1637), Newton (~1704) , Grimaldi (~1665), Huygens (~1690), Euler (1746), Gauss (~1800), Young (1803), Fraunhofer(1814), Fresnel (1819) , Abbe (1887)... allowed to deepen the understanding of classical optics by extending the notion of rays to the notion of waves. This has led to the development of new instruments and to define their resolution limit because of diffraction. Maxwell (1873) derived a set of four famous equations based on the electromagnetic nature of light waves to model light propagation. An important revolution started with Planck (1900) describing the blackbody radiation by assuming that it could only change as an integer number of small quanta. Einstein (1905) was able to explain the photoelectric effect based on these quanta of light named photons by Lewis (1926). In the sixties Gould, Townes, Schawlow, Maiman, Basov, Prokhorov were the pioneers of laser...

With the steady development of microelectronics and now of nanoelectronics, the question of developing very small optical components and systems arises. The main problem was first to cross the barrier of diffraction limit. Progresses in photolithography are obtained by using EUV (Exteme ultraviolet) and immersed optics to reduce the Critical Dimension, still dealing with difffraction. Quite early, in the middle of the twentieth century, materials with dimension smaller than the wavelength were already studied to make optical coatings which are used to control the spectral distribution of light and this is still a very active field of research with a wide range of applications [2]. 1D gratings were used to control the spatial distribution of



▾ FIG 1: (a) SEM image of Black Silicon surface obtained by cryogenic process. (b) Cryogenic plasma process black silicon reflectivity compared with unprocessed silicon. [10]



▲FIG 2: (a) Photograph of the optical metafilter. (b) Top and (c) tilted views from SEM images of the tungsten inverted cone gratings.[11]

light. These components are based on interferences or diffraction. Most of optical thin films exhibit naturally a complex nanostructure, in particular a columnar structure when deposited by conventional thermal evaporation. This structure induces anisotropy . By acting on the deposition conditions thin films can be sculptured (STF) to control light polarization [3]. Surface roughness induces light scattering. In some extend, the spatial distribution of the scattered light can be shaped by controlling the roughness statistic [4]. we will see later that surface micro/nanostructures can be used to make broadband antireflection effect on silicon.

With technical progresses it now becomes possible to consider controlling both spectral and spatial properties of light by using materials with defined 2D or 3D structures. This very rich field of photonic crystals (PCs), still in development, finds already numerous applications such as chemical and biological sensors, solar light harnessing , broadband optical filters, controlled light emission, very small integrated optical circuits, low threshold lasers, interconnections... The optical density of state and the band dispersion can be engineered with PCs by using Bloch functions and band diagrams as in electronics [5]. It is then possible to control the permittivity and the permeability of matter by mixing several materials at small dimensions. Such metamaterials can exhibit effective refractive index not readily available in nature such as negative or nul effective index. They are used to slow light, to transform a gaussian beam in a plane wave, to make flat lenses, to perform high resolution imaging, cloaking, more generally to structure light. They can also be designed to engineer radiative decay or to exhibit functions inspired by quantum physics. Photonic Floquet topological insulators [6] can be obtained; optical vortices can be generated giving an orbital angular momentum to photons.

Another field of nanophotonics is based on the use of evanescent waves. As example, Scanning Near field Optical Microscope uses evanescent waves collected by a tapered optical fibre to make a high resolution image of a surface lightened in total reflection from below.

The optical properties of low dimensional materials get a better understanding since a few years. The permittivity and the permeability of materials depends on phenomena at such small scale. The susceptibility is coming from local oscillators. In classical physics, atoms and molecules in dielectrics can be seen as dipoles with resonant frequencies. Absorption bands are centered on these frequencies. Generally light interaction with matter takes place on a length in the order of the wavelength. It concerns a large number of atoms or molecules. The response of the matter is then an incoherent sum of the individual responses and the absorption band is broad (inhomogeneous broadening). In a mixture of matter at dimension smaller than the wavelength the effective permittivity can be obtained by the effective medium theory. When the matter is in smaller dimension, like in nanocrystals of dimension less than about 10nm, the local oscillators give a coherent response leading to much narrower absorption bands.

On the quantum physics point of view, the optical properties of matter depends on the discretise electron energy levels in the atoms and on phonon levels in molecules. The oscillators are the dipoles composed of the nuclear and a peripherial electron in case of atoms and of discrete vibrational/rotational modes in molecules. When a material limited in 1D, 2D or 3D is surrounded by a material in which electrons have a higher potential, the electron are confined and their wavefunction may exhibit resonances, like a particle-in-a-box or an electromagnetic wave in a microcavity. The electron energy levels are then discrete, as in an atom. It is necessary for this that the dimensions are limited to less than the thermal de Broglie wavelength of a few tenths of nanometers or less, depending on the wavelength and the semiconductor concerned. These materials are called quantum wells, quantum wires and quantum dots.

Not only the absorption spectra and the complex refractive indices are dependant on the size of the structures but also their emission spectra. Some quantum dots are now well known to exhibit a size dependant photoemission wavelengh with quantum yield which can be close to 100%.

Quantum wells are widely used to make microlasers useful for numerous applications, including telecommunications. Functionalized Quantum dots (QD) can be used as tags and have more and more importance in imagery for biology and health. QDs are also used to make single photon source. They can be embedded in thin films for down conversion of solar energy or for backlighting in colour enhanced flat TV (QDTV).

It is now well known that a surface wave called plasmon polariton can be excited with an evanescent optical wave at the surface separating a metal and a dielectric. For metallic nanoparticles (NPs) in the order of some ten nanometers a plasmonic resonance can be excited with a propagating optical wave having the matched wavelength. The optical field can then be strongly localized around the NPs. This is exploited in particular to make sensors, to perform enhanced Raman scattering , to have local heating, single particle detection [7] *etc.*

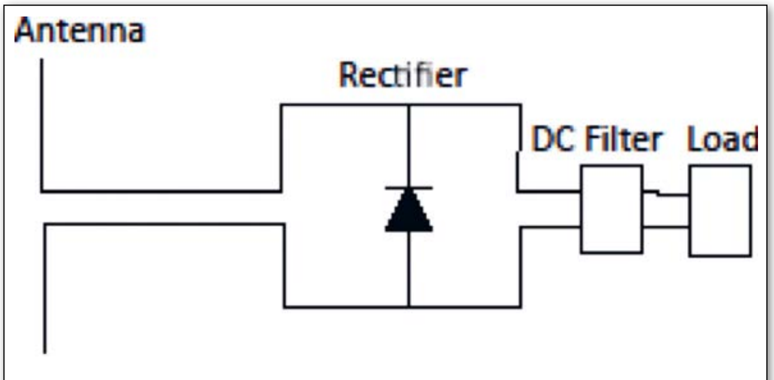
Metallic nanostructures can also be seen as optical antennas localizating the optical field. Coupled to a molecular diode they can be used to rectify the optical field (rectenna).

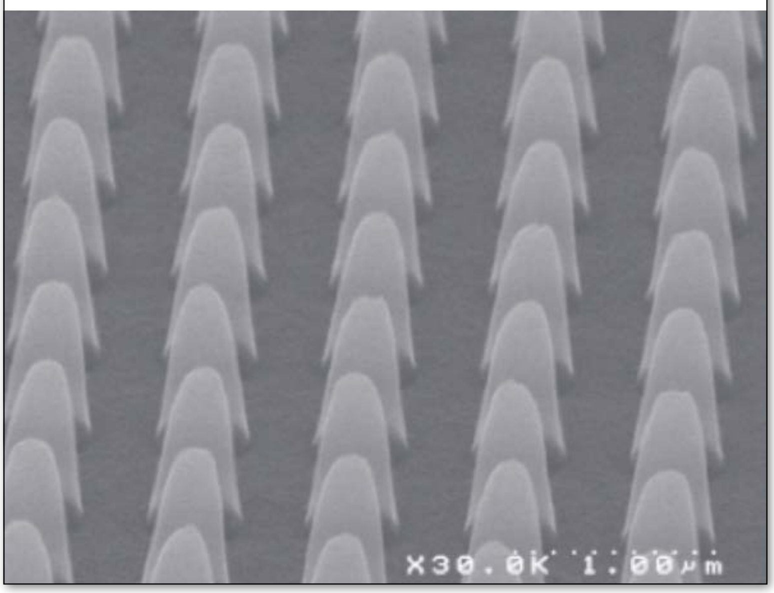
Some recent advances in nanophotonics applications are illustrated below.

Some examples of application of nanophotonics

Black Silicon

The silicon surface can be structured down to scales of some tens to some hundred of nanometers, on the order of the micron height, either on a periodic frame to get anti-reflective effects as efficient as those obtained with optical thin-films, either randomly to get what is called black Silicon (BS) [4,8,9]. The BS (see figures 1a: surface of BS and 1b: R versus λ) allows absorbing light very efficiently by trapping the photons in nanostructures. It is used in particular to realize photodetectors showing increased sensitivities in the Near InfraRed but also to improve the conversion efficiency of solar cells. The BS can be obtained by engraving the silicon surface using laser shooting through a sulphur vapour [8], by cryogenic etching, but also by room-temperature reactive ion etching (RIE) using appropriate process parameters [10].





▼FIG 3: (a) Schematic of a rectenna. (b) SEM image of nanopyramids obtained by nano-imprint lithography. [16]

Metafilters

It is also possible to combine effects of 3D structuring of flexible materials with thin coatings in order to realized more complex optical filtering functions [11]. For example, the figure 2 below shows an optical metafilter realized by NanoImprint Lithography (NIL) of a PVDF (Polyvinylidene fluoride) film covered with a thin layer of tungsten. Absorption of visible light and near IR is almost complete with the nanostructuring and the tungsten absorption, so the reflectance is close to 0, while in the Infrared reflectance is maximum close to 100% and therefore the coating emissivity is close to 0. This flexible metafilter finds applications in the field of coatings for optical stealth but also for thermophotovoltaics.

Optical antennae

If we were able to associate an optical nanoantenne, highly resonant in some wavelength range for example using plasmonic effects or gap plasmons, with diodes to rectify an alternating current at very high frequency to get a continuous current, one can imagine going beyond the photovoltaic effect and get a direct conversion of incident photons into a flow of electrons under the form of a Direct Current (DC). In doing so, it is theoretically possible to convert 44% of the photons of a spectral domain into current [12] as compared to the maximum theoretical efficiency of 33.2% achieved in a traditional single junction PV cell. These components, combining an antenna and a diode, are called rectenna for "rectifying antenna" (see schematic on figure 3a). It is possible to use Metal - Insulator - Metal (MIM) diodes [13] or even molecular diodes which rectifying properties are obtained by the asymmetry of the molecule for example with ferrocenyl alkane thiol, which ferrocenyl group is placed either on one side or the other of the molecule [14-16]. Figure 3b presents nanopyramids periodically positioned in order to be a set of resonant antennae. The resonant wavelengths are imposed by the sizes of the nanopyramids and by their periodicity. The molecular diodes are directly self-assembled on the nanopyramid surface.

Conclusion

There are many other important aspects of nanophotonics concerning high resolution microscopy, microparticle manipulations, structured light generation, quantum optics, non linear optics...

Even though many applications with impressive impact on information and communication society emerged, nanophotonics is still in its enfancy. It requires to consider jointly electromagnetic theory, condensed matter physics and quantum physics. Nanophotonics is more and more intimately associated with nanoelectronics.

Thanks to the rapid advances in nano technologies one can expect in the near future the development of applications, today unimaginable, by using coupled QDs to make artificial molecules, coupled metallic NPs, structures at the molecular or atomic level *etc.* with exciting fundamental problems to be solved, going closer to the intimate nature of light, matter and particles. ■

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Gerard Berginc received his Dipl-Engineer Physicist degree from Ecole Centrale de Marseille and his doctorate in theoretical physics. Currently, he is Chief Scientist at Thales Optronique and president of OPTITEC, the French photonics and image cluster. His research activities include fundamental electromagnetic scattering phenomena in ordered and disordered media, coherent effects in random media, localization phenomena, and nanophotonics. He has authored more than 200 papers and communications and holds more than 80 patents. He is a fellow member of the Electromagnetics Academy.

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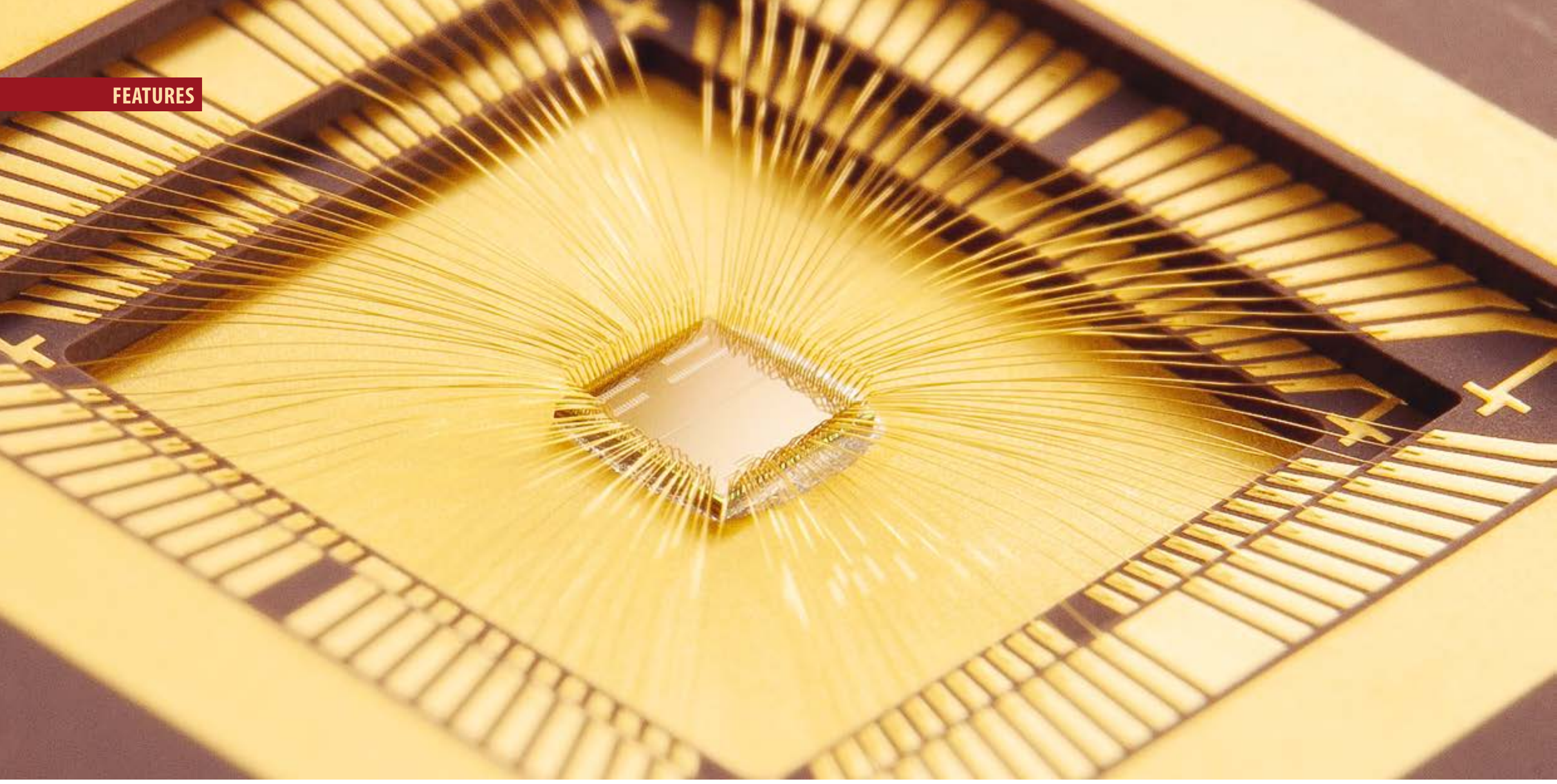

SCALING WITHOUT SCALING

A PARADIGM SHIFT IN THE SEMICONDUCTOR INDUSTRY

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Microelectronics is as pervasive as it is invisible. It is however impacting every moment and aspect of our daily lives and has radically transformed all industries. Yet, this adventure began only about 60 years ago, with the first integrated circuits by J. Kilby and R. Noyce.

