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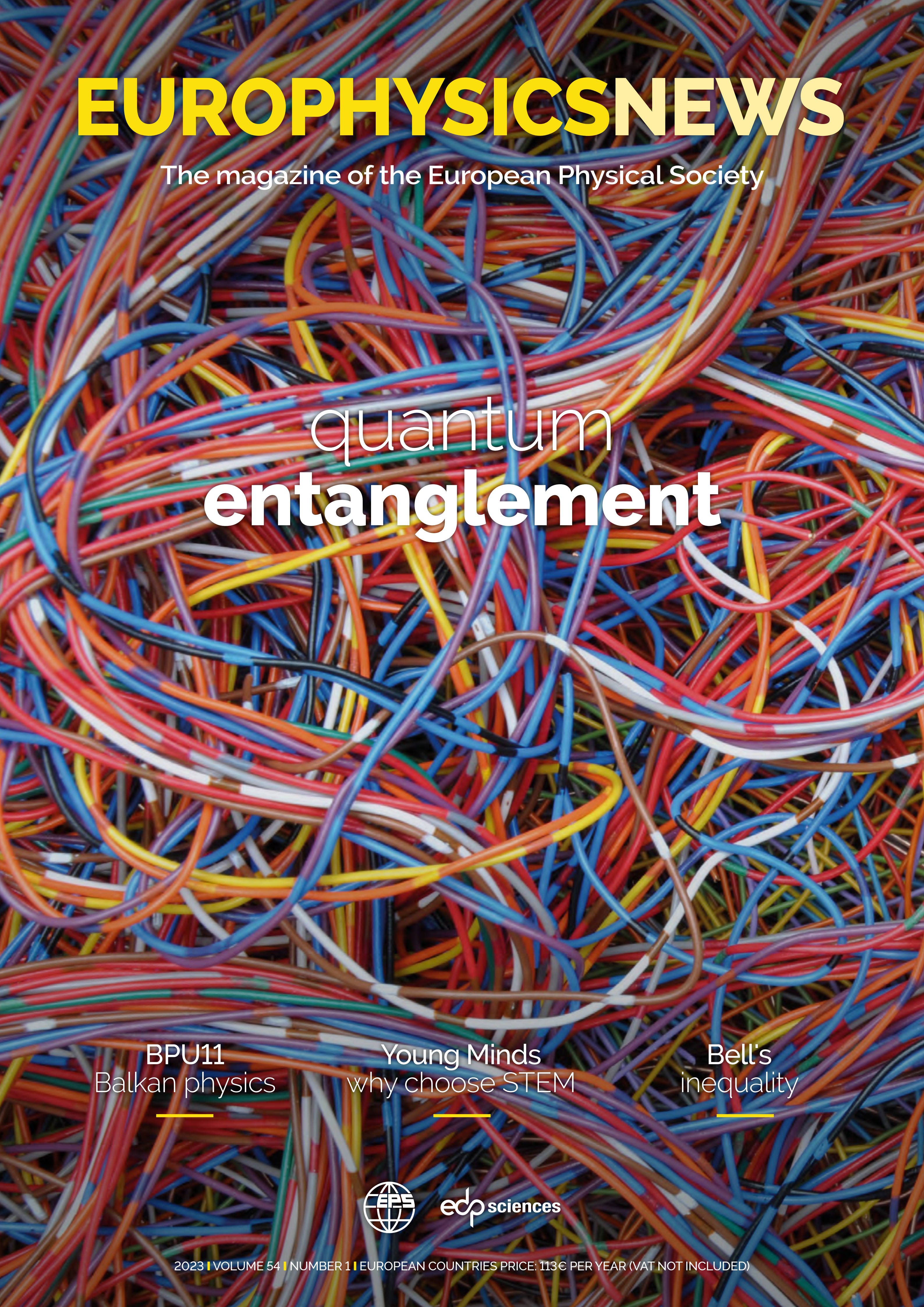

quantum
entanglement

BPU11
Balkan physics

Young Minds
why choose STEM

Bell's
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EPS edp sciences

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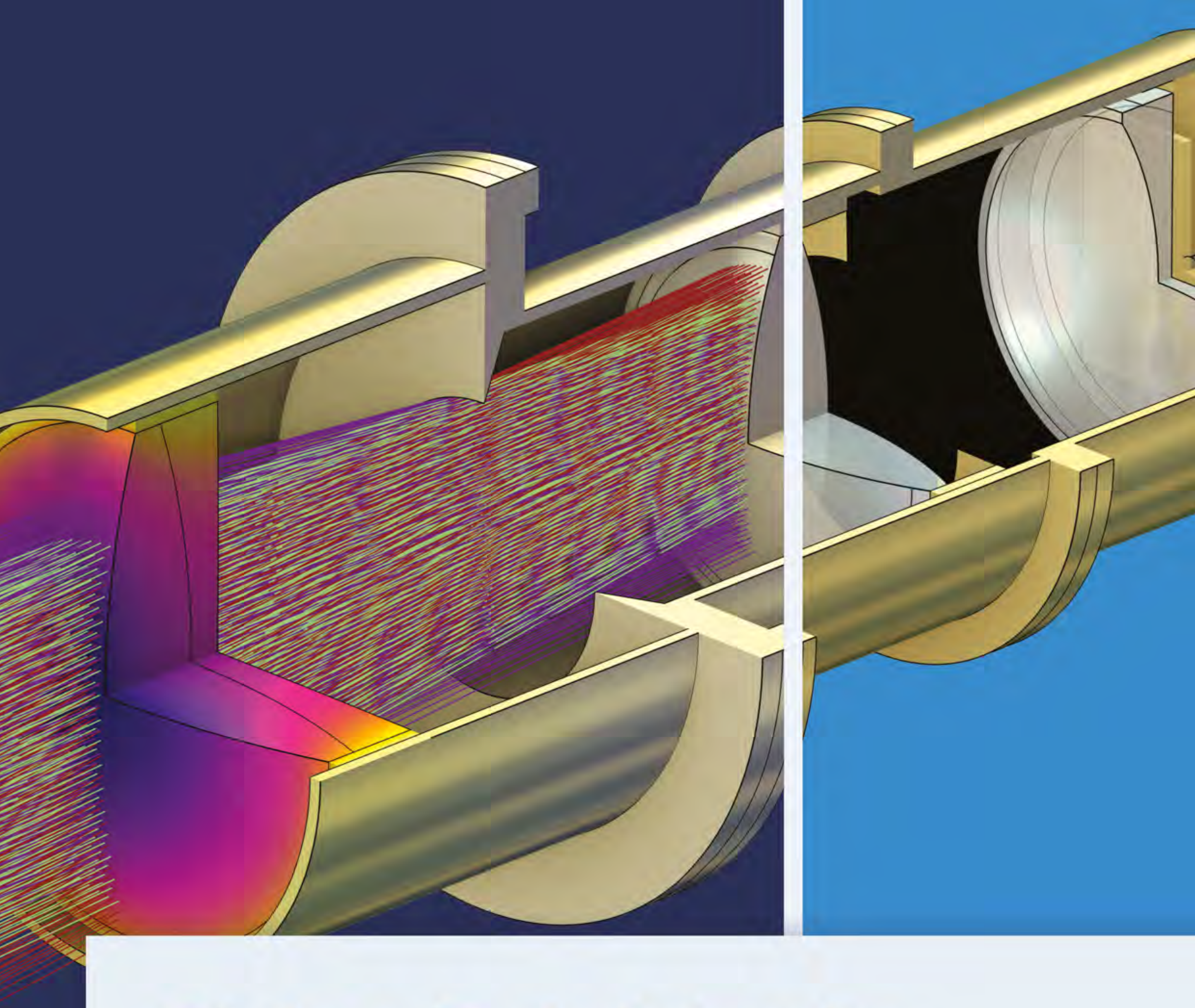

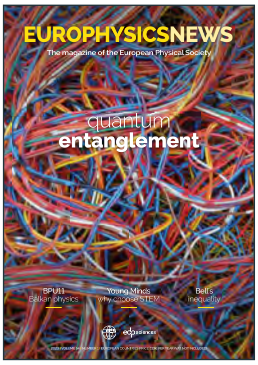

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Cover picture: Entanglement, although not Quantum entanglement. The latter is explained in the features articles in this issue. ©iStockPhoto

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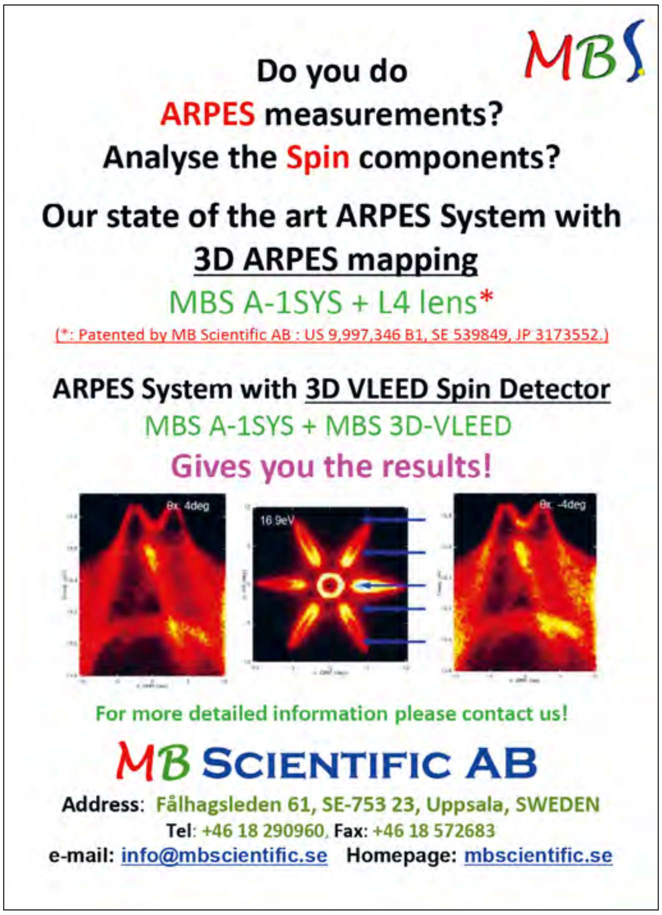
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[EPS EDITORIAL]

And Now for Something Completely Different?