To become pervasive, being small and power efficient turned into the DNA of microelectronics. Scaling transistors has been the ultimate goal for many years, and allowed engineers to make circuits more complex, working at lower power, and cheaper to produce. This unique alignment of planets did last for 50 years.

Today, scaling alone cannot feed the growing needs for mobile and power electronics, automotive and healthcare applications to name a few. As an example, mobile electronics perfectly illustrates the burning challenges ahead of us: Being power efficient for better mobility, integrating functions to improve our mobile capacities and enabling cognitive technology for smart services. To support this evolution, the semiconductor industry needs disruptive concepts, from materials to devices and systems.

A winding road ahead for efficient logic

After four decades of pure geometrical scaling of Si CMOS technology, the semiconductor industry entered the 21st century with a new phase of scaling powered by material-driven innovations. Besides strained-Si and silicon-germanium, high-k gate dielectrics and metal-gates were introduced, as well as low-k dielectrics in the back-end-of-the-line or non-planar channels requiring conformal control of materials at the nanoscale. High-aspect ratio field effect transistors (FinFET) are today's CMOS standard technology envisioned until the 7 nm node [1]. They consist of a tall (≈ 50 nm) and thin (≈7 nm) channel of Si with a gate wrapped around it Fig. 1).They provide superior electrostatic control over the channel and superior channel perimeter per footprint compared to a planar transistor.

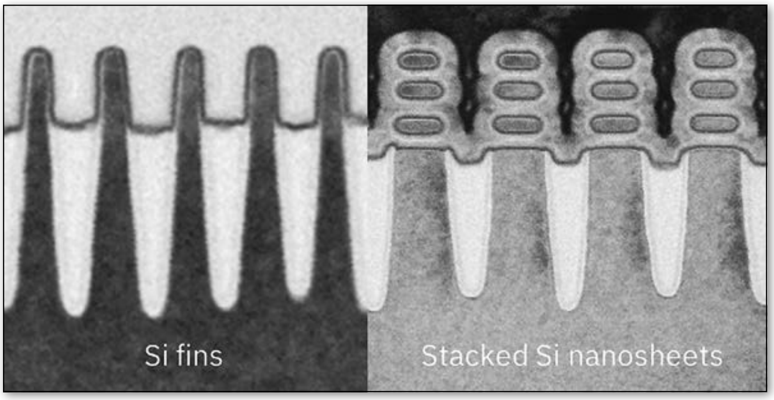
Beyond FinFETs, innovations on materials will keep being key drivers to continue improving the power vs performance vs density trade-off of CMOS technology. Near-term, fin-channels will evolve into stacked nanosheet channels [2]: sheets of semiconductors that are few nanometers thick and few tens of nanometers wide, stacked on top of each other to provide augmented channel perimeter per footprint and superior electrostatic control. These nanosheets are formed by epitaxy of crystalline superlattices, *e.g.*, Si/SiGe, that are patterned to form the width of the sheets. One of the two constituents is selectively removed (*e.g.*, SiGe) to leave suspended stacked nanosheets of Si. The ability to control the deposition and patterning of gate dielectric, gate metal, sidewall spacers in the tiny horizontal gaps between the sheets is an essential area where materials and process innovation will ensure that this new technology becomes a reality.

Further innovation will follow two main parallel routes intrinsically linked to the transistor performance and energy efficiency metrics at a given footprint: the amount of current that can be driven, and the on-state to off-state current ratio that can be achieved, for a certain operating supply voltage. First, increasing the drive current of transistors implies boosting the transport properties of the channel material, *e.g.*, by replacing Si in the channel by other materials which are intrinsically better such as germanium or III-V compound semiconductors. They allow carriers to travel faster but require a whole new set of innovations to tackle their epitaxy on Si, the formation of high-quality reliable gate dielectrics, the realization of ultra-low resistance contacts, and the mitigation of off-state leakage owing to their lower bandgap than Si. Tremendous progress in the past ten years has led to the several demonstrations of CMOS circuits on Si with indium gallium arsenide (InGaAs) and silicon germanium as channel materials for n- and p- transistors [3].

Second, novel device concepts leveraging material innovations are explored to increase the steepness on the off-to-on transition in a given gate voltage range. III-V heterostructures have been used to demonstrate transistors relying on tunneling current to achieve a 10-fold increase of the current for a record-low gate voltage increase of only 48 mV, well beyond the 60 mV limit given by Boltzmann statistics in standard transistors [4]. An alternative approach is to introduce a new family of materials that possess a phase transition giving rise to an abrupt change of their conductivity (*e.g.*, with insulator-metal phase transition materials such as VO_2) or polarization (*e.g.*, with ferroelectric materials such as $Hf(Zr)O_2$). Such phase transitions can be exploited in novel device concepts to drastically increase the steepness of the off-to-on switching, by introducing these materials as part of the gate dielectric or source/drain contacts.

Merging functionalities in the third dimension

Future efficient scaling of hardware will demand not only device-level but also system-level innovations, referring to the organization of transistors or blocks of transistors on the semiconductor die. In the hyper-scaling era, 2021 and beyond, system-level improvements are predicted to be one of the main drivers for technology [5]. Such improvements can enable not only density scaling, but also new functionalities, so-called "more than Moore" approaches. In this era, two interrelated system-level technologies are envisioned: 3D sequential and heterogeneous integration.

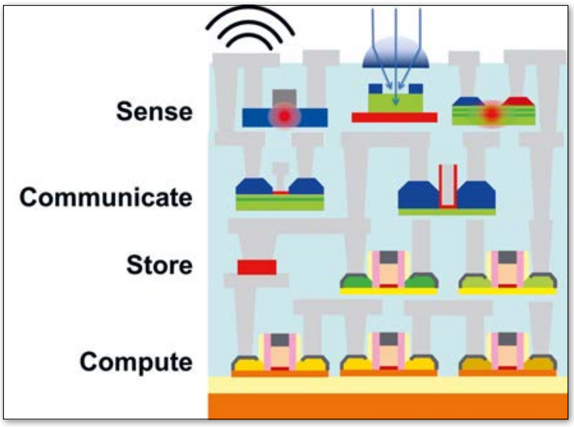


▲ **FIG. 1:** Transmission electron microscopy cross-sectional view along the gate (across the carrier transport direction) of FinFETs (left) and nanosheet-FETs. The fin channels are approximately 7 nm wide, while the 3-layer stacked nanosheets are approximately 5 nm thick.

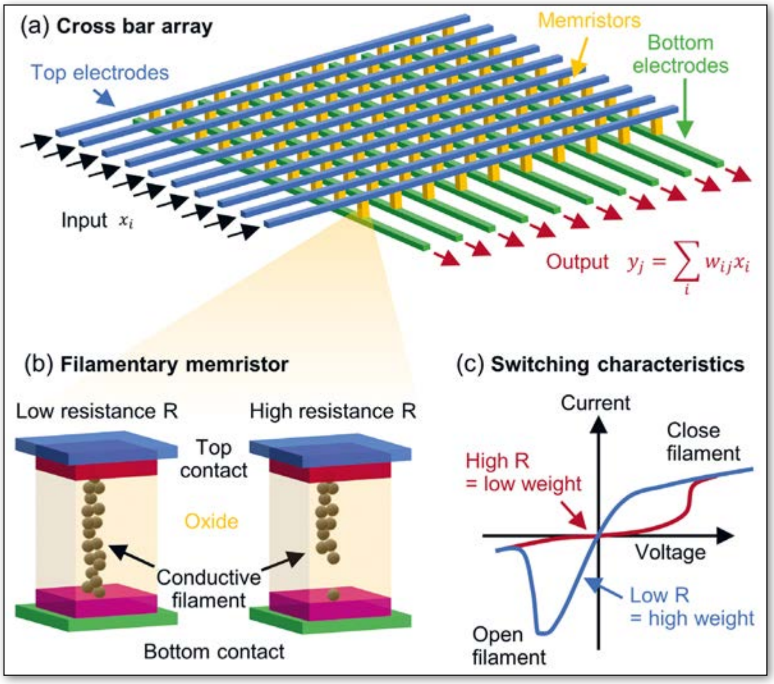
In 3D sequential integration multiple layers of transistors are fabricated *in situ* on top of each other (Fig. 2). This is different from 3D stacking packaging technologies utilizing through-silicon vias in that it offers transistor-level granularity of inter-level vias, resulting in two or three orders of magnitude higher via density, providing overall shorter wires, lower energy consumption and latency. 3D sequential integration will allow not only for subsequent stacking of Si CMOS layers, but also layers in different technologies – referred to as heterogeneous integration – such as III-V HEMTs, wide-band gap semiconductors and photonics, enabling high via densities between technologies which have hitherto required costly integration schemes in terms of both form-factor and energy consumption.

One of the key challenges facing these integration schemes is the combination of traditional Si CMOS fabrication processes with the additional thermal budget requirements of a subsequent layer. Due to the sensitivity of the gate oxide/channel interface in most MOSFET technologies, fabrication of layers beyond the first is typically limited to 450 °C, significantly reducing available process options. Moreover, when combining Si CMOS technology with non-standard materials, *e.g.* III-V compounds or photoactive materials such as $BaTiO_3$., process and material incompatibilities must be resolved.

Nevertheless, significant progress in system-level integration has been made in recent years, with approaches following two main routes. In the first route, subsequent active layers are grown *ex situ* and integrated on the 3D stack by direct wafer bonding, a transfer method whereby



◀ **FIG. 2:** Schematic figure showing how sequential 3D heterogeneous integration could merge different functionalities on the same chip. From the bottom up: Si CMOS, novel memories, III-V RF transistors and photoactive materials, all linked by electrical paths or vias (grey color).



▲ **FIG. 3: (a)** Illustration of array of memristors that can be used to perform a power-efficient, analog vector matrix multiplication based on Ohm's and Kirchhoff's laws. **(b)** Illustration of a filamentary memristor. Oxygen vacancies form a conductive path that can partially be switched. **(c)** Schematics of the IV characteristics of a memristor with two different resistance values.

two oxide-coated surfaces are placed in physical contact, adhering after thermalization. The strength of this approach is the flexibility of material choices – due to the ex situ growth, there is no concern of crystal lattice mismatch between stacked layers – manifested in a host of experimental demonstrators, ranging from GaN power switches to III-V high-frequency transistors and $BaTiO_3$ optical modulators, all integrated on silicon substrates [6,7].

In the alternative route, subsequent active layers are grown *in situ* using various selective epitaxial schemes, typically entailing the patterning of a growth mask as well as a method of maintaining low crystal defect density, such as aspect ratio trapping or confined epitaxial overgrowth. This approach promises reduced fabrication costs compared to direct wafer bonding, since it minimizes the quantity of grown material and omits the need for a costly non-Si growth substrate. It has been explored for instance using vertical nanowires, or growing templates in cavities, both to integrate III-V's on silicon [8,9].

Neuromorphic cores for the data-driven economy

While device and system-level innovations will continue to optimize computing systems, they will still fundamentally support the von Neumann architecture, where the processing unit, the control unit, and the external memory are three separate entities. In spite of being excellent at addressing a vast amount of computational problems, the von Neumann architecture has limitations to handle workloads related to big data processing and to train and execute neural networks. For algorithms such as deep learning, the memory-processor bottleneck strongly limits the computational task, because the system is busy exchanging data between the memory and the processor during two distinct phases. First, the training phase of the network utilizes a large set of examples to iteratively tune the network. Second, the pre-trained networks are executed in the inference phase to analyze new, unknown input data.

Novel types of non-von Neumann computing architectures are therefore in the focus of intense research, leading to new microprocessors operating either in the digital or in the analog domain. Memory and processing units are close or co-located, similar to the synaptic and neuronal functions in brains. They are often referred to as "brain-inspired" or "neuromorphic" computing.

Dedicated digital neuromorphic chips, such as TrueNorth (IBM) and Loihi (Intel Corp.), are based on standard CMOS processes and devices. In TrueNorth, packets are digitally routed between one million neurons, which are small, programmable logic units [10]. The synaptic weights are stored in SRAM (static random-access memory) cells distributed across the chip. This co-location of memory and processing units allows low-power inference tasks *e.g.* on image classification. To allow learning in such distributed networks, other approaches (*e.g.* SpiNNaker) connect many processors in large clusters and apply local, brain-inspired learning rules such as spike-time dependent plasticity (STDP).

Analog or mixed-analog approach to neuromorphic microprocessors are also proposed. Bio-inspired processors emulate the biological functions of neural networks such as synapses and neurons with analog electrical circuits designed in CMOS technology [11]. While the spiking neurons are analog circuits, synapses and intra- and inter-chip communication is typically done in the digital domain. In this domain, Europe is at the forefront of research (*e.g.* www.neuram3.eu, to which the cover image is related).

A second type of analog neuromorphic circuits rely on memristive materials as an analog local memory, motivated by the increase in the local density of synaptic weights. A simple exploitation of Ohm's and Kirchhoff's laws allow to multiply and accumulate values in the analog electrical domain. Assembled as cross-bar arrays (Fig. 3a), networks of memristors can then be applied to strongly accelerate both the inference and the training phase of neural networks by orders of magnitude compared to von Neumann-based hardware [12][13]. Having such analog accelerators depend on the discovery of novel materials with dedicated non-volatile resistive switching properties, such as low drift, a large number of analog states, and low-power and voltage operation. Great progress has been made using different mechanism such as phase-change in GeSbTe, filamentary conduction in dielectrics (Fig. 3b) such as HfO2, and domain switching in STT-MRAM (Spin-transfer torque magnetoresistive random-access memory) or ferroelectrics. However, no satisfying solution has been found yet. Novel circuit concepts might have to be co-developed to compensate for the imperfection of such analog devices [14]. Nevertheless, since its first description in the late 1980's, neuromorphic computing has made great progress in the last few years, One example of its potential use is the detection of correlations in weather forecast data as shown in Fig. 4 a&b.

Conclusions

Through these selected examples, we have shown that the end of geometrical scaling does not imply that microelectronics technologies are frozen and can only be incrementally optimized. The potential for innovation is remarkable, be it to improve the power efficiency of digital devices, to integrate functionalities in complex, yet compact systems, or to enable new type of computational tasks. At the core of these innovations, novel materials, devices and integration concepts will be the key elements that will make such a disruptive evolution happen. It will require different skills from scientists and engineers. First, a broadening of the technical horizon will be needed to include unusual materials and revolutionary devices as possible solutions. Moreover, there will be a clear demand for a holistic view on the technologies, leading to the co-development of materials, devices and system towards specialized chips. ■

About the Authors

Cezar B. Zota received the Ph.D. degree in electrical engineering from Lund University, Sweden, in 2017. Presently, he is a researcher at the IBM Research Zurich laboratory, Switzerland, where his research interests include high-frequency electronics and quantum computers.

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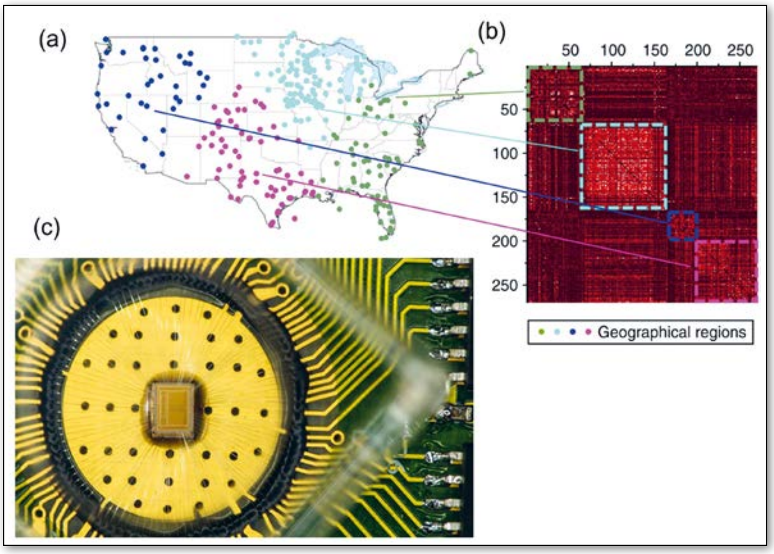
Stefan Abel studied nanoscale engineering at the University of Würzburg (Germany) and holds a PhD from the University of Grenoble (France). He has gathered strong knowledge in materials science related to oxide materials, integrated photonics, and neuromorphic computing. His work currently focuses on the research and development of new memristors, including their application for accelerating deep-learning algorithms and implementing non-von Neumann reservoir computing schemes.



▲ **FIG. 4: (a)** Rainfall data from different weather stations across the USA, **(b)** Covariance matrix mapped in an array of phase change memory (PCM) cells used for detecting correlations in the weather data. **(c)** Photograph of a neuromorphic PCM chip for cognitive data analysis [15].

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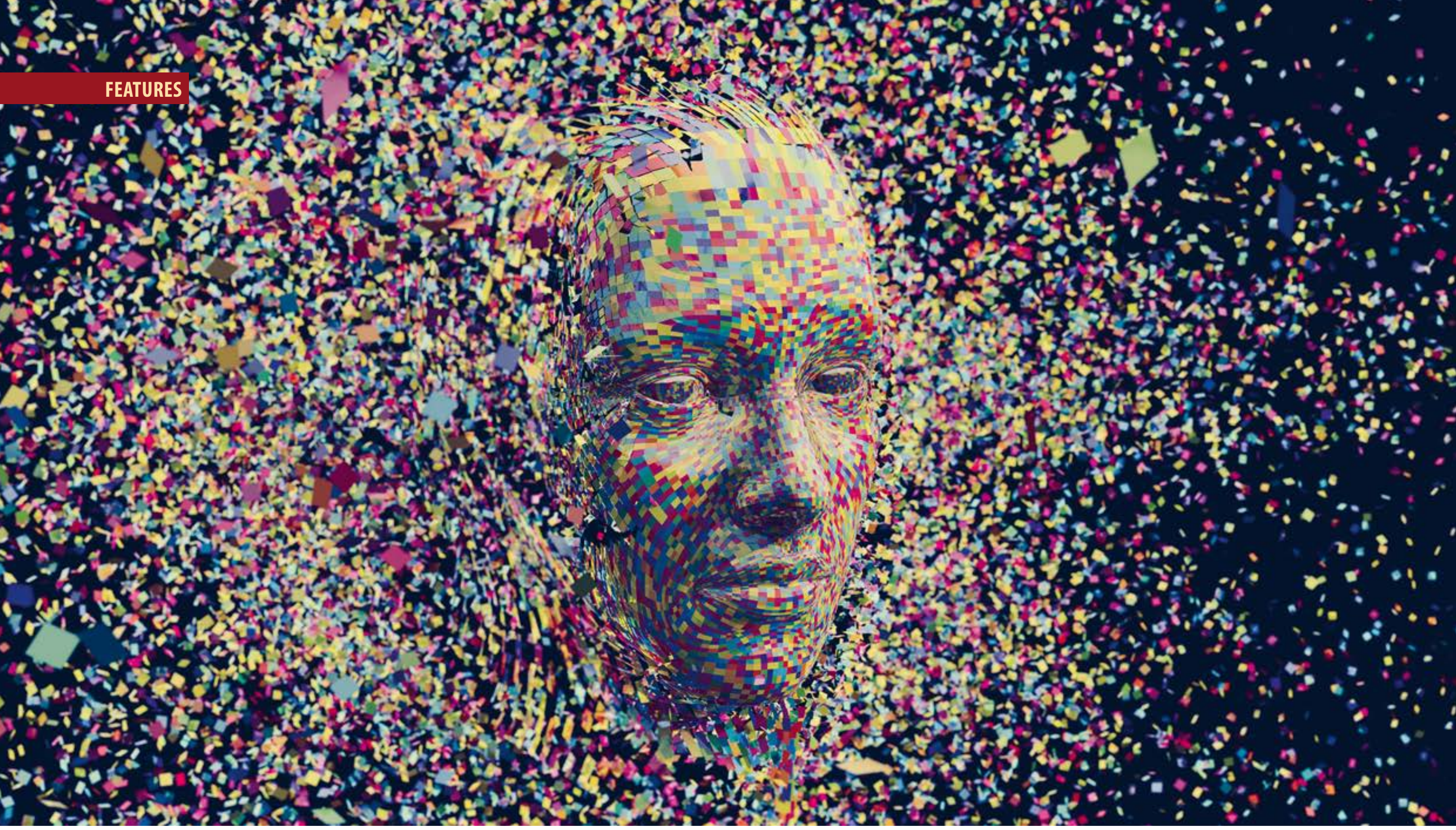

ARTIFICIAL INTELLIGENCE AND ITS LIMITS[1]

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By now, everybody should know that the recent progress of Artificial Intelligence (AI) is about to have a dramatic impact on many sectors of human activity. In the last ten years, we have seen spectacular breakthroughs on applications of AI, and much more is to come, but should we speak of "intelligence"?

After more than 50 years of existence – with results that did not really match the expectations-, AI has been recently revolutionized, notably through the use of "deep neural networks". Last year, a new algorithm managed to beat the world's best Go player. And now, we can automatically process images, segment them and provide a semantic description of their content. Moreover, voice recognition and automatic translation are progressing rapidly. Most importantly, algorithms are competing with the best professionals at analyzing skin cancer symptoms or detecting specific anomalies in radiology.

It is likely that many aspects of our society -including work organization- will be completely reshaped by these new technologies. Here are few examples among many others:

- Artificial vision and scene analysis are opening the road to autonomous cars and trucks. With 13 million heavy trucks on the EU roads, the impact of these changes in the next decades will be major.
- In the health sector, it is clear that AI will soon change medical practice. Algorithms to assist in medical diagnosis will be developed, starting with very specific problems, before gradually evolving towards more general issues. One can anticipate that the very activity of medical doctors will be deeply transformed.

[1] This text is an expanded version of a tribune that has appeared in EPN49/2

- In many sectors, the monitoring of individual behaviors and the feeding of algorithmic recommendation systems are currently revolutionizing commercial activities at large and relations to clients. They also change the basic rules and principles of personal and professional insurance.
- This surveillance could also be used to control individuals in totalitarian regimes.
- The possibility of autonomous-decision-making robots can open new sectors of commercial activities, but it can also lead to the terrifying perspective of warrior-robots.

Predicting the future is always difficult, and this is a challenge that AI is not yet ready to meet! AI-fanatics predict a radical change in our societies, the end of labor, a much better medicine leading to much longer lifetime, and some of them foresee the emergence of new machine-enhanced "human" beings. Others, the pessimistic ones, predict the end of civilization and the advent of a society in which robots will take power. As for the most cautious colleagues, they already envision major professional changes, and for the first time they consider changes which will not only affect low-wage activities, but mainly intermediate, and sometimes highly specialized jobs, in which repetitive tasks can be well-modelled and taught -such as radiology, law, software development, *etc.*

The rivalry in the leadership of AI high-technology has already started. This leadership is supposed to give the capacity of leading tomorrow's world (and perhaps of dominating it militarily). In the US, DARPA has just launched a $2 billion campaign, "AI next", that aims at exploring "how machines can acquire human-like communication and reasoning capabilities, with the ability to recognize new situations and environments and adapt to them". China has announced its ambition to become the world leader in AI, and invests several billion dollars in a AI technology research center in Beijing. The multinational companies - including the GAFAM[1] and BATX[2]- that currently dominate the data-AI world, are making major investments of tens of billions of dollars.

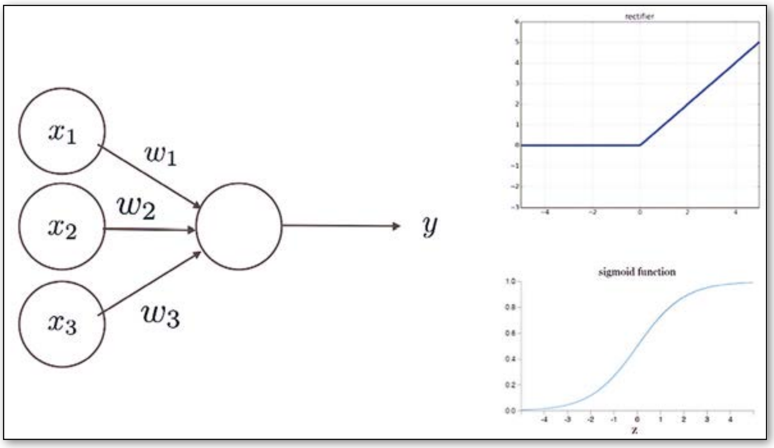
Having recognized the importance of this technological revolution (even if I am unable to predict it in its full depth), I would like to challenge the term "intelligence" in AI. This requires us to have a closer look at the way these new machines operate. Fortunately, it is rather easy.

The recent breakthrough is based on "machine learning", in which the machine is programmed to learn by itself, from examples. In deep networks, the machine is an artificial neural network, built from millions of elementary units, artificial "neurons", that somewhat mimic the activity of neurons in the brain (figure 1). Each neuron receives information from neurons in the previous layer, performs a simple computation (typically a weighted sum of the inputs, to which a threshold function is then applied) and in turn sends a few bits of information to the next layer. A modern "deep" network with hundreds of layers, analyzing an image, can contain hundreds of millions of adaptable parameters ruling these elementary computations (figure 2). They must be determined through supervised learning. For this we need a large "training set" of examples for which the teacher of the machine knows the answer.

Imagine for example that you want to teach a neural network how to distinguish whether a given picture shows a cat or a dog. Although a few-years old child easily answers this question, this remained for years a main challenge in computer vision, and it was only solved recently, by deep networks. A crucial ingredient is the availability of large database showing cats and dogs pictures. Then you design a layered network, where the input layer contains one neuron per pixel of the image, and the last layer has two neurons, one for "cat", one for "dog". The design of the rest of the network, how many layers, how many neurons in each layer, the nature of the non-linear function used by each neuron, is an art: there is no theory or model guiding the designer, but she uses quite a lot of accumulated experience, of know-how, and of trial-and-error. Experimental evidence indicates that, in practice, learning is easier when you use a 'deep network", one that contains many (tens or hundreds) intermediate layers.

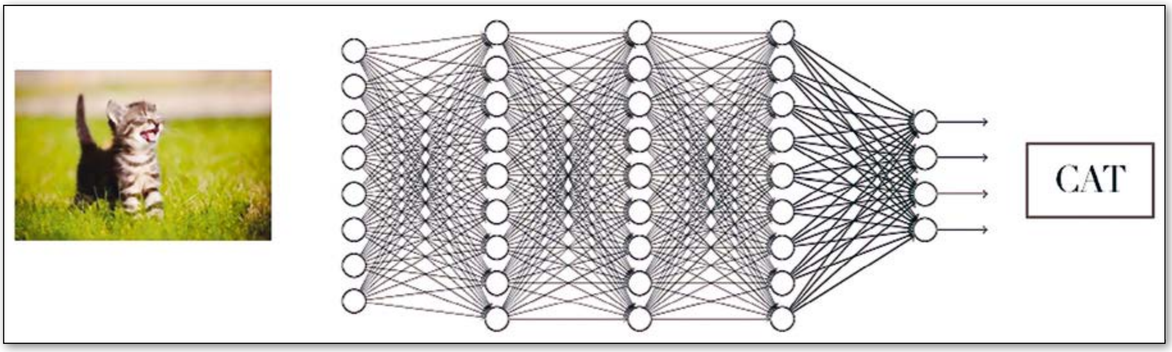
Ideally, one would like a machine that, whenever there is a cat on the image, outputs a 1 on the output "cat" neuron, and the same for dogs. Given a machine, namely a set

▼ **FIG. 1:** Artificial neurons. Left : Given the values $x_1, x_2, x_3, \dots$ that it receives from other neurons, the neuron computes its output y as follows: it first compute a linear combination of the inputs, $s=w_0+w_1*x_1+w_2*x_2+w_3*x_3+\dots$, and then outputs y=f(s), where f is a nonlinear function, which can be for instance a linear rectifier (right, top) or a sigmoid function (right, bottom). The parameters $w_0, w_1, w_2, w_3, \dots$ must be learnt by the machine during the training phase



[2] Google, Apple, Facebook, Amazon and Microsoft

[3] Baidu, Alibaba, Tencent, Xiaomi



▲ **FIG. 2:** In a layered network, the input is presented to the left layer. The signal is then propagated to the right, each neuron doing its weighted sum of the inputs it receives, followed but the non-linear function. The output is read in the last layer. Supervised learning is done by presenting a large database of images, each associated with the desired output, and updating the weights in order to get the desired output for each item in the database.

of values of weight parameters, one can define an error, a function of these parameters that measures the distance between the performance of the machine and the ideal one. In this supervised learning process, one optimizes the values of the parameters, using typically a stochastic gradient descent which iteratively improves each of the parameters in the direction which lowers the error. In practice, you have to train the machine using hundreds of thousands of images, with a supervisor telling in each case whether there is a cat or not. Having found the parameters of the machine such that it performs well on the training set, the real issue is the machine's ability to generalize. This is tested on a new dataset, distinct from the one used for training.