In 1997, the European Union (EU) was called the European Economic Community (EEC) and it had 15 Member Countries. Over the past 25 years the EU has grown to 27 Member Countries, with a further 8 candidate countries hoping to join. The current international crises (war in Ukraine, the COVID19 pandemic, *etc.*) have not only shown the value of a unified Europe, but also that the EU is a robust institution that can adapt to rapidly evolving situations. Over the same period (1997-2023), the budgets for the Framework programmes have seen a significant increase. The budget for Framework Programme 4 (1994-1998) was 13.2 billion euros. The current Framework Programme 9 - Horizon Europe - has a budget of over 95 billion euros. Creating a world class knowledge-based economy and investing in the research and technologies that will allow us to address future challenges are among the many reasons for supporting frontier research in Europe. Over the same period, the European Physical Society grew to 42 Member Societies and has become a recognised stakeholder, providing regular input into EU Science policy. The EPS has also played a key role in organising large international events, including the provision of logistical support for 1st International Conference on Women in Physics (Paris 2002), The International Year of Physics in 2005 and the International Year of Light in 2015. The EPS has been actively pursuing its goals of creating and representing the European physics community.

Given the success of European collaborations and the growth in European funding programs where else can the EPS contribute in the transformed landscape?

The rise in European research programmes and their frequent requirement for researcher mobility has increased the diversity of research groups across the continent, with researchers bringing new perspectives and expertise to their new groups. Mobility, however, can be challenging on a personal level, it takes time to settle into a new country and find a community whilst simultaneously carrying out research. The EPS Young Minds Sections play a valuable role in creating communities, providing opportunities for engagement with the academy and the possibility for EPS members at the start of their careers to develop leadership skills. There is an opportunity here for EPS and the European physics community to further support its members from the very earliest stages of their careers.

Another area in which the EPS can play an even greater role is in highlighting the role of physics beyond the academy. Our active Physics Education Division works to improve and inform the teaching of physics in schools and in informal settings. We should remember that for many policy makers, high school is their last contact with physics. It is vital that EPS demonstrates the value of physics beyond the laboratory, both to the economy and to informed policy making. Physicists can be found in both established industries and in developing technologies, and their influence in policy making goes beyond contributions to traditional areas of policy such as space or energy to encompass the development of epidemiological models during the pandemic or inform transport policy. Our Associate Members provide a vital link to this community of scientists, but we can still do more to engage them in the broader physics community.

What does this mean concretely for EPS? We will continue with our core business, supporting our members, recognising excellence, advocating for physics education and research, and representing the physics community. We are participating in two new European projects in physics education and informal scientific education. We are developing and testing new digital tools for community engagement, to help our Divisions and Groups connect to their members and to better communicate within and beyond our community. Finally, as the world returns to in-person meetings we hope to use the tools developed during our enforced virtual interactions to enrich our conferences and include as many people as possible.

Whilst we have plans and ambitions, the last few years have taught us that adaptability is key and nothing is certain except the inviolability of the second law of thermodynamics. ■

Anne Pawsey and David Lee,
Secretaries General EPS

EPS Young Minds

Why choose STEM fields?

Hripsime Mkrtchyan[1], Anna Grigoryan[2], Tsovinar Karapetyan[1], Stella Avetikyan[3]

[1] Yerevan Young Minds section, [2] Artsakh Young Minds sention, [3] Strong Mind NGO

Which profession should I choose? Which specialisations are demanded? How much money will I earn after getting my degree? Those are questions which school kids are trying to answer when they are going to take one of the most important decisions in their lives. At the STEM Summer Camp 2022 in Armenia, young students were introduced in STEM (Science, Technology, Engineering, and Mathematics) fields. Are these fields popular among the young? Are they attractive and promising for them?

The problem

During the last decade the number of STEM students in the universities of Armenia drastically decreased. For instance, the number of enrollments applications in the physics faculty at the Armenian State Pedagogical University has decreased with a factor 200 in the period 2010 to 2021. The same situation occurred in other universities in Armenia and some other parts of the world. This endangers not only the education system, but also scientific institutions as the number of young researchers is also decreasing. The main reason for the decrease seems to be the lack of information and communication. Many of the students don't know about the advantages and perspectives of working in STEM fields. For instance, Armenia has diverse institutions and organisations, which can provide them a good working experience, knowledge, mentorship, and salary.

About the project

To find a solution to the problem, during the summer of 2022 the EPS Yerevan Young Minds section in collaboration with the 'Student Home' project and the 'Strong Mind' NGO organised a STEM Summer Camp for 50 high school students from the different regions of Armenia. The goal of the camp was to break the stereotypes about professions in STEM fields and to discover the path of a scientist. The project helped to promote STEM among school kids, expand knowledge in natural science and mathematics subjects and bridge the gap to science. The participants visited the developed scientific institutions of Armenia and discovered the real life of scientists.

> **"The STEM Summer Camp 2022 provided students a valuable learning environment"**

▼ Participants of the STEM Summer Camp 2022

The organising team coordinated and scheduled visits to scientific centers, and organised individual meetings with scientists. The agenda was designed for the full presentation of strong and developed scientific institutions and research centers of Armenia. During the camp the participants visited Engineering city, the Faculty of Physics of YSU, the A. Alikhanyan National Laboratory of Armenia, the Bazoomq Space Research Lab, the Acopian Center for the Environment and College of Science and Engineering, AUA *etc.* The visits and meetings with

▴ Hands-on experience with lab-work.

successful scientists and researchers included as many branches of STEM disciplines as possible. Different scientists gave presentations about their experience and informed them about the career opportunities and importance of different branches of science. They had the opportunity not only to learn the importance of STEM directions but also had a chance to take part in different activities, aimed at the support of the development of soft skills and personal growth. So, the STEM Summer Camp provided a valuable learning environment for participants in extraordinary ways.

The ages of participants were varied between 14 - 17, as most young people in these ages are concerned about choosing their academic specialisation path. They have been selected from 48 high schools from all regions of Armenia, including Artsakh and abroad. In Yerevan they have stayed at the 'Students Home' which has provided not only accommodation but also a unique platform for self-development. The STEM Summer Camp was highlighted in Armenian leading TV media and on social platforms.

Ongoing steps

Currently, we, the organisers, have created a small focus group which is keeping contact and monitoring the career path of the participants. Moreover, active participants have the opportunity to be involved in scientific projects organised by the institutions and laboratories that they have visited. In January 2023, 10 of them will be selected and will work for one week as a 'shadow' of scientists in their preferred institutions. The project is funded by the YSU Association of Physics Alumni and Friends (APAF). The activities like the STEM Camp broke the stereotypes about 'poorly' developed laboratories in Armenia and gave the opportunity for school students to see and feel real science with their own eyes. ■

'Im (westlichen) Balkan nichts Neues ?!' the BPU11 Congress

The idea for a Balkan Physical Union (BPU) was first proposed by Prof A. Milojević, who was the first director of the Institute of Physics in Belgrade. His idea was put in motion at the last Congress of the Union of Yugoslav Societies of Mathematicians, Physicists and Astronomers (UYSMPA), held in Pristina (Yugoslavia) in November 1985. Nowadays, the BPU is a unique regional physics organisation committed to building bridges of collaboration with the physics community of the whole European continent. A report by Goran Djordjević.

Paradoxically, the idea for official regional cooperation was raised, and soon widely accepted, when political tension in the Socialist Federal Republic Yugloslavis increased. The framing of such a non-governmental, non-profit scientific organisation stemmed from positive experiences of Scandinavian scientific unions and some other ideas from the Mathematical Union. The first BPU Council meeting was held in Bucharest in 1987, when the constitution of the BPU was signed by the Balkan National Physical Society delegates from Albania, Bulgaria, Greece, Romania, and Yugoslavia. Turkey's signature was accepted later. Prof. Ioan Ursu, from Romania and former EPS president, was the first BPU president. With the Montenegrin Society of Mathematicians and Physicists joining BPU in 2006, the number of BPU members has grown to ten national societies in physics: Albania, Bulgaria, Cyprus, Greece, Moldavia, Montenegro, North Macedonia, Romania, Serbia, and Turkey.