This paradigm of supervised learning in neural networks has existed for over 50 years. However, until the field's recent revival, it was not successful on real-size practical applications. Its revival is due to the increase in computing power, to the availability of very large labeled datasets for training (in fact, the development of "big-data" and the progress in machine learning are strongly correlated), and to some clever network-design know-how, pre-processing and training tricks developed in the 2000's.

In spite of its practical success, the scientific understanding of deep networks lags far behind. The learning process is poorly understood. Gradient descent in a complicated 108-dimensional parameter space should typically be trapped in inefficient regions. If one defines the training error -measuring the number of images that are misclassified by the machine- as an "energy function", the learning process amounts to finding the lowest energy configuration -the ground state- of a statistical mechanics problem with 108 variables (the adaptable parameters of the machine). This energy is a complicated function which depends on all the examples presented during training. Such large disordered systems have been much studied in the last four decades, in order to understand glasses. The result is well-known: typically, the glass energy landscape is very rough, with "traps" at all scales. The relaxation dynamics of stochastic gradient descent in a glass is extremely slow, making it very hard to reach the ground state. Yet, in practice, in all problems mentioned above, and many other ones, training in deep networks finds a good-enough set of parameters, producing a machine that can be smarter than us at some tasks. It is therefore an experimental fact that the learning problem in deep networks seems to have a much smoother energy landscape than expected, particularly when the number of layers becomes large. Why is it so? In spite of the many theoretical papers on this issue, proposing as many conjectures and ideas, it is fair to say that this is still a mystery, and I will refrain from presenting here these conjectures (including mine)!

So here we are: after observing many labelled examples, the machine has found the values of millions of parameters, and it does perform well. But what is our understanding of its performance? I claim that, if we know everything, we understand very little. On the one hand, we know everything at the microscopic level: we can observe all the operations that every neuron is doing, and we can read out all the parameters that it uses in order to perform these operations. But this is the same situation as that of an observer who would only see the microscopic structure of a computer: she could list all the transistors, how they are connected to other transistors, *etc.*, but still totally miss the point of what the computer is doing, how the information is stored and transformed.

We are slightly better-off in our understanding of layered network, but not much. We can see experimentally that the information obtained in each layer becomes more and more high level and global when one gets deeper into the network. For instance, in image recognition, the first layers tend to be sensitive to small scale patterns like local edges, and progressing deeper into the network we will find layers that are sensitive to lines and contours, then to specific patterns, eyes maybe, or whiskers, and in the last layer the abstract information comes out: this is a cat! Information is stored collectively in each layer: each neuron separately does not know anything, it is only by looking collectively at the activity of a large group of neurons that one can see information emerging.

This phenomenon of emergence is crucial. It is well known in statistical physics: for instance, the notions of pressure or entropy are "emerging" concepts that make sense only in presence of many particles, as the result of a collective behavior. Similarly, it was already understood in the 80's that the storage of information in a neural network is radically different from the one used in standard computers. In a standard computer, if you flip a bit, the information is changed radically. In a neural network, the information is kind of delocalized in the activity of a large number of neurons. A mistake in one of them does not change much the information. Similarly, the values of weight parameters do not need to be fine-tuned: a rough approximation is enough, the final behavior of the machine is robust to small changes.

Emergence is a complicated phenomenon, and at the moment we understand little of how information is processed in smart deep networks. One might ask whether this lack of understanding is actually a problem: after all, if we don't understand the machine that nevertheless functions well, who cares? Actually, it is a problem, because without a clear understanding we are not able to give any guarantee that our smart deep network always performs the task for which it was trained. A particularly nasty case is that of adversary examples. A group of our colleagues has worked with a neural network that was trained at distinguishing a panda from a gibbon, and had excellent performance. Then they picked a picture of a panda, and they were able to change a very small fraction of the pixels in such a way that this tiny alteration, totally invisible to our eye, which fooled the machine: on this slightly altered image, the network answered that our panda was a gibbon. The existence of such "adversarial examples", that can be obtained by automatic learning, may seem anecdotal when your aim is to identify species of apes, but it no longer is when you think that someone could fool a machine that is supposed to identify a "STOP" road sign and action the breaks. The absence of guarantee, linked to our poor understanding of the real processes at work, can be a serious obstacle to many practical applications, and a real nightmare for legal issues.

The second big problem raised by the absence of understanding is much deeper, and relates to the very notion of "intelligence". I will argue that, however smart these machines are, as far as "intelligence" is concerned, they are very limited. They can certainly achieve specific tasks, characterized by simple answers, in a well-defined setup, and in this they can be very useful. But they are far from elaborating a representation of the world, and even further away from any kind of creative reasoning. This raises fundamental questions. Is our brain more than a machine that reacts to inputs and produces outputs (maybe with some degree of stochasticity)? Let me mention here one small aspect of this question, dealing with science. An extreme position has been taken by Chris Anderson, chief Editor of "Wired". In a 2008 paper he declared "the end of the scientific method", arguing that the traditional way of doing science, building models, putting forward hypotheses, testing them and modifying the model, is obsolete because data science, and AI, allow to practice science purely on the basis of correlations, without any need for models and theories. Imagine that we have taken many movies of falling objects, and trained with these movies a deep network that is then able to determine the trajectory of objects of various sizes and shapes thrown in the air, as precisely as the solution of Newton's equations incorporating friction, wind speed *etc.* This network is a nice device, maybe useful for gun-manufacturers, for instance. But it stays very far behind the "model" described by Newton's laws in several key aspects. First of all, it does not capture the generality and the universality of a law: it can never figure out that the same law describes the move of planets around the sun. Secondly, a model or a law has a major virtue, its compactness, which will make it possible to use it as a building block for further developments, by combining it with other laws, equations, and models. This is one of the major ingredients of intelligence applied to the description of the world: it creates a concise, workable and predictive representation of the world, built of elements that can be combined. You start from Newton's law, then work out the approximation for an object at the surface of the earth, combine it with the laws of friction, and there you are. But you can also use it on the moon, or understand its limitations and discover a new theory, relativity…

The spectacular progress in AI is a major technological breakthrough. New machines will be able to make decisions, or, if we implement appropriate controls, to help us making decisions. They will affect our lives, for better or for worse. But they are very far from being intelligent. ■

About the Author

After graduating from École normale supérieure, **Marc Mézard** became a CNRS research associate in 1981 and obtained his PhD in 1984 on spin glass theory. In 2001 he moved to Université Paris Sud as CNRS research director, and became director of the Laboratoire de physique théorique et modèles statistiques, and of the "Labex" Physics, Atoms, Light, Matter. Between 1987 and 2012 he worked as associate professor and then professor at École Polytechnique. Since 2012 he is the director of École normale supérieure in Paris. His main field of research is statistical physics of disordered systems and its use in various branches of science.

EUROPE'S QUANTUM FLAGSHIP IS TAKING OFF

Max F. Riedel[1], Immanuel Bloch[2,3], Thierry Debuisschert[4], Frank Wilhelm-Mauch[5], Valerio Pruneri[6], Nikolay V. Vitanov[7], Stephanie Wehner[8], Tommaso Calarco[9] – DOI: https://doi.org/10.1051/epn/2018506

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The European Quantum Flagship is a 10-year, 1 billion Euro initiative, expected to bring quantum technologies from the lab to the market. The initiative is now taking off: The implementation and governance models are decided and the first research projects are commencing their work.

October 29 was a big day for quantum technologies (QT) in Europe: In a festive act at the Vienna Hofburg, the Quantum Flagship was officially kicked-off. More than 400 guests, among them distinguished scientists, CEOs of multinational corporations and high-level politicians from all over Europe attended the event. There is good reason for this celebration: The Quantum Flagship is one of the most ambitious research and innovation initiatives of the European Commission, with an expected run-time of 10 years and worth at least one billion Euro of funding money. Its goals are two-fold: On one hand, European scientific leadership and excellence in quantum research, including training the relevant skills, should be consolidated and expanded. On the other hand, the Flagship aims to make Europe a dynamic and attractive region for innovative research, business and investments in QT, thus accelerating their development and take-up by the market and positioning Europe as a leader in the future global commercial QT landscape. To reach these ambitious goals, the Quantum Flagship creates a federated effort from member states and the European Commission, bundling resources to reach a critical mass, competitive with other quantum technology initiatives in the world.

It was a long way to go before the start of the initiative: Europe is not only home to some of the most successful QT research groups, its community is also well connected and organized. A scientific roadmap, written by leaders in their field while taking into account the input of the whole community, was first published in 2005 and has been regularly updated since then (the latest version was published in August 2018 []). In 2016, the European QT community called on the EC to strategically invest in QT as a core future technology. The "Quantum Manifesto" [] was endorsed by over 3500 representatives from academia and industry. The EC decided shortly thereafter to launch the Quantum Flagship initiative, as the third of its kind after the Graphene Flagship and the Human Brain Project.

Implementation and governance

After announcing the Quantum Flagship, the EC appointed an independent expert group (the High-Level Steering Committee or HLSC), to propose a Strategic Research Agenda (SRA), an implementation structure and a governance model for the initiative []. The initial SRA recommended by the HLSC is based on the previously mentioned QT Roadmap, including milestones for the next 3, 6 and 10 years.

The Quantum Flagship is implemented through a series of peer-reviewed open calls for research and innovation actions (RIA), making it possible for new ideas and new researchers to contribute throughout the life span of the initiative. They are published as part of H2020 FET and Horizon Europe's Global Challenges pillar, with a foreseen total funding volume of at least 500M€. The EU member states will contribute at least an equal amount through national QT initiatives. A series of coordination and support actions (CSA) accompanies the RIAs to coordinate between the EC and national initiatives, bring academia and industry closer together, and gather input from the QT community to refine and regularly update the SRA. They will also drive standardization and coordinate access to technological infrastructure, such as chip foundries. The CSAs will reach out to the general public and potential end users on behalf of the whole Flagship, and coordinate education and training of a future quantum workforce. Finally, they will act as a coordinator and secretariat for the governance bodies.

The governance of the Quantum Flagship consists of three main elements: *The Strategic Advisory Board* monitors the progress of the Flagship and advises the EC on strategic measures. It is essentially the successor of the HLSC, chaired by Jürgen Mlynek. Further members will be nominated by the EC in late 2018. The coordinators of the funded projects meet regularly in the *Science and Engineering Board* to foster knowledge exchange and collaboration between the projects and develop synergies, such as the joint use of facilities. Finally, the *Quantum Community Network* consists of QT experts from the member states and associated countries, who are well respected and connected both with their national QT community and with their national government. The QCN ensures that input from the broader QT community is taken into account in the Flagship strategy and provides a link to national QT initiatives.

Research and innovation actions of the ramp-up phase

The first Quantum Flagship call was published in Fall 2017, with a funding budget of 110M€ for RIAs in the areas Quantum Communication, Quantum Computing, Quantum Simulation and Quantum Sensing & Metrology, an additional 20M€ for Basic Science projects and 2M€ for a CSA. Until the deadline in February 2018, 141 proposals were submitted, bidding for more than 600M€. The evaluation through peer-review resulted in 20 accepted projects, which start on October 1st 2018 (see figure 1 and table 1 for details).

Some project examples

To give the reader a flavour of the scope, size and ambition of the Flagship RIAs, we describe in the following six particular projects in more detail, samples from each area.

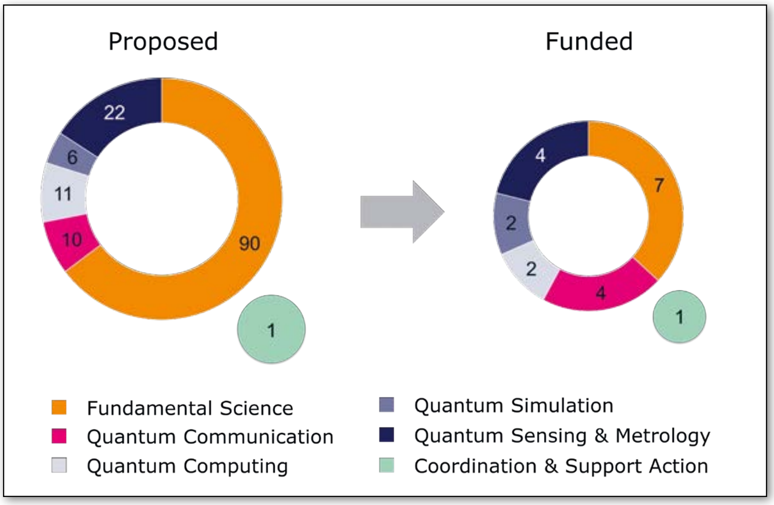
QIA - Quantum Internet Alliance (Quantum Communication)

The Quantum Internet Alliance [] will create a Blueprint for a pan-European Quantum Internet by developing all essential subsystems - quantum repeaters, end nodes as well as the first quantum network stack - culminating in the first experimental demonstration of a fully integrated stack running on a multi-node quantum network.

For this, QIA will push the frontier of technology in both, end nodes (trapped ion qubits, diamond NV qubits, neutral atom qubits) and quantum repeaters (rare-earth-based memories, atomic gases, quantum dots) and demonstrate the first integration of both subsystems. The project will achieve entanglement and teleportation across three and four remote quantum network nodes, thereby making the leap from simple point-to-point connections to first multi-node networks. It will demonstrate the key enabling capabilities for memory-based quantum repeaters, resulting in proof-of-principle demonstrations of elementary long-distance repeater links in the real-world, including the longest such link worldwide.

Hand in hand with hardware development, QIA will realize a software stack that will provide fast, reactive control and allow arbitrary high-level applications to be realized in platform-independent software. QIA's industry partners examine real world use cases of application protocols and their hardware requirements. The project will validate the full stack on a small Quantum Internet by performing an elementary secure quantum cloud computation. QIA will validate the design of the Blueprint architecture by a large-scale simulation of a pan-European Quantum Internet. Through synergy of leading industrial, academic and RTO partners, QIA's Blueprint will set the stage for a strong European Quantum Internet industry.

▼FIG. 1: Number of project proposals (left) and accepted projects (right) per area in the first Quantum Flagship call



CiViQ – Continuous Variable Quantum Communication (Quantum Communication)

The CiViQ project will aim at developing quantum-enhanced physical layer security that can be combined with modern cryptographic techniques, to enable unparalleled applications and services in the teleommmunications arena. It will also put forward novel quantum cryptography systems and protocols, with the ultimate goal of offering accessible, innovative services to individuals, industries and institutions and thus to meet the needs of the secure telecommunications market.

Quantum Key Distribution (QKD) is the most widely used among quantum cryptography protocols. However, its potential for applications in cybersecurity has not yet

▼TABLE 1: List of accepted projects in the Quantum Flagship ramp-up phase

TITLE	ACRONYM	COORDINATOR NAME	COORDINATOR ORGANISATION
FUNDAMENTAL SCIENCE			
Two-dimensional quantum materials and devices for scalable integrated photonic circuits	2D-SIPC	Dmitri Efetov	ICFO, Spain
Microwave driven ion trap quantum computing	MicroQC	Nikolay Vitanov	Foundation for Theoretical and Computational Physics and Astrophysics, Bulgaria
Sub-Poissonian Photon Gun by Coherent Diffusive Photonics	PhoG	Natalia Korolkova	The University Court of the University of St Andrews, United Kingdom
Photons for Quantum Simulation	PhoQuS	Alberto Bramati	Sorbonne Université, France
Quantum Microwave Communication and Sensing	QMiCS	Frank Deppe	Bayerische Akademie der Wissenschaften, Germany
Scalable Two-Dimensional Quantum Integrated Photonics	S2QUIP	Klaus Jöns	Kungliga Tekniska Hoegskolan, Sweden
Scalable Rare Earth Ion Quantum Computing Nodes	SQUARE	David Hunger	Karlsruher Institut für Technologie, Germany
QUANTUM COMMUNICATION			
Continuous Variable Quantum Communications	CiViQ	Valerio Pruneri	ICFO, Spain
Quantum Internet Alliance	QIA	Stephanie Wehner	Technische Universiteit Delft, Netherlands
Quantum Random Number Generators: cheaper, faster and more secure	QRANGE	Hugo Zbinden	Université de Genève, Switzerland
Affordable Quantum Communication for Everyone: Revolutionizing the Quantum Ecosystem from Fabrication to Application	UNIQORN	Hannes Hübel	AIT Austrian Institute of Technology GmbH, Austria
QUANTUM COMPUTING			
Advanced quantum computing with trapped ions	AQTION	Thomas Monz	Universität Innsbruck, Austria
An Open Superconducting Quantum Computer	OpenSuperQ	Frank Wilhelm-Mauch	Universität des Saarlandes, Germany
QUANTUM SIMULATION			
Programmable Atomic Large-Scale Quantum Simulation	PASQuanS	Immanuel Bloch	Max-Planck-Gesellschaft zur Forderung der Wissenschaften eV, Germany
Quantum simulation and entanglement engineering in quantum cascade laser frequency combs	Qombs	Augusto Smerzi	Consiglio Nazionale delle Ricerche, Italy
QUANTUM SENSING & METROLOGY			
Advancing Science and TEchnology thRough dIamond Quantum Sensing	ASTERIQS	Thierry Debuisschert	Thales SA, France
Integrated Quantum Clock	iqClock	Florian Schreck	Universiteit van Amsterdam, Netherlands
Miniature Atomic vapor-Cells Quantum devices for SensIng and Metrology AppLications	MACQSIMAL	Jacques Haesler	CSEM Centre Suisse d'Electronique et de Microtechnique SA - Recherche et Dévelopement, Switzerland
Leveraging room temperature diamond quantum dynamics to enable safe, first-of-its-kind, multimodal cardiac imaging	MetaboliQs	Christoph Nebel	Fraunhofer Gesellschaft zur Förderung der Angewandten Forschung eV, Germany
CSA			
Quantum Technology Flagship Coordination and Support Action	QFlag	Markus Wilkens	VDI Technologiezentrum GmbH, Germany

been fully exploited, mainly because the systems currently used are often expensive, exhibit poor flexibility, and cannot operate seamlessly in telecommunication networks. CiViQ will overcome the critical valley of death by developing flexible and inexpensive QKD systems that can be well integrated into telecom infrastructures.

As an alternative to common encoding schemes that use expensive and bulky single photon detection techniques, CiViQ's protocol will measure electric field amplitudes using coherent detection (widely used in modern coherent optical telecommunication). The measured outcomes are continuous values of the amplitudes of electric fields and the detection technique is the ultimate hallmark of CV-QKD (continuous variable), which will lead to the development of inexpensive technology that can be integrated in many more applications, specifically for industrialization and integration in telecommunication networks.

The project brings together a consortium of 21 partners that cover the entire supply chain of QKD, from academic research groups, component manufacturers, industrial equipment suppliers to telecommunication network operators/end users.

OpenSuperQ - An Open Superconducting Quantum Computer (Quantum Computing)

The collaborative research project OpenSuperQ aims at developing a quantum computing system of up to 100 qubits and to sustainably make it available at a central site for external users. The system consists of a full computing stack: The hardware will be centred on superconducting integrated circuits and contain the necessary technological infrastructure, including a control system and user-friendly cryogenics. The software stack will be integrated from user access all the way to low-level control. The computer will be among the leading platforms in the world and the first of its kind developed in Europe.

The team brings together 11 renowned players from universities, research organisations and businesses covering the fields of science, engineering and application development. The final computer will be located at the world-class supercomputing centre in Jülich, Germany. The core experimental teams build the mission-critical central parts of the quantum computer, while the involved technology partners develop the complex engineering around the device. The theory team supports the experiments by detailed modelling and develops critical applications. Management and dissemination are professionally run by a co-located project management team headed by Professor Frank Wilhelm-Mauch of Saarland University.

One of the unique features of OpenSuperQ is its open and integrative approach, enabling the underlying technologies to serve a large community of users. The central site will allow early adopters to learn how to develop quantum software. The consortium particularly targets applications for quantum simulation in chemistry and materials science as well as for optimisation and machine learning.

PASQUANS - Programmable Atomic Large-Scale Quantum Simulation (Quantum Simulation)

The PASQuanS project builds on the impressive achievements of the most advanced quantum simulation platforms to date, based on atoms and ions. The neutral-atom simulators handle more than 50 cold atoms in optical lattices or arrays of optical tweezers, interacting via either collisional or Rydberg-state-mediated interactions. The ion-trap platform reaches unsurpassed control with up to 20 ions.

By scaling up these platforms towards >1000 atoms or ions, by improving control methods and making these simulators fully programmable, the goal of PASQuanS is to push these already well-advanced platforms far beyond both the state-of-the-art and the reach of classical computation. Full programmability will make it possible to address quantum annealing or optimization problems much sooner than digital quantum computation. One important aspect will be to demonstrate a /quantum advantage for non-trivial problems, paving the way towards practical and industrial applications. PASQuanS will result in modular building blocks for a future generation of quantum simulators.

The PASQuanS project consortium unites five experimental groups with complementary methods to achieve the technological goals, connected with six theoretical teams focusing on certification, control techniques and applications of the programmable platforms, and five industrial partners in charge of the key developments of enabling technologies and possible commercial spin-offs of the project. Possible end-users of these simulators, major industrial actors, are tightly associated with the consortium to help identifying and implementing key applications where quantum simulation provides a competitive advantage.

ASTERIQS - Advancing Science and TEchnology thRough dIamond Quantum Sensing (Quantum Sensing & Metrology)

ASTERIQS [] will exploit quantum sensing based on nitrogen-vacancy-centres in ultrapure diamond to bring solutions to societal and economical needs for which no solution exists yet. Its objectives are to develop:

1. Advanced applications based on *magnetic field* measurement: a fully integrated scanning diamond magnetometer instrument for nanometer scale measurements, a high dynamics range magnetic field sensor to control advanced batteries used in electrical car industry, a lab-on-chip Nuclear Magnetic Resonance (NMR) detector for early diagnosis of diseases, a

magnetic field imaging camera for biology or robotics, and an instantaneous spectrum analyser for wireless communications management;
2. New sensing applications to sense *temperature* within a cell, to monitor *new states of matter* under high pressure and to sense *electric fields* with ultimate sensitivity;
3. New measurement tools to elucidate the chemical structure of single molecules by NMR for the pharmaceutical industry or the structure of spintronics devices at the nanoscale for a new generation of spin-based electronic devices.

To achieve these goals, the project will develop enabling tools, such as highest grade diamond material with ultralow impurity level, advanced protocols to overcome residual noise in sensing schemes, and optimized engineering for miniaturized and efficient devices.

ASTERIQS will disseminate its results towards academia and industry and educate the next generation of physicists and engineers. The consortium federates world leading European academic and industrial partners to bring quantum sensing from the laboratory to applications.

MicroQC - Microwave driven ion trap quantum computing (Basic science)

The construction of a large-scale trapped-ion quantum information processor can be made decisively simpler by using the compact microwave technology present already in today's mobile phones and other devices. Microwave technology has tremendous simplification potential by condensing experimental effort down to an engineered conductor microstructure embedded into a chip surface and a few off-the-shelve microwave components. This technology can be the key enabling step for addressing the formidable challenge of a scalable quantum processor for it allows execution of quantum gates by the application of a voltage to a microchip, thereby replacing millions of laser beams, and it can operate at room temperature or mild cooling.

MicroQC aims to demonstrate, through state-of-art quantum engineering, fast and fault-tolerant microwave two-qubit and multi-qubit gates and to design scalable technology components for multi-qubit quantum processors. The successful accomplishment of these objectives, in a combined effort by five leading groups in this field – three experimental groups, including the pioneers in microwave quantum logic with static and oscillating magnetic gradients, and two theory groups – will make large-scale quantum computation and simulation with microwave-controlled microfabricated ion traps possible. Consequently, MicroQC will produce a roadmap to take microwave quantum computation to high technology readiness levels.

Outlook

The Quantum Flagship is setting sail and we are excited to see this high commitment from all European stakeholders. We find it important to note that quantum technologies will be fostered also beyond the Quantum Flagship through different European funding instruments, possibly including the QuantERA co-fund, the space programme, through the European Research and Innovation Councils and Marie-Skłodowska-Curie-Actions, and the Digital Europe Programme. Concrete steps are already taken: The next QuantERA call will be published in November 2018, a call for a Quantum Key Distribution (QKD) test bed is currently running as part of the H2020 cybersecurity strategy [], and ESA is exploring space-based QKD in its Artes-ScyLight programme []. The German QT initiative was recently announced and further national QT initiatives are expected to be coming soon. The Quantum Flagship thus is really becoming one ship in a larger "quantum fleet". ■

About the Authors

Max Riedel holds a PhD in quantum physics and is a Senior Consultant for University Relations at Siemens AG. From January 2017 to September 2018 he was delegated to the University of Ulm as project manager for European activities to support Tommaso Calarco in the preparation of the Quantum Flagship.

Tommaso Calarco is the director of the Institute Quantum Control (PGI 8) at Forschungszentrum Jülich, where he develops control techniques for many-particle quantum systems in order to make quantum technologies more efficient. For more than a decade, he has been instrumental in coordinating the European quantum technology community and is considered one of the intellectual fathers of the Quantum Flagship. Photo credit: Helmholtz/Stefanie Herbst

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Available at: https://qt.eu/resources/

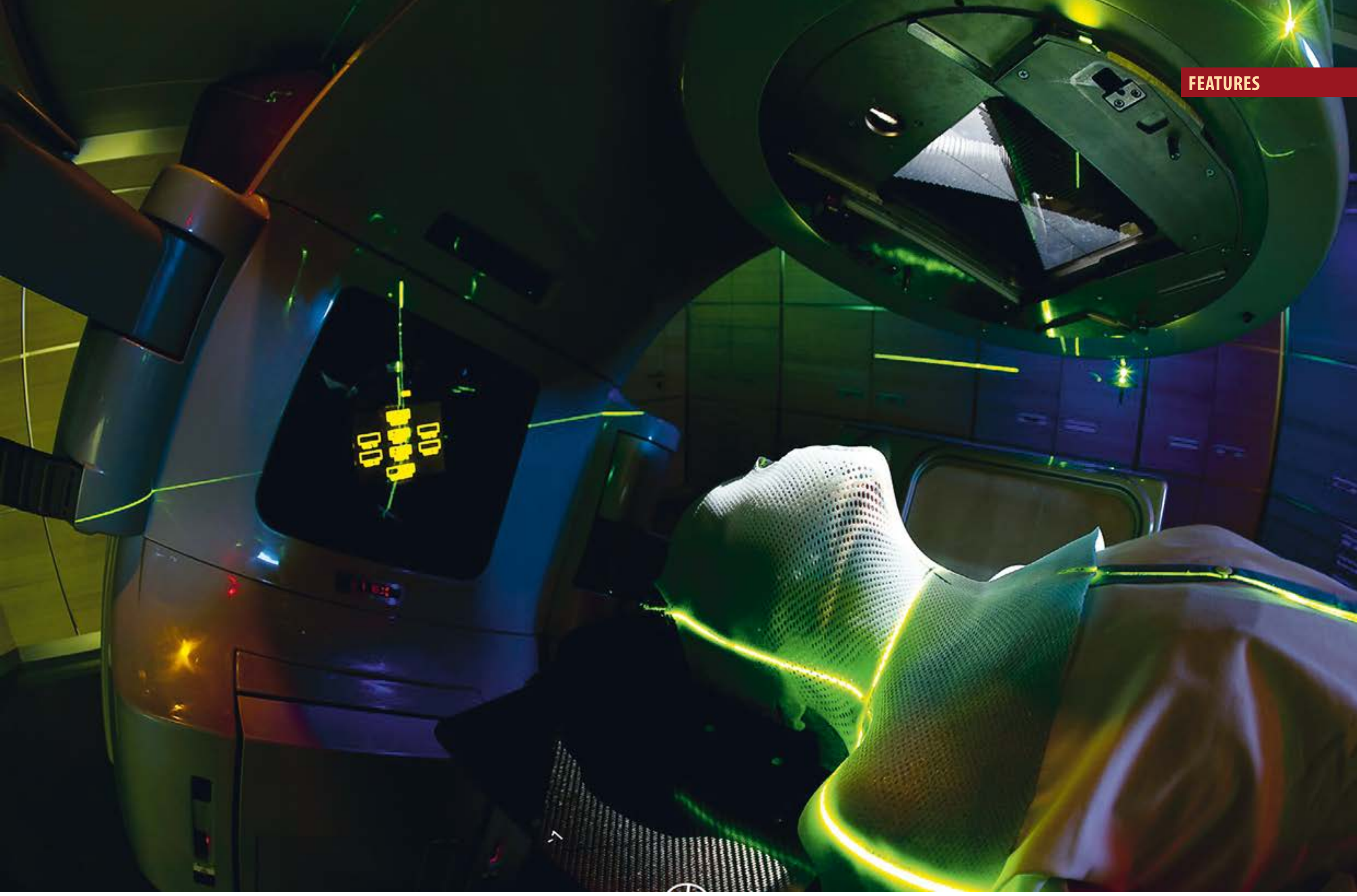
[3] High-Level Steering Committee Report, 2017.
Available at: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=46979