The BPU11 Congress

The BPU Congress was initiated in 1991 with BPU1 and is an important part of the BPU program of activities. It is an international general physics conference, open for participants from all over the world. The agenda of the BPU11 Congress[1] covered experimental and theoretical research in all major physics research fields and also included contributions about physics education, meteorology, environmental physics, alternative sources of energy, physics of socioeconomic systems and metrology. As a novelty, the program contained a special scientific section 'Frontiers' and several round tables on broader issues like studying physics, physics education, employment of young physicists, quantum and new technologies, and research funding issues in the physics community in Eastern and Southern Europe[2]. An exhibition of scientific-artistic posters was organised under the CERN art@CMS/Origin and Cultural collisions programs.

▲ Young participant of BPU11.

As a hybrid event, the BPU11 attracted about 476 participants from 31 countries with around 325 onsite. Loosely speaking, every 3rd participant and every 4th lecturer/poster-presenter was a student. In this respect the BPU1 Congress was "young"!

During the opening ceremony representatives of EPS (President Prof. L. Bergé, and Secretary General David Lee), CERN (Prof. J. Mnich, Director for Research and Computing) and numerous academies and universities from the Balkans were present. Representatives of the Serbian Academy of Sciences and Arts (SASA) and practically all universities, faculties, departments of physics, and several of mathematics in Serbia took an active part in the program[3]. Twenty-one posters were awarded thanks to the support of the European Physical Journal (EPJ) and the SEENET-MTP Network[4]. The BPU and the SEENET-MTP Councils awarded David Lee with the Charter and honorary membership for his great contribution to BPU and the SEENET-MTP program and for strengthening their cooperation with EPS for decades.

The proceedings of the conference will be published in a special issue of Proceedings of Science; several invited lectures will be published in a Focus Point Issue of EPJ Plus "On Physics in the Balkans: Perspectives and Challenges", while topical articles in Theoretical High Energy Physics and related fields, from both the Congress and its satellite events, will be published with IJMPA.

[1] https://bpu11.info
[2] More details and some reports are available at https://bpu11.info/about-bpu11/round-tables
[3] https://bpu11.info/about-bpu11/program
[4] Southeastern European Network in Mathematical and Theoretical Physics. See https://www.seenet-mtp.info

▲ Participants of BPU11 with invited speakers and guests on the first rows.

Satellite events

The BPU11 Congress had four high-level scientific satellite events: the COST CA18108 Workshop on theoretical aspects of quantum gravity; the SEENET-MTP Assessment Meeting and Workshop BWAM22; the COST School on Quantum gravity phenomenology in the multi-messenger approach; and the CERN – SEENET-MTP – ICTP Ph.D. School Gravitation, Cosmology, and Astroparticle Physics - BS2022, with additional 140 on-site participants.

The BS2022 school was the closing event in the 2nd cycle of the CERN – SEENET-MTP – ICTP Ph.D. program. This program was initiated by SEENET-MTP and CERN in 2015 and formalised by the CERN-SEENET framework agreement in 2017. In 2018, the agreement was joined by ICTP, while EPS supported the program through its Committee of European Integration (CEI). It might be a unique regional program in HEP in Europe that contributed to the training of more than 200 students in 12 SEENET countries, so far.

EPS, BPU and the BPU11 Congress

EPS and BPU jointly contributed to the success of the BPU11 congress. Prof. L. Bergé and Dr. K. Grandin gave the plenary lectures; practically all round table sessions were organised and supported by EPS, EPS YM, and the EPS Office in Brussels represented by Dr. E. Sanchez. Prof. G. Zwicknagl and a high-level delegation of DPG highly contributed to several round tables and to the Program of the EPS-CEI. EPS representatives and members were active in various committees and programs.

Besides the strong financial and organisational support of EPS, the BPU11 would not have been possible without the support from ICTP and CEI-Trieste, CERN, EPJ, as well as the Ministry of Education Science and Technological Development, Serbia, SASA, numerous Faculties, Departments, and Institutes active in Sciences, from Serbia.

Is there anything new in 'Balkan physics'?

Nowadays, four BPU-countries are member states of the EU, while the Western Balkan (which means Former Yugoslavia minus Croatia and Slovenia, plus Albania) has been stacked, at least formally, in the EU integration for decades now. Unfortunately, despite the fact that most or all BPU countries may apply for EU funds, in practice and for many reasons, the Balkan physics community rarely wins in these 'races'.

▼ David Lee (left) receives the award paraphernalia from the hands of BPU president Goran Djordjević (right) (see text).

In August 2022, during the 11th BPU Congress in Belgrade, Serbia, the BPU accepted a new constitution and became a legal entity with its Headquarters at the Department of Physics of the Aristotle University in Thessaloniki; a chain of four Balkan Physics Olympiads and a few new programs were established and ongoing BPU programs confirmed.

Being aware that financing for research and education comes through completely different channels most of the leading physicists in BPU states are less active in their national societies. As a result, independent of the size of the BPU state, the organisations of these national societies are fragile and their budgets are usually low. Because of that, but also in a wider framework, an active role and financial support from EPS for 'cohesive' activities remain important for the Balkan physics societies. In particular in the Western Balkan with specific actions for Albania and North Macedonia.

On the personal level, the BPU11 Congress and 20 years of activities in BPU and SEENET of both my colleagues and myself have been our contribution to preserve and strengthen 'Balkan' cooperation, and (re)build bridges of collaboration with the physics community of the whole European continent. In this, we had the significant support of almost all EPS presidents, David Lee (as the EPS Secretary General), and numerous colleagues from EPS. Thank you all for that.

See you at BPU12 in Romania! ■

Prof. Goran S. Djordjević, BPU president 2018-2022

Interview with María Pilar López Sancho

María Pilar López Sancho is Research Professor at the Materials Science Institute of Madrid-CSIC. She works on field theory in condensed matter physics. Kees van der Beek, Chair of the jury, spoke with her about her career, the effectiveness of advocacy of gender equality and the future of actions for equality.

Congratulations with the Winter 2021 Emmy Noether Distinction! How did you choose physics as a career path? What was it like for women to engage in a scientific career in the late nineteen-sixties, early nineteen-seventies?

"At the time, most schools in Spain were of religious character, and schools were separated by gender. Therefore, all my classmates were girls. At age 14, we had to decide on our future studies, whether we preferred humanities or the sciences. In my class, we were five to choose physics. I wished to look beyond pure mathematics and study other areas of the natural sciences. While as women we were certainly a minority in the scientific field, we were not few, in particular in fields such as chemistry. The first time I realised that we were indeed a minority was during my laboratory work at the university. Those years corresponded to the final convulsions of Franco's regime. University life was punctuated by intense political activity, and by external policing of university affairs. Nevertheless, I look back on them dearly: they were filled with comradeship, intensive learning, and acquiring very many formative experiences. After university, many of us wanted to pursue theoretical physics, in which there were few professional opportunities and very few professorial chairs. I therefore came to experimental physics, where I was immediately drawn to surface physics and the interaction of gases with metallic surfaces. At the time, the development of new experimental techniques such as Angle-Resolved Photo-Emission Spectroscopy (ARPES) was absolutely spectacular. However, the funding of Spanish science in the day was such that many experimentalists, including myself, moved to modelling of the latest results, and, from there, to theoretical condensed matter physics. I am surrounded by laboratories though, and have maintained proximity with experimentalists."

How did you move into the field of low-dimensional materials?

"I had been working on the physical and electronic properties of metals and had developed techniques that I could quickly apply to the cuprate high temperature superconductors discovered in 1986, to other highly correlated electronic systems, and to carbon nanotubes. In parallel, several colleagues of mine worked on the hypothesis of Dirac-like electron physics in two-dimensional carbon, or graphene, even before this was isolated. When it was, it was natural to shift our attention to that system."

Among the many areas of condensed matter topics that you have studied, which appealed the most to you as a particular challenge?

"Twistronics and the currently much studied twisted bilayers and multilayers built of two-dimensional materials are extremely interesting and very challenging. They require taking very large numbers of atoms into account for any computational effort. Besides that, I am most interested in the topological properties of electronic systems, and the relation between topology and disorder."

You have built a very rich "second career" in furthering gender equality and the cause of women physicists. How did you start?

"For most of my career, I took no notice of the position of women in physics. However, in 1999, the Massachusetts Institute of Technology published an astounding report assessing gender segregation, bias, and inequality within their faculty. The MIT study was quickly followed by assessments of gender bias in scientific institutions in Europe, published by the European Commission. I then realised, with my colleagues, that at ICMM and in Spain we were in a similar situation: there was profound inequality in career progress, with not a single woman in the higher ranks of our institutions. I started to undertake action in 1999. The American Physical Society had founded their Committee on the Status of Women in Physics (CSWP), so I requested that the Royal Spanish Physical Society RSEF create a similar section – this happened in 2001. To build the case, we had gathered figures on the role and representation of women physicists in Spain. It was thus that I got noticed, and then invited, with three RSEF colleagues, to attend the 2002 IUPAP International Conference on Women in Physics in Paris, where I met our colleagues who lead the first actions at MIT. With many others, from all over the world, we decided that physics should be done differently, and that we should do all we could to attract young women to a physics career. Once involved, I could not go back. I realized the importance of the issue, and before long had many responsibilities."

How did you balance your activity with your research?