[4] More information on QIA: http://quantum-internet.team

[5] More information on ASTERIQS: https://www.asteriqs.eu

[6] SU-ICT-04-2019: Quantum Key Distribution testbed

[7] More information on Artes ScyLight: https://artes.esa.int/artes-scylight-secure-and-laser-communication-technology



FROM PARTICLE PHYSICS
TO MEDTECH AND BIOMEDICAL RESEARCH

Manuela Cirilli, CERN – DOI: https://doi.org/10.1051/epn/2018507

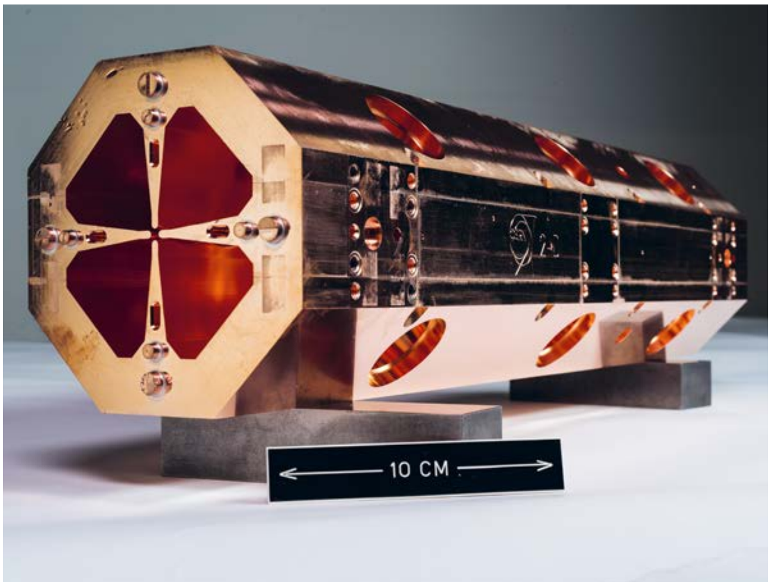
Physics phenomena underpin many techniques and technologies that are used for both diagnosis and treatment of a variety of diseases. This is the case for radiotherapy, Magnetic Resonance Imaging (MRI), and Positron Emission Tomography (PET) that are based on our knowledge, respectively, of how particles interact with matter, of how atomic nuclei behave in oscillating magnetic fields, and of how positron decay.

▲ One of the most important of all applications of particle accelerators is their application in the treatment of cancer. Photo credits: CERN

Particle physics has also played a role in developing innovative technologies that made their way into the Medical Technology (MedTech) sector: frontier instruments like the Tevatron at Fermilab or the Large Hadron Collider (LHC) at CERN, and their detectors, require frontier technologies, well beyond the industrial know-how at the time these experiments were conceived. Advances in fields including accelerators, detectors, and computing have had a positive impact in many fields of society, and in particular in medical and biomedical technologies and research.

Accelerator technologies for health

Linear accelerators are routinely used in hospitals for conventional cancer radiotherapy with X-rays. Radiotherapy is a mainstay of cancer treatment, its main limitation being the maximum tolerated dose to healthy tissues traversed by the X-ray beam: in fact, photons loose energy slowly and mainly exponentially as they penetrate tissue, meaning that they will deposit radiation dose before and after the target tumour. Nowadays, techniques such as intensity-modulated radiation therapy (IMRT), image-guided radiation therapy (IGRT),



▲ FIG. 1: An innovative linear accelerator designed by CERN to be compact, modular, low-cost and suitable for medical applications. Photo credits: CERN

and stereotactic radiotherapy (SBRT) enable precise delivery of the dose to the exact volume of the tumour, while minimising the irradiation of healthy tissues.

A novel form of radiation therapy was proposed in 1946 by accelerator pioneer Robert R. Wilson, first Director of Fermilab, who published an article in *Radiology* about the therapeutic interest of proton beams for treating cancer. The clinical interest in hadron therapy[1] resides in the fact that it delivers precision treatment of tumours, exploiting the characteristic shape of the dose deposition as a function of the depth of matter traversed: unlike photons, hadrons deposit almost all of their energy in a sharp peak – the Bragg peak – at the very end of their path.

The Bragg peak makes it possible to target a well-defined cancerous region at a depth in the body that can be tuned by adjusting the energy of the incident particle beam, with reduced damage to the surrounding healthy tissues. The dose deposition is so sharp that new techniques had to be developed to treat the whole target. These fall under the categories of passive scattering, where one or more scatterers are used to spread the beam, and spot scanning, where a thin, pencil-like beam covers the target volume in 3D under the control of sweeping magnets coupled to energy variations.

While the advantages of protons over photons are quantitative in terms of the amount and distribution of the delivered dose, several studies show evidence that carbon ions damage cancer cells in a way that they cannot repair themselves. Carbon therapy may be the optimal choice to tackle radio-resistant tumours; other ions, such as helium, are also being investigated[2].

The complexity of the infrastructures required for hadron therapy is a limiting factor for its exploitation, and particle physics has constantly contributed to advancing the needed accelerator technologies (Figure 1). The first patients were indeed being treated in physics research institutes, starting in Berkeley, until the construction of the first dedicated proton therapy centre in Loma Linda (California). While various companies are now offering turn-key solutions for proton therapy centres and even single-room systems, custom design – often realised in partnership with research institutions – is still the norm for multi-ion facilities.

Accelerators are also increasingly needed for the production of radioisotopes, which are used in nuclear medicine imaging and therapy. Artificially-made radioisotopes are still mostly produced by research reactors, which are frequently shut down for maintenance. Dedicated cyclotrons are playing an increasingly relevant role, and new accelerator-based technologies are being explored for next-generation facilities that would replace the wobbly reactors. The ISOLDE accelerator facility at CERN has constantly been developing the so-called Isotope Separation Online (ISOL) technique, which is now being taken one step further by the CERN-MEDICIS installation, dedicated to the production of a wide range of innovative radioisotopes for medical and biomedical research.

The growing energy reach of particle accelerators has pushed the development of novel superconducting magnet technologies able to generate higher magnetic fields: this is the case of Niobium-titanium (Nb-Ti), an alloy that was identified in 1962 as having superior superconducting properties paired with easy workability. In the early seventies, just when Fermilab started building the Tevatron accelerator, American chemist Paul Lauterbur published on *Nature* his paper describing a new imaging technique based on NMR. Both the Tevatron design and the infant MRI technology were in dire need of very strong magnetic fields, which could only be provided by Nb-Ti coils that nobody was capable of producing at that time with the necessary specifications. This is where the role of big science in pushing technologies beyond state-of-the-art becomes manifest: Fermilab bought the raw material in quantities that were orders of magnitude larger than standard orders for Nb-Ti at that time, and worked alongside manufacturers to achieve the perfect wires for the Tevatron. This paved the way for commercial use of Nb-Ti in MRI machines and, later-on, in medical accelerators[3].

Particle detectors

Medical imaging has radically transformed medicine, changing the way doctors can detect, diagnose, and treat a variety of diseases. Technological breakthroughs have made imaging faster, more precise, and less invasive, generating a wealth of new imaging

[1] https://cerncourier.com/the-changing-landscape-of-cancer-therapy/
[2] http://cds.cern.ch/record/1734611/files/vol51-issue10-p037-e.pdf
[3] https://www.symmetrymagazine.org/article/december-2008/deconstruction-mri

techniques and methods. These innovations have often been driven by the latest developments in particle detectors and electronics, whose increasingly challenging requirements keep pushing technologies beyond state-of-the-art.

The epitome of the cross-fertilization between particle physics detectors and imaging tools is the technology for PET scanners. As in the case of Nb-Ti for MRI, high-energy physics has played a major role in making scintillating crystals available at industrial scale and affordable (Figure 2). The calorimeters of the Crystal Ball detector at the Stanford Linear Accelerator Center and of the L3 experiment at the Large Electron Positron (LEP) collider at CERN pioneered, respectively, the large-scale use of sodium iodide (NaI) and bismuth germanate (BGO), two key scintillators for PET scanners. Similarly, the mammoth scale of the CMS detector at the LHC required the development of 120000 avalanche photodiodes (APD) for scintillator readout in a high magnetic field: the CMS experience highlighted the limitations of APDs and gave a positive impulse to the R&D on silicon photomultipliers (SiPM), first developed by Russian institutes (Moscow and Dubna)[4].

In some cases, technologies developed for particle physics detectors have been directly transferred to the medical imaging field. A recent example is a breakthrough application of a chip developed at CERN by the Medipix3 Collaboration for LHC experiments: a New-Zealand company developed a scanner based on this technology and managed to take the first 3D colour X-ray images of a human body[5] (Figure 3).

Particle detectors also find important applications in the field of dosimetry, where novel technologies can considerably improve the performance and reliability of dose monitoring procedures. Advances in radiation therapy technology – such as intensity modulated radiation therapy (IMRT), image-guided radiation therapy (IGRT) and hadron therapy – have called for an increased reliability and accuracy in dosimetric techniques. During treatment, ion chambers measure the integrated dose and shut off the beam once the required therapeutic dose, as specified by the treatment plan, has been reached. Before treatment, periodic Quality Assurance procedures are required to verify for example the homogeneity of the radiation field, by means of radiochromic films or a matrix of active monitors such as pin diodes or ion chambers. In hadron therapy, dosimetry also implies the verification of the position of the Bragg peak (where the majority of the radiation is deposited) in a water phantom. Additional in-vivo dose measurements during the actual radiation treatment of an individual patient represent an additional safety measure. The relatively recent field of micro dosimetry also needs sophisticated detectors to detect the energy deposited in cellular and sub-cellular structures.

Computing and simulation

Computer simulations are ubiquitous in medical applications, from detector modelling, to accelerator studies for medical use, shielding design, radioisotope production, treatment planning for radiation therapy, evaluation of radiation exposure for astronauts. Particle physics excels in the domain of Monte Carlo (MC) simulations, and simulation codes initially developed for High-Energy Physics (HEP), such as Geant4 and FLUKA[6], have also become crucial to modelling the effects of radiation on biological tissues for a variety of applications in the medical field.

Geant4 is true reflection of the collaborative model of HEP: it is a world-wide collaboration of scientists and software engineers whose goal is to develop, maintain and provide support for the Geant4 toolkit. Today, it is adopted by thousands of users worldwide for application in domains beyond high-energy physics[7]: examples of Geant4 extensions for use in the medical field are GATE, TOPAS and Geant4-DNA. The latter offers the possibility to model physical, physicochemical, and chemical processes up to the microsecond scale, therefore allowing for the simulation of early biological effects induced by ionizing radiation at the subcellular scale.
Among other medical applications, Geant4 is being used to study the radiation environment on the ISS, as well as radiation effects on possible future manned space missions to the Moon or Mars.

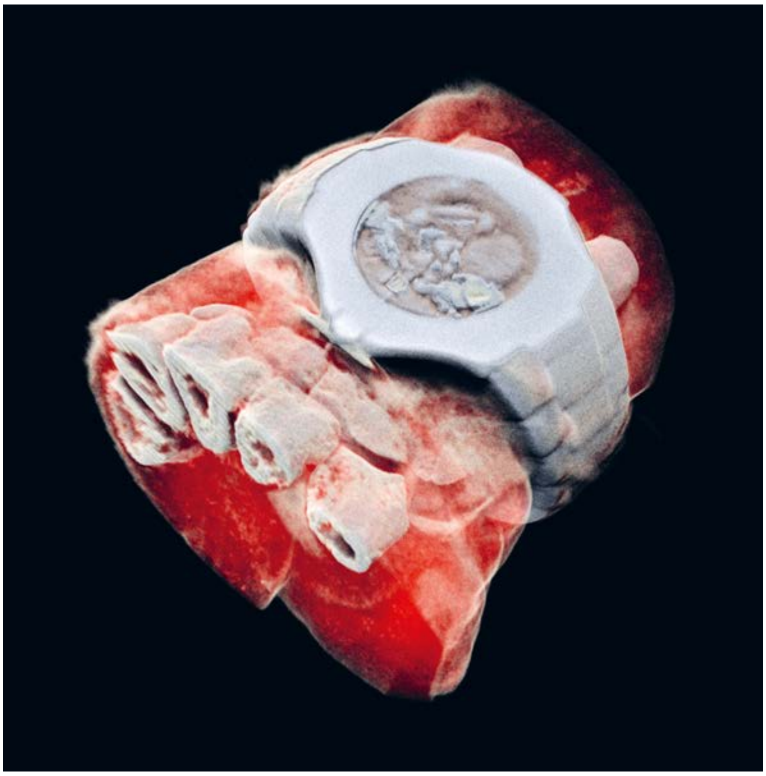
▾ **FIG. 2:** Scintillating crystals are used both in particle detectors for high-energy physics experiments and in PET scanners to detect photons. The photo shows some of the almost 80000 precision-grown crystals for the CMS experiment at CERN. Photo credits: Peter Ginter/CERN

[4] https://indico.cern.ch/event/164917/contributions/1417121/attachments/198512/278663/PhotoDet12_-_collazuol_-_v3.pdf

[5] https://home.cern/about/updates/2018/07/first-3d-colour-x-ray-human-using-cern-technology

[6] http://www.fluka.org/fluka.phpw

[7] http://www.geant4.org/geant4/applications.1



▲ **FIG. 3:** A 3D image of a wrist with a watch showing part of the finger bones in white and soft tissue in red, taken with the MARS scanner using the technology developed by the Medipix3 collaboration at CERN. Photo credits: MARS Bioimaging Ltd.

Computing tools, infrastructures and services developed for HEP have also great potential for applications in the medical and biomedical field. Health is a vital part of society, and as such is affected by the same technology trends, including the pervasive use of computer techniques for data sharing and patient referral or the rise of Artificial Intelligence (AI) and Machine Learning (ML) techniques. The "big data" trend in the healthcare sector is going strong, as doctors and researchers realise that they are sitting on a goldmine of data. Medical data comes from many different types of sources (instruments, sensors, imaging devices, environmental data), disciplines (genome sequencing, metabolomics, metagenomics) and formats (publications, digital data sets, software code). It is therefore increasingly difficult for researchers to make efficient use of the available inputs, analyse data, store and share results. Furthermore, most of the medical data is produced by a large number of institutes and has stringent privacy and confidentiality constraints. The increasingly large quantity and variety of data make the discovery, identification, reuse and reproducibility of relevant data sets and results more and more difficult. Data analytics tools hold the promise of better disease identification and diagnosis, improved efficiency *e.g.* in screening new pharmaceuticals, increasingly personalised treatments, better outbreak prediction or novel intelligent electronic health records. Meanwhile, the HEP community has been applying ML techniques for quite some time, and in particular since the LHC started data-taking in 2010 generating an unprecedented amount of collisions and of data from the equipment. The challenges faced in HEP are similar to those in other fields, including the medical sector: they range from speeding up computer simulations, developing modern code optimisation techniques, to real-time analysis, particle reconstruction and identification, monitoring of detectors, hardware anomalies and preemptive maintenance.