"I am a theoretical physicist, and do not head a permanent group. Therefore, my scientific production depends directly on the number of hours I personally put in. Once I got involved in the Women and Science Commission (Comisión Mujeres y Ciencia) of CSIC and in the Association of Women Scientist and Technologists (AMIT), I was solicited for a much wider range of issues that I initially foresaw, urgent issues that demanded action. For example, many young women encountered great difficulties reconciling maternity and their scientific career. If nothing were done, their career would collapse. Even if it was not my original role, these women had nowhere else to turn. I believe that we did much for science by helping create conditions that allowed them to continue. The payoff was that I have met an incredible amount of very diverse and interesting people from all backgrounds. This was extremely satisfactory to me and has more than made up for any scientific papers not published in the process."

As delegate president for the Women and Science Commission, how do you assess the impact that such a commission has, or can have?

"The creation of the Women and Science Commission was very important because it was the first Spanish public instance to officially publish figures on women in science, *i.e.*, to make the "diagnosis". The physicist Rolf Tarrach, president of CSIC at the time, played a fundamental role by approving the formation of the Commission, thus demonstrating the importance of the attitude of men and authorities to equality. Once the numbers were established, it became impossible to deny the reality of gender bias. We next started to recommend gender-neutral language use in science. This encountered quite a lot of resistance, and only recently have we come to a more equilibrated use of our language in a scientific environment. Since 2007, Spain has a law on gender equality, as well as established protocols on how to handle sexual or gender-based harassment. Thanks to initiatives such as of the Women and Science Commission, things are better now. Still, it remains very difficult to progress on gender issues, since bias is so strongly engrained. It is important to recognize the work done in this regard by the Women and Science Unit of the European Commission."

Isn't furthering gender equality an issue of constant vigilance?

"Yes. I am often astonished that even when young colleagues organise a conference, they invite only male speakers, claiming that they cannot find any women! Fortunately, young women today are more vocal, they are more aware that we have laws, laws that regulate and protect gender equality. They do not hesitate to appeal to these."

You have worked in the U.K. as well as in Spain, and were on the 'Helsinki Group on Women in Science'. How do you situate Spain with respect to other European countries, with respect to the gender equality issue in science?

"There is a difference between Mediterranean Europe and Northern Europe. For example, during my time at Imperial College in the late nineteen-seventies there were significantly less women physicists than in Spain. A striking case is Turkey, where a large percentage of scientists – and physicists – are women. Among reasons, the different social status of scientists in protestant- with respect to catholic and other cultures has been evoked. In the first, teachers' and professors' status would have been relatively higher with respect to the cleric, whereas in the latter women were perhaps more easily admitted to academic roles. More specific to Spain, Portugal, Greece, and Turkey would the liberating effect after the fall of national dictatorships in the nineteen-seventies. The liberation of society empowered women and stimulated many to pursue the career they wanted, including academia. Still, even before that time, many teachers in Spain were women. A big problem is the propagation of role models. Even if a large proportion of primary school teachers in Spain are women, education experts assess that they tend to be more demanding towards boys than towards girls."

You have had a wonderful career in science as well as in furthering the cause of women scientists. If you would be solicited for a further role in either, would you accept?

"I have now resigned from both the Women and Science Commission of the CSIC and from the Group of Women Physicists (the Grupo Especializado de Mujeres en Física) of RSEF. Times have changed, and there is a need for new people to step forward, people with new perspectives and new perceptions of society. We have been very successful in raising awareness and in changing the climate in our research organisations. Now, we should realise that science and engineering is to be pursued not only for the benefit of men, but for all of society including women. Beyond adapting our institutions, the very object of research should take into account the reality of diversity. A good first step is the implementation of the diversity issue in projects, such as is now requested by the European Union. To progress though, experts are needed. Even if I truly want to help on all issues, I do not hold this expertise, and I think younger people should take the lead."

What recommendations or advice would you give young women in science?

"Young women should be aware that differences do exist. They should also be aware of micro-bias, and that it can have a large effect on scientific practice and on society if it is not tackled in time. For example, it appears that the outcome of scientific evaluation depends on whether a male or a female CV is under consideration. Such bias is surely unconscious and unintentional, but, nevertheless, very real. To improve we need objectivity and transparency and everyone's effort." ■

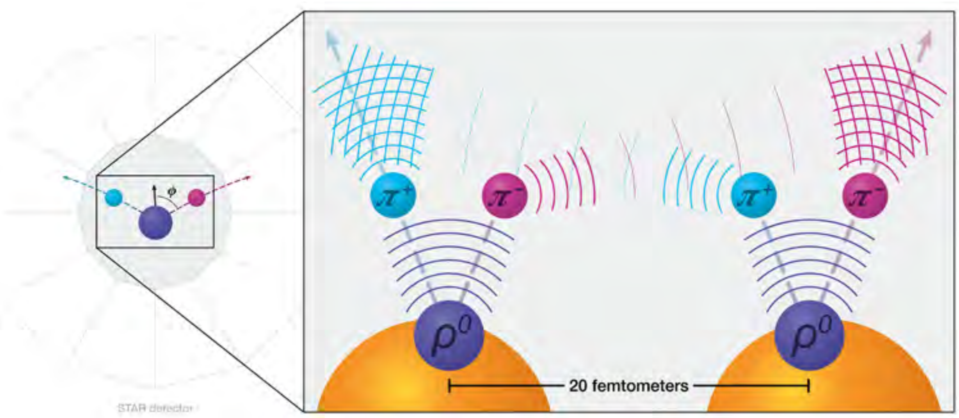
Entangled pions in a study of the interior of atomic nuclei

Early January 2023, the STAR collaboration published a paper in Science Advances about a measurement of the 'Tomography of ultrarelativistic nuclei with polarised photon-gluon collisions'. They used a new form of quantum entanglement.

▲ The STAR detector at RHIC. Credit: Brookhaven National Laboratory

Atomic nuclei consist of protons and neutrons. Inside the protons and neutrons, quarks are bound by gluons as the mediators of the strong interaction. To study how the quarks and gluons exactly form atomic nuclei, the STAR collaboration used polarised photons, which were created by accelerating charged heavy nuclei in the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory, USA. The ultrarelativistic nuclei form a cloud of linearly polarised photons. When two relativistic heavy nuclei pass one another at a distance of a few nuclear radii, a photon from one nucleus may interact through a virtual quark-antiquark pair with gluons from the other nucleus and form a short-lived vector meson such as the rho-meson. The rho-meson decays in a pair of oppositely charged pions. By measuring the velocity and angles at which the pions strike the detector, information about the photons can be traced back and the distribution of the gluons within the nucleus can be mapped (Figure 1).

▼ Figure 1 - The wavefunctions of the negative pions from each rho decay interfere and reinforce one another, while the wavefunctions of the positive pions do the same. The reinforcing patterns would not be possible if the π+ and π- were not entangled. Credit: Brookhaven National Laboratory.



During the measurements it turned out that the two pions were quantum mechanically entangled. Quantum entanglement is not new, but usually two identical particles become entangled. It is the first observation of entanglement between dissimilar particles. The quantum entanglement of the pions made the measurements at the atomic nucleus ten to hundred times more accurate. It was shown that protons in the atomic nuclei at high speed clump together in the center while neutrons form a shell on the outside. The nuclear radii of the strong-interaction were reported to be 6.53 ± 0.06 fm (^{197}Au) and 7.29 ± 0.08 fm (^{238}U), which is larger than the nuclear charge radii.

Details of the measurements are described in a paper published in Science. It is not yet understood how the pions become entangled with each other. Further investigation is needed. ■

Reference

[1] STAR Collaboration, *Sci. Adv.* 9, eabq3903 (2023) 4 January 2023

Alain Aspect: The physicist who made entanglement an experimental reality

For Einstein and other physicists of his generation, the strongly counter-intuitive features of quantum mechanics were very hard to accept, given that our intuition is based on the classical world around us. This EPJD Topical Issue examines the discoveries, motivations, and continuing legacy of Alain Aspect: the physicist whose experiments, along with those of John Clauser and Anton Zeilinger, have made that quantum entanglement, an essentially non-classical feature, is now also an experimental reality, exploited in science and technology.

In 1935, a trio of physicists, Albert Einstein, Boris Podolsky, and Nathan Rosen, introduced an argument concluding to the "incompleteness" of quantum mechanics. Their ideas stimulated a major work in 1964 by John Bell, who was able to turn a somehow philosophical discussion into mathematical inequalities, and from there into possible experiments.

In January 2023, *EPJ D* presents a Topical Issue in honour of Alain Aspect: the physicist who put Bell's inequalities under particularly stringent test, through a set of ground-breaking experiments at the beginning of the 1980s. This Topical Issue is particularly well timed, since Alain Aspect, along with John Clauser and Anton Zeilinger, have received the 2022 Nobel Prize in Physics on 10 December 2022, in recognition of their major contributions to the understanding of the world around us.

After the initial publication of Bell's inequalities in 1964, it took some time to give them a form allowing a first experimental test. This was first achieved by John Clauser in 1972, followed by several other experiments. The next major step was achieved by Alain Aspect in his doctoral thesis, completed in 1983, and saw his results confirmed in more and more refined experiments. In particular, several results obtained by Anton Zeilinger and his team established definitively that observations are in full agreement with quantum mechanics, and violate Bell's inequalities – and thus, the "local realistic" worldview attached to them.

This Topical Issue was initially designed to honour Alain Aspect's achievements on the occasion of his 75th birthday, and it could hardly be more timely. It provides a set of personal and historical perspectives on Alain's career. It also presents a series of scientific articles providing fascinating perspectives for quantum technology and information science, whose principles are founded on quantum entanglement, as evidenced in Aspect's experiments.

▾ Aspect's 1983 thesis revolutionised quantum mechanics. © Wikipedia

Together, the papers in this *EPJ D* Topical Issue highlight the story and continuing legacy of a bold, friendly, and enthusiastic physicist, who was never deterred from questioning the deepest issues posed by nature to the wider physics community. ■

Reference

[1] D. Clément, P. Grangier, J. H. Thywissen (Eds.), Quantum Optics of Light and Matter: Honouring Alain Aspect, Topical Issue *Eur. Phys. J. D* (2023) https://epjd.epj.org/component/toc/?task=topic&id=1662

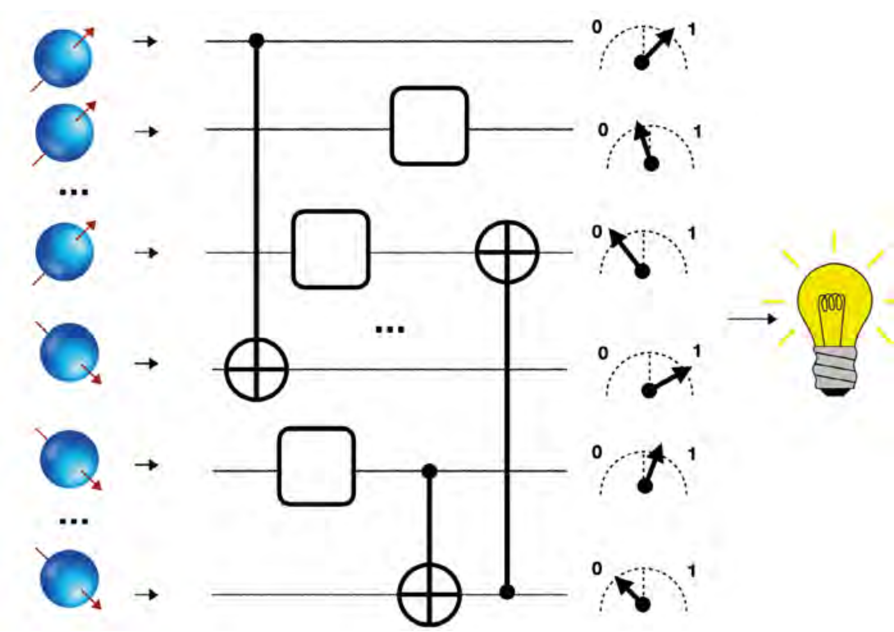
Universal algorithms for quantum data learning

Quantum communication and computation technologies promise unprecedented applications, such as unconditionally secure communications, ultra-precise sensors, and quantum computers capable of solving specific problems with a level of efficiency impossible to reach by classical computers.

These revolutionary technologies were first envisioned as tools to better and faster process classical data, that is, information that can be written on a piece of paper, or more commonly as bit strings stored in conventional computers. The quantum then came in how we process this information, for example by feeding the classical data into quantum processors that exploit phenomena like quantum entanglement and superposition to speed things up.

As the revolution progresses, new scenarios appear where not only the processing of information is done by exploiting quantum resources, but also data presents itself in a quantum form. Imagine that two quantum devices are exchanging information, and they do so by sending each other electrons whose spins point in particular directions. These directions encode the relevant information, but the device receiving the electrons cannot fully access it, for it has first to measure the electrons and then infer their spins' directions from the measurement results, and quantum mechanics tells us that this is a probabilistic process with inherent errors. Hence, the information being transmitted here has a different nature; it is *quantum* data, and cannot be simply written on a piece of paper.

The notion of quantum data appears naturally when we have quantum devices acting as nodes of a network where connections are established via quantum channels, as in the example above, but also when we want to certify that a certain quantum process, say the preparation of a collection of quantum particles in finely tuned states, has occurred as intended. In general terms, the key problem becomes how to determine that a *quantum dataset*, that is, a set of quantum states of which we lack a classical description, holds a certain property of interest. Such property can be as simple as determining whether all quantum states in the dataset are identical to each other, or estimating the degree of similarity between the states.



▲ A collection of spin states is processed and measured to extract information.

In this Perspective article, we review several relevant algorithms designed to learn properties of quantum datasets. Examples we address are programmable processors for discriminating types of quantum states, supervised quantum learning algorithms, unsupervised classification of quantum data, quantum change point detection, and learning of distance measures between states in a quantum dataset. All these algorithms share two key features. First, much like machine learning algorithms, they are *universal*: they are designed to work on any input dataset that fulfills some structural assumptions. And second, they exploit *symmetries* present in the data to their advantage. We show that requiring these features gives rise to an elegant mathematical description that facilitates the design of optimal learning algorithms, and thus we identify a powerful tool to tackle new learning problems of increasingly complex quantum datasets.

Quantum data learning will be an indispensable part of upcoming quantum-technological applications, be it as part of their normal operation or as a tool to certify that they work as intended. It is easy to imagine that this type of tasks will become more and more relevant in the context of future quantum networks, where quantum data are the natural carriers of information. ■

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[1] Marco Fanizza et al 2022 EPL 140 28001. doi: 10.1209/0295-5075/ac9c29

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The Road to and from Quantum Entanglement Experiments

DOI: https://doi.org/10.1051/epn/2023101

Four articles by Nicolas Gisin, Jian-Wei Pan, Emanuele Polino & Fabio Sciarrino and Marek Zukowski provide an overview of the history of quantum foundations, from the early pioneer to today's quantum information research - the significance of which was recognized by the 2022 Nobel Prize awarded to Alain Aspect, John F. Clauser and Anton Zeilinger. They also write about the future development of quantum information science and shared their thoughts on how this new technology could in turn enable addressing new questions in fundamental physics.

In their independent historical tour de forces, Gisin and Zukowski recall that the initial discussion on the foundations of quantum mechanics triggered by the Bohr-Einstein dialogue was soon replaced by the culture of "shut-up-and-calculate", in which working on quantum foundations was "a kind of scientific suicide". What has changed the physics community's perception of the research field so dramatically since then? The two authors give three reasons for this change. First, some researchers, most notably John Bell, and the three Nobel laureates, did not follow the crowd and continued to work on fundamental questions. Secondly, advances in quantum optics made the "thought experiments" of the Bohr-Einstein debate feasible. And finally, these developments eventually led to quantum information science and technology. For example, the spontaneous parametric down-conversion source became the workhorse in experimental tests of Bell's inequalities, and was instrumental in demonstrating new ideas such as quantum teleportation, superdense coding or entanglement swapping. In parallel, the development of single photon detectors not only enabled the demonstration of quantum key distribution, but also to industrialize and commercialize it.

In their articles, Pan and independently Polino & Sciarrino focus on the use of emerging quantum technology for new frontiers in physics and the implementation in quantum networks and quantum metrology. Pan presents the vision of a global quantum network that began with the launch of the first quantum satellite, Micius, in China in August 2016. A series of experiments established the satellite-based free-space quantum link, connecting multiple ground stations. In future, a space-based platform could enable fundamental experiments over distances that were previously inaccessible on the ground. For example, the interface between gravity and quantum physics or the applicability of quantum theory at larger length scales can be tested. Polino and Sciarrino write about realizations of photonic quantum networks violating classical causal constraints beyond the simple Bell scenario. They also identify open challenges to be faced in the research area: the characterization of the classical-quantum gap in complex networks and exploration of different causal structures with independent entanglement sources and entangling measurements. ■