Conclusions

Innovative ideas and technologies from particle physics have been playing an increasingly important role in healthcare over the past 100 years, since the advent of radiation-based medical diagnosis and treatment following the discovery of X-rays and radioactivity. Nowadays, state-of-the-art techniques derived from particle accelerators, detectors, and physics computing are routinely used in clinical practice and medical and biomedical research: from technology for PET scanners, to dedicated accelerators for cancer therapy, to simulations and data analytics instruments.

As physicists continue to develop cutting-edge instrumentation to achieve their far-reaching goals, the MedTech and biomedical sector will be able to reap the benefits of the technological advances. Examples are: novel accelerator designs that would allow more effective and affordable ion therapy for cancer treatment; research and development aimed at improving the time resolution of scintillating crystals, which could lead to dramatic improvements in the sensitivity of PET scanners; more powerful ML tools driven by the exacting needs of particle physics, which could be applied to similar challenges in the medical field.

Last but not least, the experience gained in the organisation of particle physics projects can contribute to the shaping of medical research: HEP collaborations have been bringing together thousands of scientists from every corner of the world, and particle physicists have learned to work collectively for a common goal, to rely on consensus to take decisions, and to implement flexible yet effective management structures for their experiments. This collaborative framework can serve as model and inspiration for medical and biomedical research, where multidisciplinary, multinational collaboration is beginning to bloom. ■

About the Author

Manuela Cirilli works at CERN, the European Organization for Nuclear Research, where she leads the Medical Applications section of CERN's Knowledge Transfer group. Prior to this, she was an experimental researcher in particle physics: first in the NA48 experiment at CERN, aimed at measuring CP violation in the kaon system, and then in the ATLAS collaboration at CERN's Large Hadron Collider. In parallel to her scientific career, Manuela has been engaging in science communication and popularization, and in promoting STEM careers among young women and girls.

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50 YEARS OF CMD

Jozef T. Devreese[1], Eoin O'Reilly[2], and Kees van der Beek[3] – DOI: https://doi.org/10.1051/epn/2018508
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Condensed Matter Physics touches some of the deepest phenomena in nature. Fascinating physics occurs throughout this very broad area of physics, largely enabling the technologies that underpin modern society. Since 50 years, the EPS Condensed Matter Division is the voice and the tool of the strong European Condensed Matter community.

The founding of the European Physical Society (EPS) came relatively soon after the invention of the transistor in 1947[1], at a time when the latter steadily gained importance in applications such as radios. It was a time when "Solid State" was *en vogue*. Research units chose names like "Solid State Physics Department" and "Division of Solid State Science". Still, when divisions were created in 1969 as working units within the brand-new EPS, it was a "Condensed Matter Division" (CMD) that resulted. Presumably the fact that Sam Edwards, founder and chairman of the division from 1969 till 1972 was a pioneer in the field of polymers played a role in baptising our division. The corresponding division of the APS was given the name CMD only in 1978; initially it was called "Division of Solid State Physics".

▾ **FIG. 1:** Gero Thomas and Jozef Devreese at CMD1 in Antwerp, 1980

It is not easy to pinpoint a single "parent" of the condensed matter concept. Experimental studies on the vapour – liquid transition were referred to by Hooke as Boyle's "condensation" experiments[2] in *the Royal Society's Journal Book* in 1662. The term "*Condensed phase*" was commonly used in the 19th century and work by *e.g.* Gibbs and Van der Waals is devoted to it. In the nineteen-sixties there was a growing interaction and overlap between solid state physics and the study of liquids at the atomic level and – as stated by Conyers Herring - the enlarged concept of *physics of condensed matter* was increasingly used in universities and in industry. Today the concept "condensed matter" has come to include, beyond the solid and the liquid state per se, superconducting and superfluid phases, quantum Hall and topological phases, large parts of quantum physics, with, in particular, condensed matter quantum simulators consisting of cold atoms, but, also, the vast domain of surface science, polymers, soft matter, biological matter, and a wide spectrum of materials science, including nanomaterials.

Manuel Cardona has argued that Einstein comes closest to being at the origin of "condensed matter physics": "*... I shall demonstrate that (Einstein) is also the father of Solid State Physics, or even (its) broader version ... known as Condensed Matter Physics (including liquids)*"[3] and "His first publication (1901)[4] could already be considered to

[1] https://www.aps.org/programs/outreach/history/historicsites/transistor.cfm
[2] Royal Society's Journal Book, See "The Hooke Folio online": *e.g.* October 1 (1662)
[3] M. Cardona, arXiv:physics/0508237v1 [physics.hist-ph] (2005)
[4] "Folgerungen aus den Capillaritätserscheinungen", *Annalen der Physik* **4**, 513 (1901).

be in the realm of Condensed Matter Physics (liquids)". Certain is that the journal "Physics of Condensed Matter" (Springer) started publishing in English, French, and German as of 1963.

The early years, Condensed Matter Physics in Europe (1969-1979)

The founders of EPS (1968) were inspired by the creation of CERN (1958), itself part of peaceful international collaborative efforts in the wake of the recovery of Europe from World War II. Around that time, scientists, including physicists, in Europe were taking more and more initiatives, stimulated, amongst other things, by the successful (and totally surprising) launch of Sputnik (October 1957). By 1969 physics was flourishing in Europe once again and collaboration with the USA and Japan was on the rise. In the first decade of CMD - EPS, condensed matter physics was much influenced by discoveries and inventions of the previous decades such as the transistor effect (Lilienfeld, 1925; Bardeen, Brattain, Shockley, 1947), neutron scattering and diffraction (1945), the BCS-theory of superconductivity (1957), and the Esaki and Giaever tunnelling phenomena and -diode (1958-1960). The first decade after 1969 saw spectacular miniaturisation in electronics leading to the increasing impact of computers and computational physics, a trend that continues to this day. Nobel Prizes for Néel (1970), Mott (1977), and Kapitsa (1978) honoured profoundly fundamental European condensed matter research, while the Nobel Prize of Josephson (1973) for work in 1962 rewarded an exceptional theoretical prediction with pronounced technological impact: the Josephson junction. Nevertheless, as reflected by the founding years of its sections (Table I), CMD has, from the outset, paid attention to the whole span of condensed matter physics.

Attempts towards "*topical* divisional conferences"

Sam Edwards contributed to the organisation of the Inaugural Conference of EPS (Florence, Italy, in 1969) and especially to its condensed matter aspects with talks by Casimir, Mott and Friedel, among others. Next, Edwards started, for CMD, what were called "Divisional Conferences". The initial concept was to concentrate the programme on two themes: 1) *"a particular region of condensed matter"* and 2) *"a general phenomenon"*. The first such "topical" Divisional Conference took place in Florence in September 1971, with *"metals"* as material and *"phase transformation"* as general phenomenon. This conference - helped by the enthusiasm for the new EPS – was a success and held much promise for the future. The second "Divisional conference" (Budapest, 1974) was planned as an occasion for nurturing contacts between physicists from Eastern and

CMD SECTION	YEARS IN OPERATION
Liquid physics	1982 -
Low temperature physics	1974 -
Macromolecular physics	1974 – 2017 (succ. by Soft Matter and Bio)
Magnetism	1969 – 2017 (succeeded by EMA)
Metal physics	1969 - 1999
Soft Condensed Matter and Biophysics	2017 -
Semiconductors and Insulators	1969 -
Structure and Dynamics of Condensed Matter	1998 -
Surfaces and Interfaces	1974 -

▲ **Table I:** Sections of the Condensed Matter Division of the EPS

Western Europe. However the level of participation had declined considerably, with a further decline (a "euphemism") at the third meeting in Leeds in 1977. Clearly, the "topical" scheme could not lead to a successful, recurrent, condensed matter (CM) meeting in Europe, and was therefore inappropriate as the seat of regular interaction between European CM physicists. In 1978, one of us (JTD) was approached by CMD with the request to take an initiative that could lead to a successful series of CMD conferences, and, thereby, successful CMD integration.

Antwerp 1980 and the General Conferences of CMD

It was no obvious decision to start a new series of CMD-conferences in Antwerp. Nevertheless, the challenge was accepted (by JTD) because of the conviction that there was a genuine need in the European CM physics community for an international forum, similar to the successful "*March Meeting*" of the APS. Already then, many European CM physicists attended the March meeting. The strategy for Antwerp – CMD1 was, among others,

- to conceive the conference as "general", *i.e.* encourage all CM-physicists to contribute;
- to cover a wide range of topics, in principle, all subjects of interest to CM physicists;
- to promote the "General Conference of CMD" as an international forum for discussion and exchange on the latest scientific developments;
- to form the International Advisory- and Programme Committees with great care and with relatively many and *active* members. The two committees had about 30 members each, including leading European physicists such as A. Abrikosov, H. Casimir, H. Haken, N. Mott, N. Bogoliubov, M. Cardona, S. Edwards, J. Friedel, G. Benedek, H. Fröhlich, R. Peierls, …

The team in Antwerp collected addresses (internet did not exist yet) of around 8000 physicists in Europe working in the broad field of condensed mater physics. The deadline for registration for the conference was February

▸ FIG. 2: Opening session of CMD1 in Antwerp, 1980

1, 1980. In the last three days of January- to the surprise of the organizers - around 180 letters were received per day (with abstracts or/and subscription for participation). In the end more than 600 CM physicists participated in the 1980 First General Conference of CMD-EPS. The distribution of participants over Western European countries was quite homogeneous, with relatively few participants from Eastern Europe at that time, but several from the USA, Japan and China. During the conference there was a strong interaction between the participants and there was enthusiasm about the forum provided by the new "General Conference" format.

Within two weeks after Antwerp-CMD1, two formal offers were received to organise the second conference: one for Manchester, one for Lausanne. Since then, the meeting has become "self-propelling", with spontaneous proposals coming to organise the next conference. A list of the 27 CMD Conferences to date can be found on the CMD web pages[5].

The original Antwerp "general forum"-format has evolved over the years. Typically the CMD General Conference has attracted 400 to 600 participants from outside the organising country. Attendance has ebbed and flowed, with the meeting evolving and re-inventing itself over the years. The overall attendance exceeded 1000 participants in Grenoble, Montreux, Brighton, and Paris, with a good balance in each case of "local" and international participants. The number of attendees peaked at 6735, when CMD 27 was co-organised with the German spring meeting in Berlin in 2018. Even if the attendance was predominantly from German institutions, the EPS-CMD character of the conference was distinct, due to the careful selection of a representative panel of European invited speakers. Recurring problems are the fluctuating number of delegates as function of the host country, the relative strength of its national physical society, and of the meetings CMD is combined with, and CMD's two-yearly frequency. Establishing CMD as a yearly rendezvous, thereby securing the repeated presence of graduate students and young researchers from across Europe – *i.e.*, more than once during their PhD or post-doc contract – and establishing CMD attendance as a habit is a major challenge for the years to come.

One should realise that back around 1980 not all physicists in Europe were convinced of the utility of a CMD conference at the European level – and that this sentiment remains today! Some expressed the opinion (sometimes strongly) that national physics society meetings were to be preferred in Europe. It is then no surprise that, over the years, much attention and energy of the CMD Board has been devoted to promote the conference and to convince colleagues to attend. It is truly encouraging that, for the last issues, a growing number of communities have elected CMD as its biyearly rendezvous.

▾ Table II: CMD Board chairs

YEAR	FIRST NAME	SURNAME	INSTITUTION
2014 -	Kees	VAN DER BEEK	CNRS, Palaiseau, France
2004 - 2014	Eoin	O'REILLY	Tyndall, Cork, Ireland
1998 - 2004	Hans Rudolf	OTT	ETH Zürich, Switzerland
1992 - 1998	Peter	WYDER	Max Planck Institute, Grenoble, France
1986 - 1992	Franco	BASSANI	Scuola Superiore Normale, Pisa, Italy
1980 - 1986	Jozef T	DEVREESE	Universiteit Antwerpen, Belgium
1978 - 1980	Minko	BALKANSKI	Université Pierre et Marie Curie, Paris, France
1976 - 1978	Walter	MERZ	RCA Labs, Zurich, Switzerland
1973 - 1976	André	GUINIER	Université Paris-Sud, Orsay, France
1968 - 1973	Samuel F.	EDWARDS	Cambridge University, United Kingdom

CMD Sections

Because condensed matter covers such a broad range of fields, a series of sections specializing in different areas of CM physics have been established (see Table I). Several of these have established highly successful, large specialist

[5] http://cmd.epsdivisions.org/

conferences, including the European Conference on Surface Science (ECOSS), which has been running on an annual basis since 1978, the annual Joint European Magnetism Symposia (JEMS), and the EPS Liquid Matter Conference, which takes place every three years. Other sections run and are involved with successful smaller meetings (*e.g.* the Low Temperatures, the Semiconductors and Insulators, and the Structure and Dynamics of Condensed Matter sections), or highly successful Schools (*e.g.*, the bi-yearly Cryocourse of the Low Temperature Section or the European School on Magnetism of EMA[6]).

The recognition of European Condensed Matter Physics

The greatest impact of the EPS Condensed Matter Division has probably been through the establishment and award of what is now called the "EPS Europhysics Prize for Outstanding Achievement in Condensed Matter Physics". The object is stated as: "*The award will be given in recognition of recent work by one or more individuals in the area of condensed matter physics, which, in the opinion of the selection committee, represents scientific excellence… The award will recognize research for which a significant portion of the work was carried out in Europe, and may be given for either pure or Applied research at the discretion of the Society*". Originally sponsored by Hewlett Packard, the Prize was strongly supported by Agilent Technologies until the re-alignment of their outreach activities in 2006. Most key research areas of condensed matter physics are represented and honoured through the work of the Europhysics Prize laureates. Several laureates went on to become Nobel-laureates, both in physics and in chemistry: one has, *e.g.*, Z.I Alferov (EPS-Prize: 1978/Nobel Prize 2000), K. von Klitzing (1982/1985), G. Binnig and H. Rohrer (1984, 1986), J. Bednorz and K.A. Müller (1988/1987), G. Ertl (1992/2007), H. Kroto (1994/1996), A. Fert and P. Grünberg (1997/2007), and A. Geim and K. Novoselov (2008/2010). The EPS Europhysics Prize of a laureate always preceded the Nobel Prize. This includes Bednorz and Müller, for whom the EPS Prize was announced in EPN in October 1987, although –formally- the prize was for 1988. In 1985, Hewlett, the founder of HP expressed his great satisfaction when the 1982 laureate of the HP-Europhysics prize (von Klitzing) was awarded the Nobel Prize.

In the wake of the Nobel Prizes for P.G. de Gennes in 1991 and A. Leggett in 2003, the EPS Liquid Matter Prize "*for outstanding achievements in physics of liquids*" was instated alongside the Europhysics Prize in 2005, so as to ensure that all areas of Condensed Matter physics are duly recognized. Liquid prize laureates include D. Chandler who, with H. Andersen and J. Weeks, is at the origin of our understanding of the molecular nature of liquid matter and glass formation, and R. Evans, who made fundamental and lasting contributions to the physics of interfaces, capillarity, wetting, and phase transitions in fluids.