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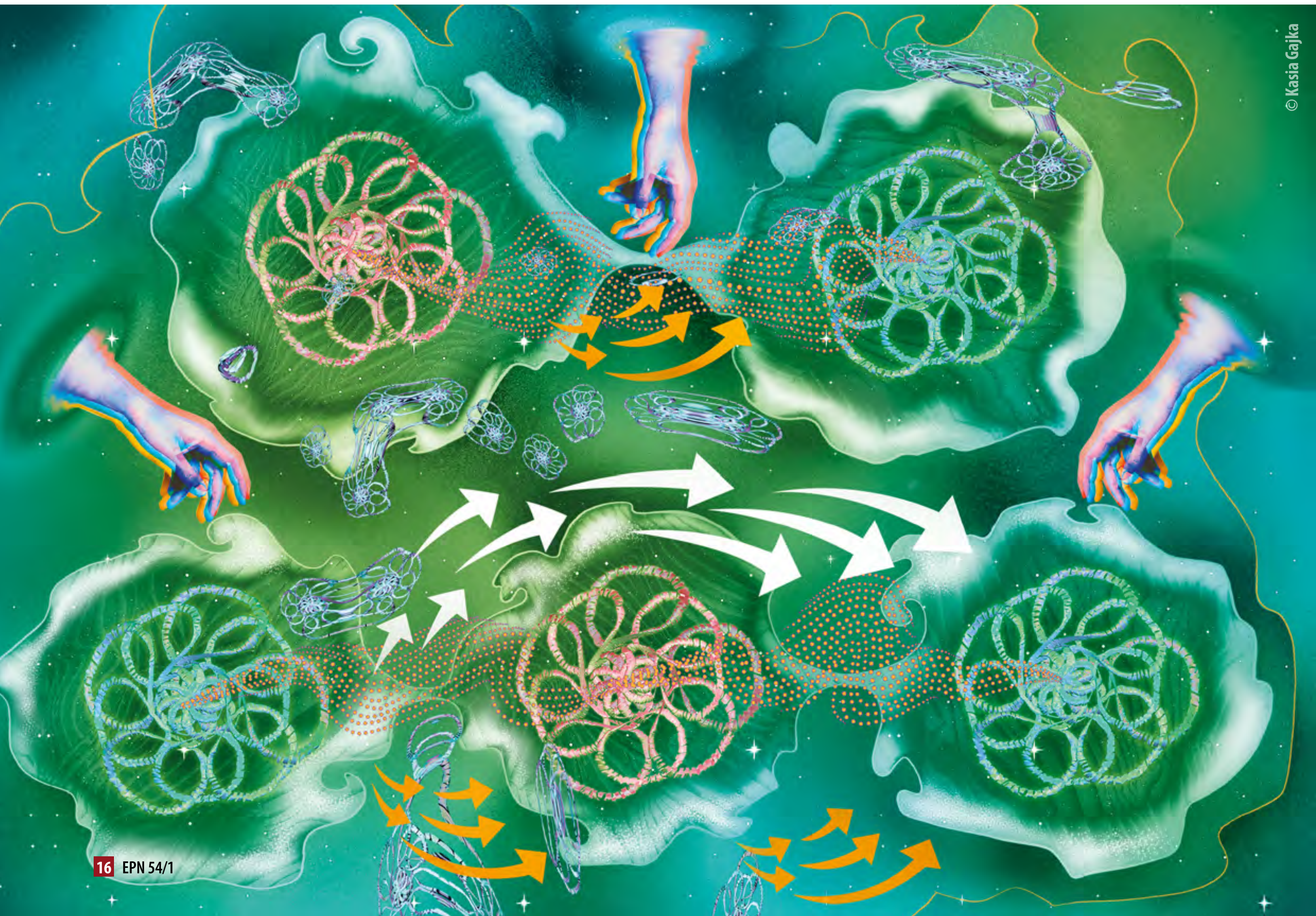
A HISTORY OF QUANTUM ENTANGLEMENT AND BELL'S INEQUALITY

THEORETICAL FOUNDATIONS FOR OPTICAL QUANTUM EXPERIMENTS WITH ENTANGLED PHOTONS

Marek Żukowski, ICTQT University of Gdansk, Gdansk, Poland – DOI: https://doi.org/10.1051/epn/2023102

Quantum mechanics gives probabilistic predictions, it is very abstract, and leads to paradoxes. It was discovered in 1925 in two acts of ingenious creativity. By Heisenberg, at the Helgoland island, and by Schrödinger half a year later in Alps. It allows to explain and predict an enormous range of phenomena, but almost immediately met an opposition. Einstein fully recognized it as a practical tool, but criticized its non-deterministic nature. The Einstein-Bohr debate began. Clauser, Aspect and Zeilinger ended it.



Einstein challenged the completeness of the theory in the EPR (1935) paper: ``elements of reality" can be defined via perfect correlations, and they are missing in quantum mechanics.

EPR noticed that perfect correlations are predicted by quantum mechanics for pairs of systems in "entangled states", a name introduced by Schrödinger for pure two-particle states which do not factorize into a product of states for each particle.

> **Perfect correlation.** Imagine two observers Alice and Bob, who respectively measure some observables A, and B, of values *a, b* = ± 1. We have a perfect correlation, if *e.g.* the conditional probability of Alice getting 1 and when Bob gets -1, equals one, $P(a = 1|b = -1) = 1$. EPR used a different wording. I follow a simplified argument by David Bohm.

The prediction does not depend on the distance of the objects and their observers and applies to simultaneous detection events. Such events cannot influence each other, as influences propagate no faster than light. Thus, the value $a = 1$ for Alice's particle must have been a predetermined "element of reality". As Alice and Bob can be far from each other and from the source, what observable they individually measure can be set also in a way that cannot influence the free choice of the other partner and his/her result and the operation of the source. The possibility of choice of observables, meant for EPR that a possibility of an alternative choice by Bob to measure a complementary observable *B'* means that the value of a certain complementary observable *A'* of Alice can be potentially predicted with certainty. Thus, it must also pre-exist, if one has $P(a' = 1|b' = -1) = P(a' = -1|b' = 1) = 1$. As Bob's choices and result cannot affect or disturb "the reality" at Alice's location, her particle must carry predetermined values *a* and *a'*. They showed an *example* of an entangled state which had such correlation properties.

Bohr's quick response: Bob can measure either *B* or *B'*, choice of one precluded measurement of the other, and this makes the argument void. Physicists reacted with relief, "shut up and calculated". Only some worked further. David Bohm found that the above properties seems to have the singlet state, $|singlet\rangle$, of two spins 1/2:

$$\frac{1}{\sqrt{2}}\left(|1/2_z\rangle_A\,|-1/2_z\rangle_B - |-1/2_z\rangle_A\,|+1/2_z\rangle_B\right)$$

Here, states of individual spins which are related with spin up or down results, if we measure components "*z*". Singlet is invariant with respect to any rotation of the full system, and thus has the same form if we use "*y*" components, or whichever identical ones for both spins. Singlet has the correlation properties mentioned earlier, if one re-scales the eigenvalues to ∓1, and treats measurement of *z* components as A and B, and measurement of "*y*" components as A' and B'.

29 years later Bell commented on EPR work. He derived his inequality, which applied to systems possessing perfect correlations, and for any theory allowing EPR elements of reality. Using $|singlet\rangle_{AB}$, he showed that the inequality does not hold in quantum theory: the EPR completion destroys quantum mechanics. Almost nobody cared.

In 1969 John Clauser with Mike Horne, Abner Shimony and George Holt (CHSH) derived the first experimentally testable Bell inequality which holds for any classical like theory satisfying Einstein's locality (not only for EPR elements of reality) and showed that it is violated by quantum predictions for $|singlet\rangle_{AB}$. They proposed a test! Specific two-photon cascades in Calcium possess polarization entanglement, which can be one-to one mapped with the singlet. In 1972 he and Freedman performed the experiment. The results followed quantum predictions. *En passant*, in another experiment based onthe same contraption he falsified the semi-classical theoryof light (Phys. Rev. A **6**, 49 (1972)). In 1974 he and Horne derived another inequality, much better for analysis of experimental imperfections.

In his 1978 review with Shimony coined the term "local realism", for general theories of the Einstein type attempting to model quantum mechanics. Such theories are sometimes called "local hidden variable theories". Hidden variables, say λ, are anything that is outside of quantum formalism, which is used to explain the stochasticity of quantum predictions. One assumes a stochastic distribution of these, $\rho_\psi(\lambda)$, related with the quantum state, ψ. For a measurement of *A* the probability of result a to happen is $P(a|A,\psi) = \int d\lambda \rho_\psi(\lambda) p(a|A,\lambda)$. Locality implies that $P(a\&b|\psi) = \int d\lambda \rho_\psi(\lambda) p(a|A,\lambda) p(b|B,\lambda)$. The Clauser-Horne inequality for this reads in a simplified notation $P(a\&b) + P(a\&b') + P(a'\&b) - P(a'\&b') - P(a) - P(b) \le 0$. The maximal quantum value of that for $|singlet\rangle_{AB}$ is $QM_{max} = \frac{\sqrt{2}-1}{2}$.

The inequality can be also derived by postulating the existence of proper probabilistic distributions of values of all observables is the formulas, ϱ(*a*, *a'*, *b*, *b'*) or even just postulating counterfactuality. The latter allows us to use in a theory values of measurements which were not performed, as unknown but defined. Hidden variables λ are sometimes called "causes", or "situations".

Alain Aspect proposed in 1976 and realized in 1980-1982 several experiments which could be called *ultimate versions of Clauser experiments*. In the last one observation stations (Alice and Bob) were switching their settings quasi-periodically using standing-wave acousto-optical switches in such a way that upon emissions no information was at the source on the settings of polarization analyzers which the photons were to face. The stations were 12 meters away from the source, which was a beam of Calcium atoms excited by a laser passing via the focal points of collection lenses. As not all pairs ●●●

▲ Q|*Cards*⟩ Online is a game introducing and teaching the basics of quantum computing, without requiring previous experience in quantum physics.

of photons were collected, and not all collected detected, the test had a "detection loophole". One had to assume that the sample of detected photons fairly reproduces the original emitted ensemble. The experiments were thought by some as conclusive, by some as non-conclusive, also because non-randomness of the switching, an effective "locality loophole".

The subject was studied mainly by researchers skeptical about quantum theory. Bell's view: "Quantum Mechanics is rotten". However, in 1970's-1980's experimental physics with single quantum objects emerged. E.g., single neutron interferometry in the case of which Zeilinger had outstanding achievements, atomic interferometry, atomic traps. "Gedanken" experiments of the Bohr-Einstein debate were becoming feasible.

Progress in non-linear quantum optics gave the spontaneous parametric downconversion (PDC) effect. Cascade emissions from atoms do not have directional correlations, thus only a fraction of photons is collected. The downcoversion gives almost perfectly directionally correlated pairs of photons, called signal and idler, with their frequencies adding up to the frequency of the strong laser pumping field propagating in a "non-linear" birefringent crystal, *e.g.* BBO or KDP, and inducing a nonlinear response of its electric polarization. From 1986 downconversion became the work horse in Bell experiments, the first ones by Mandel's group, and Shih and Alley. In 1994 Zeilinger and Shih groups showed that PDC of type II is a fantastic source of polarization entangled photons. A direct consequence of that was the Bell experiment of Weihs *et al.* of Zeilinger's group in Innsbruck which convincingly closed the "locality loophole". Alice and Bob stations were 800 meters apart, and their polarization analyzers' settings were decided by local quantum random number generators.

Before we discuss the 2015-2017 fully "loophole free" experiments, let me turn back to theoretical advances allowing observations of three-or-more photon interference. In 1989 Daniel Greenberger, Horne and Zeilinger (GHZ) showed that three or more photon interference effects lead to a direct falsification of the EPR approach. This signaled that a plethora of new quantum paradoxes was waiting to be discovered. Earlier, a rule of thumb, more particles, less quantumness dominated.

The simplest case. Take a state $|GHZ(3)\rangle$ which reads

$$\frac{1}{\sqrt{2}}\left(|a\rangle_A\,|b\rangle_B\,|c\rangle_C + e^{i(\varphi_A+\varphi_B+\varphi_C)}\,|a'\rangle_A\,|b'\rangle_B\,|c'\rangle_C\right).$$

It is describing entangled properties of three particles. Each particle goes to a different of three spatially separated observation stations of Alice, Bob and Cecile who observe time coincident detections. They are imposing local phase shifts, respectively ϕ_A, ϕ_B, ϕ_C, which transform the state, see the relative phase factor $e^{i(\phi_A+\phi_B+\phi_C)}$.

Essentials of calculation. If their detectors are measuring identical observables with eigenstates $|\mp\rangle_X = \left(\frac{1}{\sqrt{2}}\right)\left(|x\rangle_X \mp |x'\rangle_X\right)$, where $x = a,b,c$ and $X = A,B,C$, and we have $\langle x|x'\rangle = 0$, the overall probability amplitudes of coincident detections are proportional to $(1 \mp e^{i(\phi_A+\phi_B+\phi_C)})$ Following Bell, one can associate with a detection event described by the final state $|\mp\rangle_X$ values $\mp 1 = X(\phi_x)$. This leads to the following average of the products of values of the coincident events: $\langle A(\phi_A)B(\phi_B)C(\phi_C)\rangle = \cos(\phi_A + \phi_B + \phi_C)$.

Whenever $\langle A(\phi_A)B(\phi_B)C(\phi_C)\rangle = \pm 1$, see the box, one has "perfect GHZ correlations", a version of the EPR ones, defining elements of reality. Such elements of reality $X(\phi_x) = \mp 1$ must satisfy

$$A(\phi_a = 0)B(\phi_b = 0)C(\phi_c = 0) = \cos 0 = -1,$$
$$A(\phi_a = 0)B(\phi_b = \pi/2)C(\phi_c = \pi/2) = \cos\pi = -1,$$
$$A(\phi_a = \pi/2)B(\phi_b = \pi/2)C(\phi_c = 0) = \cos\pi = -1,$$
$$A(\phi_a = \pi/2)B(\phi_b = 0)C(\phi_c = 0) = \cos\pi = -1,$$

With these relations, as $X(\varphi_x)^2$, via a primary school algebra we get 1=−1. The method of EPR makes no sense.

How to observe such correlations? A solution appropriate for the times, was found in ZZHE paper, and improved in two subsequent Zeilinger *et al.* theoretical papers. One can use three pairs of entangled systems, independently emitted form three different sources, such as PDC crystals, and swap their entanglement to get $|GHZ(3)\rangle$.

Take a simpler case of two different entangled pairs with no entanglement between the pairs, say two signal and idler pairs, each pair from a different PDC source. By an arrangement for "Bells-state-measurement" which detects together both idlers, in such a way that the information on the origin of the idlers is completely erased, one can entangle the two remaining signal photons which never interacted, and can be very far away. The indistinguishability of the idlers can be reached by narrow filtering of these, while the pumping fields must be sharply pulsed, as this allows for the frequency spectral widths $\Delta\omega$ to satisfy, $\Delta\omega_{idlers=filters}/\Delta\omega_{pump} < 0.1$. In such a case the original tight frequency correlation of signal and idler from each pair, $\omega_{signal} + \omega_{idler} = \omega_{pump}$, which betrays their source, is effectively erased. Importantly, only idlers are subject to filtering, signals propagate to remote observation stations untouched, but now entangled.

As it was noticed in the last page of ZZHE variations on the theme of entanglement swapping allow one to make experimental "quantum teleportation", observe GHZ correlations, and allow for an "event-ready" Bell test, heralding the signal-events by detection of the idlers, and thus operationally defining detection failures of these.

Meanwhile theoretical quantum information science emerged. This can be traced back to Feynman suggesting quantum simulations and computing (1982), Wiesner's quantum money (1983), and Bennett's and Brassard's quantum cryptography based on Bohr's complementarity, or EPR correlations (1984). Theoretical quantum teleportation, that is a transmission of an unknown state form one system in say Alice's lab, to another one at Bob's lab, was announced in 1993.

The teleportation is a protocol involving a three-particle interference, with one particle in a state, ξ, to be teleported, and the other two in a singlet state shared by Alice and Bob. In the case of teleportation of photon polarization states, a classical transmission of just two bits of information to Bob is needed, who knowing these can unitarily transform the state of his particle from the EPR pair to ξ. Alice performs a "Bell state" measurement (jointly on the particle in state ξ and her particle of the singlet), of four equally possible results numbed by the bits 00, 01, 10, 11, which totally hides the origin of the particles and is erasing ξ. Successful teleportations were reported by Zeilinger's experimental group on 11 December1997 (in *Nature*), two-pair entanglement swapping in 1998, and observation of GHZ correlations in 1999.

In 2015-2017 four loophole free Bell experiments were announced, therefore closing the debate of the two Nobel laureates who *received* the Prize in… 1922. A Delft group of Hanson, who performed an entanglement swapping Bell experiment between separated by 1300 meters NV centers in diamonds, observed 250 such events, excluding any local realistic interpretation of them with probability of 96%. Two other experiments with a high detection efficiency observation of photon correlations, one of them by Zeilinger's group, were also announced in 2015, giving confidence of practically 100%. Weinfurter's group in 2017 reached this confidence level with entanglement swapping entangling single atoms in two traps separated by 400 meters. ■

In [PCYWZZ] review article one can find a detailed description of the story up to 2012. MZ is supported by FNP IRAP project ICTQT co-financed by EU Smart Growth programme.

About the Author

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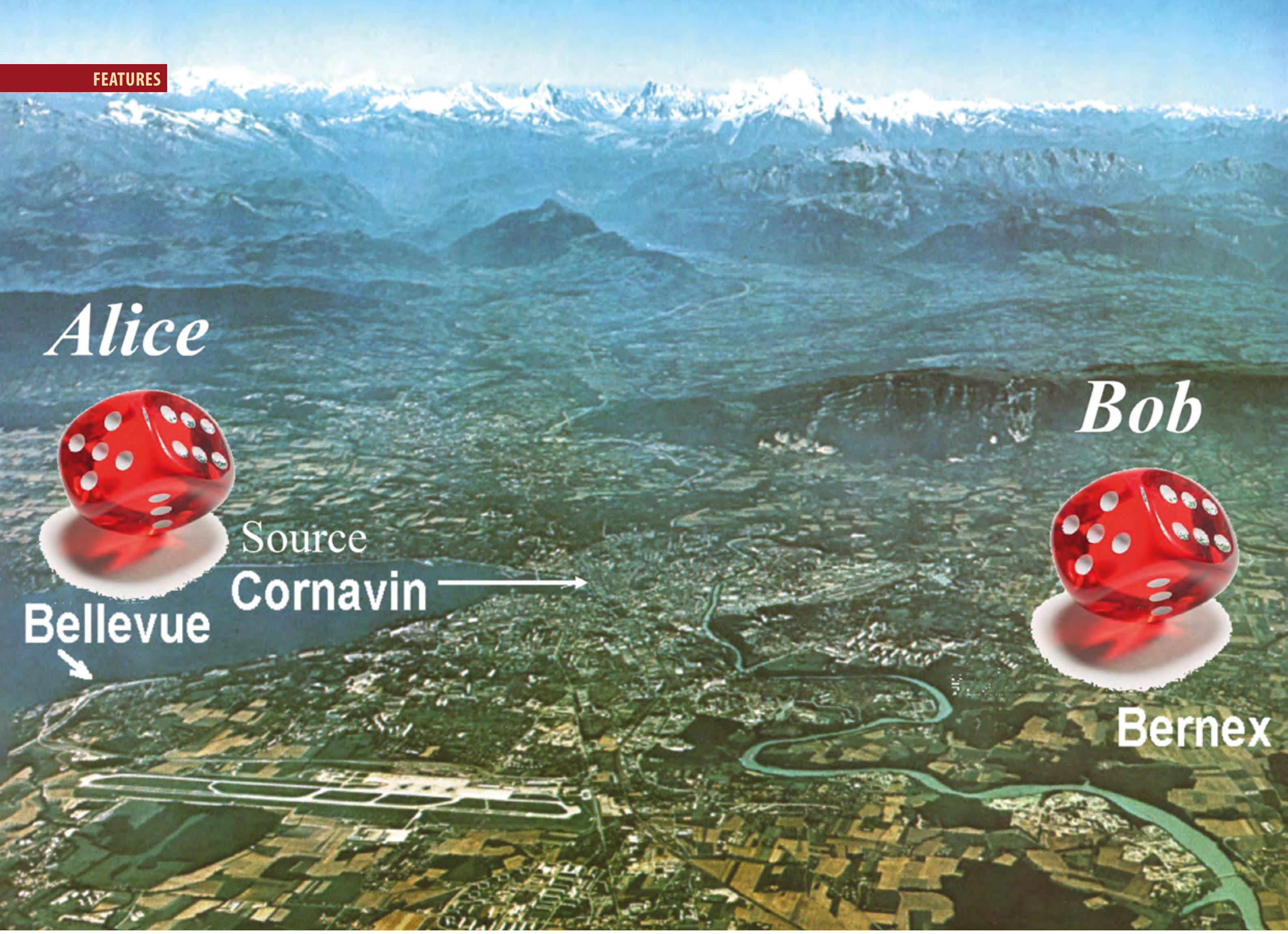