The fields covered by laureates of the two prizes attest to the vitality and pioneering character of CM research in Europe, as well as to its major impact on our daily lives. The Quantum Hall effect (QHE) constitutes a striking advance in metrology – it came as a total surprise that QED-precision experiments can be realized in a MOSFET, with the later discovery of fractional charge and a new kind of quantum fluid in GaAs/AlGaAs heterojunctions. That atomic scale resolution can be reached in scanning tunnelling microscopy (STM) by recording the vertical movement of a sharp tip across a solid surface is actually astonishing. The discovery of superconductivity in ceramic materials, with a Tc 12 K above the record of 23 K realized in Nb_3Ge in 1973, soon followed by materials with Tc's up to 150 K (discovered in Europe), came as a third explosive development in condensed matter physics. This has now been followed by the remarkable discovery of electron-phonon mediated high Tc superconductivity in H_2S under high pressure, again, a European achievement.

The QHE (1981), the STM (early 1980's), and high-Tc superconductivity (1986) have brought three breakthroughs in condensed matter physics that had an immense impact, within just a five-year span. The Nobel Prize for developing semiconductor hetero-structures used in high speed- and opto-electronics (2000) has laid the foundation of modern IT, while the 2007 Nobel Prize honouring the technology to read data on hard disks is of tremendous significance for further miniaturization. The work on graphene (2008), topological insulators and the quantum spin hall effect (2010), two-dimensional electron liquids (2014), skyrmions (2016), are likely to have a similar influence on the nano-electronics, sensors, and computational devices of the future.

▾ **FIG. 3:** Opening Session of CMD25 in Paris, 2014

[6] The European Magnetism Association, see http://magnetism.eu/

YEAR	WINNERS	TOPIC
1975	V.S. Bagaev, L.V. Keldysh, J.E. Pokrovsky, M. Voos	The condensation of excitons
1976	W. Helfrich	Contributions to the physics of liquid crystals
1977	W.E. Spear	Amorphous silicon devices
1978	Z. I. Alferov	Heterojunctions
1979	E.A. Ash, J.H. Collins, Y.V. Gulaev, K.A. Ingebrigtsen, E.G.S. Paige	The physical principles of surface acoustic wave devices
1980	O.K. Andersen, A.R. Miedema	Original methods for the calculation of the electronic properties of materials
1982	K. von Klitzing	Experimental demonstration of the quantized Hall resistance
1983	A.F. Silvera	Atomic and solid hydrogen
1984	G.K. Binnig, H. Rohrer	Scanning tunnelling microscope
1985	J. Als-Nielsen, M. Pepper	The experimental study of low dimensional physics
1986	F. Mezei	Neutron spin echo spectroscopy
1987	I.K. Yanson	Point-contact spectroscopy in metals
1988	J.G. Bednorz, K.A. Müller	Discovery of high-temperature superconductivity
1989	F. Steglich, H.-R. Ott, G.G. Lonzarich	Pioneering investigations of heavy-fermion metals
1990	R. Car, M. Parrinello	A novel and powerful method for the ab-initio calculation of molecular dynamics
1991	K. Bechgaard, D. Jérome	Synthesis of a new class of organic metals and the discovery of their superconductivity and novel magnetic properties
1992	G. Ertl, H. Ibach, J. Peter Toennies	Pioneering studies of surface structures, dynamics and reactions through the development of novel experimental methods
1993	B. L. Altshuler, A. G. Aronov, D. E. Khmelnitskii, A. I. Larkin, B. Spivak	Theoretical work on coherent phenomena in disordered conductors
1994	D. R. Huffman, W. Krätschmer, H. W. Kroto, R. E. Smalley	New molecular forms of carbon and their production in the solid state
1995	Y. Aharonov, M. V. Berry	Introduction of fundamental concepts in physics that have profound impact on condensed matter science
1996	R.H. Friend	Pioneering work on semiconducting organic polymer materials and demonstration of an organic light emitting diode
1997	A. Fert, P. Gruenberg, S.S.P. Parkin	Discovery and contribution to the understanding of the giant magneto-resistance effect in transition-metal multilayers and demonstrations of its potential for technological applications
1998	M.T. Rice	Original contributions to the theory of strongly correlated electron systems
1999	C. Glattli, M. Reznikov	For developing novel techniques for noise measurements in solids leading to experimental observation of carriers with a fractional charge.
2000	P. Carra, G. van der Laan, G. Schütz	Pioneering work in establishing the field of magnetic x-ray dichroism
2001	S. Iijima, C. Dekker, T. W. Ebbesen, P.L. McEuen	Discovery of multi- and single-walled carbon nanotubes and pioneering studies of their fundamental mechanical and electronic properties.
2002	B. Barbara, J. Friedman, D. Gatteschi, R. Sessoli, W. Wernsdorfer	Development of the field of quantum dynamics of nanomagnets, including the discovery of quantum tunnelling and interference in dynamics of magnetization.
2003	H. Finkelmann, M. Warner	Discovery of a new class of materials called liquid crystal elastomers.
2004	M. Devoret, D. Esteve, J. Mooij, Y. Nakamura	Realisation and demonstration of the quantum bit concept based on superconducting circuits.
2005	D. Awschalom, T. Dietl, H. Ohno	Work on ferromagnetic semiconductors and spintronics
2006	A. Georges, G. Kotliar, W. Metzner, D. Vollhardt	Development and application of the dynamical mean field theory
2008	A. Geim and K. Novoselov	Work on graphene
2010	H. Buhmann, C. Kane, E. Mele, L. W. Molenkamp and S. Zhang	Quantum spin Hall effect and topological insulators.
2012	S. Bramwell, C. Castelnovo, S. Grigera, R. Moessner, S. Sondhi, A. Tennant	Magnetic monopoles in spin ice.
2014	H. Y. Hwang, J. Mannhart, J.-M. Triscone	Electron liquids at oxide interfaces.
2016	A. Bogdanov, P. Böni, C. Pfleiderer, A. Rosch, A. Vishwanath	Magnetic skyrmion phase in MnSi
2018	L. Braicovich and G. Ghiringhelli	High-resolution Resonant Inelastic X-ray Scattering (RIXS)

▲ **Table III:** Europhysics Prize of CMD, list of laureates.

Perspectives

The award-winning work discussed above is inconceivable without the existing fertile ground for research in Europe. Many European physics institutes host internationally leading condensed matter groups with great impact, along with highly talented and successful young researchers, often working in worldwide collaborations: they form the basis for future innovative work. In spite of insufficient funding as a whole, European science can count on a coordinated public policy on the EU level, with, notably, the highly successful ERC and Marie Curie-Sklodovska schemes, that promote flourishing individual research as well as exchange. It is our task at EPS – and at CMD - to reflect on European research strategies, help define them, and to propel physics as a discipline essential both for gathering fundamental knowledge and for fostering innovative solutions to solve modern-day problems.

Condensed Matter Physics is a very broad field that touches some of the deepest phenomena in nature: symmetry breaking, quantum mechanics, superconductivity, superfluid matter, fractional charges, topological properties, complex systems, to name but a few. It has undergone many great changes in the last decade or two, with the advent of new experimental techniques with stunning resolution and precision, of new *in situ* and *operando* techniques, the treatment of data sets the magnitude of which was inconceivable until recently, and the use of phenomenal computational power. Developments in material physics, notably nanomaterials, functional materials, and hybrid materials set the stage for new revolutions. The impact of condensed matter physics and its methods on disciplines such as chemistry and the life sciences is greater than ever. Thus, the developments in condensed matter research enable the technologies of our modern, technological society, and allow physicists to work at the frontiers of both science and technology. EPS - CMD and its sections have represented and accompanied the strong European Condensed Matter community over the last 50 years. and are committed to not only continue doing so, but to play a central role as a forum for discussion, reflection, organization, and proposition - for at least the next 5 decades! ■

About the Authors

Jozef T. Devreese is emeritus professor at Universiteit Antwerpen (Belgium), where he founded the research group TFVS (Theoretische Fysica van de Vaste Stoffen). He is also 'professor extraordinarius' at the Technische Universiteit Eindhoven (the Netherlands). He notably contributed to the theory of polarons, to quantum theory of solid matter, to superconductivity, and superfluidity, and to nanophysics). Jozef was chair of the first CMD General conference, CMD1 Antwerp, in 1980, chair of the EPS Condensed Matter Board from 1980 to 1986, and member of the Board from 1989 until 1995.

Eoin O'Reilly is Professor of Physics at University College Cork, Ireland, and Chief Scientist at Tyndall National Institute. His research interests mainly concern the physics and applications of semiconductor devices and materials and optoelectronics. Eoin O'Reilly chaired CMD19 in Brighton in 2002. He was Chairman of the EPS Condensed Matter Division Board from 2006 to 2014.

C.J. (Kees) van der Beek is a senior researcher at the French Centre National de Recherche scientifique, and head of the Physics of Light and Matter Department of the newly founded Université Paris-Saclay. His research interests concern superconductivity, magnetism, and the physics of disordered materials. Kees chaired CMD25 in Paris in 2014, and has been EPS-CMD Board chair since 2015.

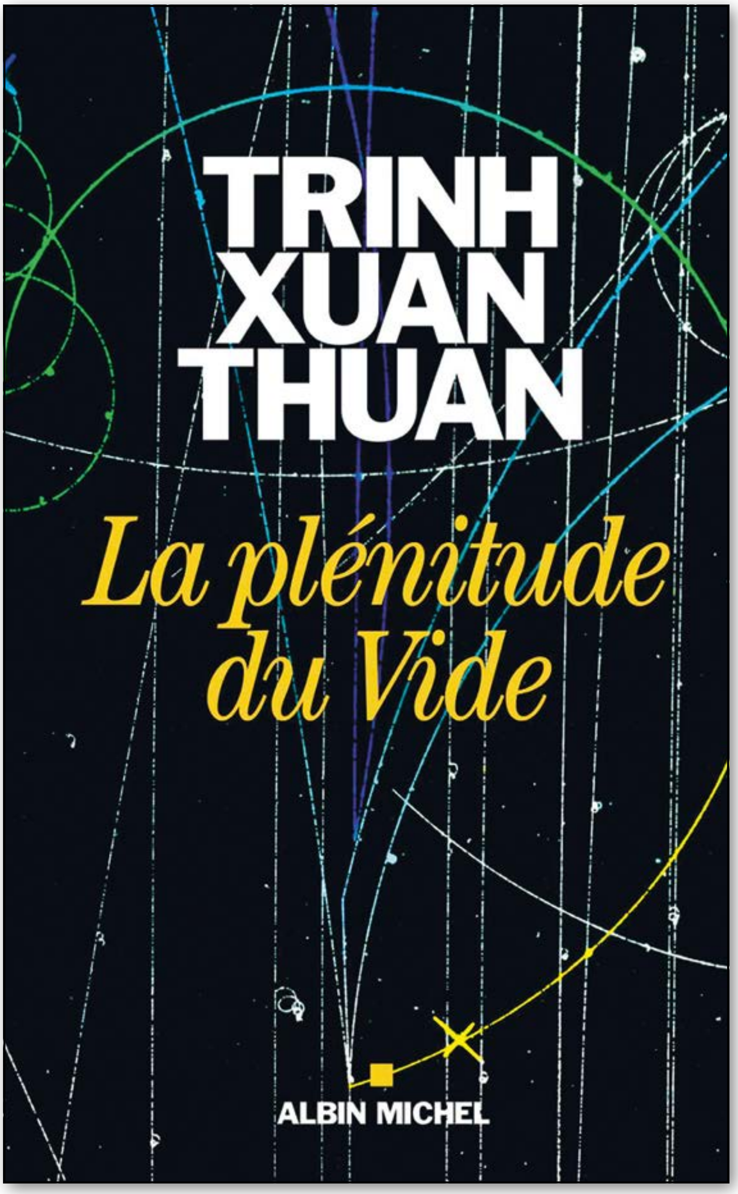
▼ **FIG. 4:** Anna Minguzzi, Eoin O'Reilly, and Jean-Marc Triscone at CMD25, Paris, 2014.

2017	Jacob Klein	Soft and liquid matter under confinement
2014	Robert Evans	Application of density functional theory to the statistical mechanics of liquid matter,
2011	David Chandler	The molecular nature of liquid matter
2008	Henk Lekkerkerker and Peter Pusey	The phase behaviour of, in particular, rodlike and plate-like colloids
2005	Jean-Pierre Hansen	The statistical mechanics of complex fluids and biomolecular assemblies

◀ **Table IV:** Liquid Physics Prize of CMD, list of laureates.

BOOK REVIEW
"LA PLÉNITUDE DU VIDE"

This fascinating book - unfortunately not yet translated into English - offers an extremely rich overview of the evolution of our conception and understanding of vacuum.



Author: Thuan Trinh Xuan
Editor: Albin Michel
Collection: A.M. GD FORMAT
ISBN: 978-2226326423
Price: 20.90 €
352 pages

Although brilliantly written in terms understandable for the general public, the many physical concepts make it certainly more enjoyable and easy to read for physicists. Chapters are very well constructed and one topic naturally leads to the next one, while informative illustrations embellish the reading. The book starts with a history of mathematics from antic times and the difficulty or reluctance to introduce the digit zero, which is so useful in daily calculation. In the second chapter, the author returns to Ancient Greece with the emergence of an atomistic vision of the world, quickly forgotten for an Aristotelian view leaving no space to emptiness. This "horror vacui" will last for some twenty centuries until Galileo, Torricelli, and then Pascal are able to change this view with vacuum experiments in glass tubes. The idea that light needs a medium called ether to propagate was also a long-lasting idea followed among others by Newton, Fresnel, Faraday and Maxwell until the end of the XIXth century. At that time, the famous experiment of Michelson and Morley opened the way to Einstein's theory of relativity getting finally rid of the notion of ether. The author retraces these main chapters of the history of science with brevity, but still striving for correctness and always pointing out the remarkable achievements of these outstanding scientists. The following chapter is devoted to the building up of quantum mechanics and the emergence of the notion of quantum vacuum having a measurable Casimir effect, and leading to the evaporation of black holes via Hawking radiation. The author then moves to cosmology, with the birth of the universe out of vacuum and the growth of initial quantum fluctuations into galaxies and large scale structures. Inflation, multiverses and other complicated concepts like string theory, super-symmetry and folded extra-dimensions are always introduced with simple terms, and sometimes enlightening comparisons with arts, music or painting. The last chapter attempts to bridge rational science with spirituality in oriental traditions like Hinduism, Buddhism and Taoism. An amazing dive into the contemplative notion of non-duality between fullness and emptiness echoing the scientific exploration of an acting vacuum. A truly full vacuum wonderfully depicted in this book as being the underlying essential source of our material universe and sustaining its subsequent evolution towards increasing diversity and complexity.

Marc Türler
Swiss Academy of Sciences

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