QUANTUM NON-LOCALITY:
FROM DENIGRATION TO THE NOBEL PRIZE, VIA QUANTUM CRYPTOGRAPHY

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In the late 1960s, a young physicist was sailing along the coast of California towards Berkeley, where he got a post-doc position in astronomy. But his real goal was not astronomy, at least not immediately. First, John Clauser eagerly wanted to test some predictions of quantum theory that were at odds with a then recent and mostly ignored result by an Irish physicist John Stewart Bell, working at the celebrated CERN near Geneva.

Bell, inspired by David Bohm's hidden variable model of quantum theory, proved that all possible correlations that can be described by *local* variables necessarily satisfy some inequalities, today known as Bell inequalities. These inequalities are mathematically quite trivial. However, quantum theory predicts that they can be violated even when the correlation is between outcomes of far distant measurements. Denote a and b the measurement outcomes and x and y the measurement settings (*e.g.* polarizers' orientations), and denote λ the hypothetical hidden local variables. Accordingly, the entire statistics of the experiment is captured by the so-called "correlation" - strictly speaking, conditional probability distribution - $p(a,b|x,y,\lambda)$. The λ's are hidden in the sense that they are not part of quantum theory, though the usual quantum state Ψ could well be a part of λ. Here, local - or Bell-local - refers to the assumption that the correlation factorizes in two parts, one for each of the distant sides of the experiment:

$$p(a,b|x,y,\lambda) = p(a|x,\lambda).\, p(b|y,\lambda) \tag{1}$$

That's the only assumption necessary to derive Bell inequalities. The λ's denote the state of the system as described by any possible future physical theory (except that the settings x and y are assumed to be independent of λ). In this sense, Bell inequalities go way beyond quantum theory: a violation of a Bell inequality proves that no future theory can satisfy the locality condition (1).

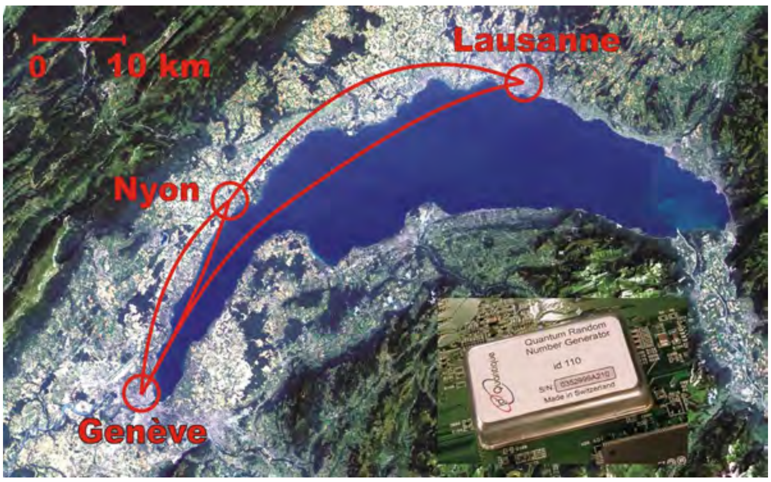
John Clauser, Abner Shimony, Michael Horne and Richard Holt were among the very few who understood this in the 1960s and all wanted to test Bell inequalities, Clauser to prove quantum theory wrong, Holt, a young student at Harvard, to prove the Bell-locality assumption (1) wrong. Clauser was in a good position thanks to existing equipment at Berkeley. Indeed, Carl Kocher had done a similar experiment in 1967, though for other purposes. Unfortunately, Kocher, and even earlier Chien-Shiung Wu, had only measured the correlations when the polarizers were either parallel or orthogonal, while a proper violation of Bell inequality requires intermediate orientations. Note that assuming that polarization is a 2-dimensional quantum system, a qubit as one says today, correlations at 45° can be derived from the parallel and orthogonal correlations assuming no-signaling [1]: $E_{45} = (E_{\parallel}+E_{\perp})/\sqrt{2}$. That wasn't known at the time. But regardless, the visibilities measured by Kocher and Wu were below 50%, while a proper violation requires visibilities larger than 71%. Hence the race was on. Clauser got there first, confirming quantum predictions, against his expectation. But then Holt obtained his own result, confirming the inequality, against his expectation. Somehow, the score was one to one.

At that time, these fascinating and intriguing results interested almost no one, except some hippies who could later claim to have saved physics [2]. Clauser had long discussions with them, though the last time I met him he had turned into a loud climate skeptic.

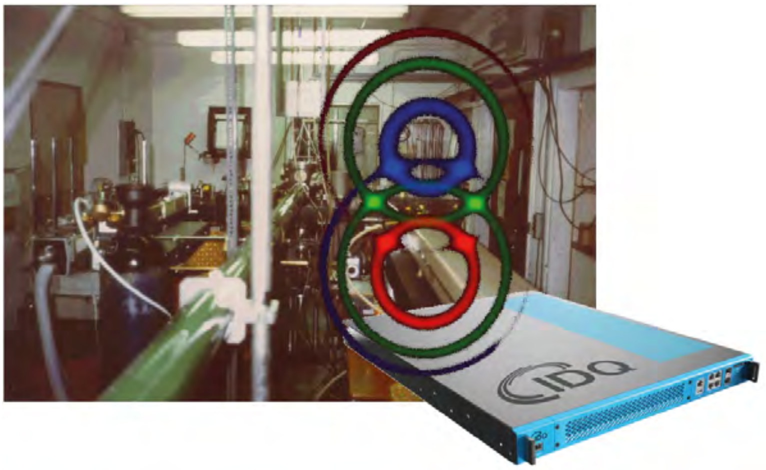
In the 1970's, my friend Alain Aspect was doing his French civil service in Africa, reading physics, as we all do. When he hit on Bell inequalities, it was love at first sight: "I want to work on that". Back in Paris, he traveled to Geneva to meet John Bell and told him about his plans. Bell replied: "Do you have a permanent position?". Indeed, in those times, working on - or even just showing interest in - Bell inequalities was a kind of scientific suicide. Bohr had it all solved, went the dogma. Looking back, it is difficult to appreciate how deeply denigrated was all research around Bell inequalities and entanglement - the quantum resource necessary to violate them. At the time, French had no agreed-upon translation of entanglement, some used "enchevêtrement", others "intrication" (the latter has by now been officially recognized by the French academy).

Fortunately, the French system allowed young physicists such as Aspect to hold permanent positions, so he decided to score the winning goal. Crucially, he planned to add fast switches that would allow one to choose the measurement settings x and y while the photons were already too far away to possibly influence the other side. Aspect was able to achieve this using newly developed lasers to pump his entanglement source, while Clauser and Holt had to use flash lamps. In a series of three beautiful experiments in the early 1980's, Aspect settled the dispute in favour of quantum theory. Accordingly, no future theory will ever satisfy the locality condition (1). Today, this is often expressed by the short expression non-local, which really means not-Bell-local.

Despite these beautiful experiments and the intellectually fascinating discoveries, Bell inequalities remained dismissed and poorly understood. Even to this day, the clear terminology non-local (equivalently, not-Bell-local) is too often blurred as not satisfying "local-realism", as if non-realism was a way out [3,4]. The fact is that assumption (1) is no longer tenable. As an example, consider the scientific background provided by the Nobel Committee [5]. A few lines after correctly presenting Bohm's non-local hidden variable model, one reads that Bell inequality violation shows "that no hidden variable theory would be able to reproduce all the results of quantum mechanics", contradicting the just cited Bohm model (which does predict violation of Bell inequalities). The correct statement is that no *local* variable theory is able to reproduce all results of quantum mechanics. And a few lines further, locality is defined as no-signaling - no communication without any physical object carrying the information, despite the fact that one of the ● ● ●



▼ **FIG. 1:** Quantum cryptography under Lake Geneva was the first quantum experiment requiring a satellite photo to illustrate it. Nowadays in commercial use [9].



▲ FIG. 2: A picture of Aspect's lab around 1981, followed by a commercial quantum cryptography equipment [9], with the entanglement source used by Zeilinger in the middle (photo by Paul Kwiat and Michael Reck).

main contribution of quantum information to the foundations of physics is a clear distinction between these two concepts. Next, realism is defined as determinism, even though Bell inequalities also hold in all stochastic theories satisfying (1). All this illustrates that Bell inequalities are still poorly understood by the general physics community. The 2022 Nobel Prize in physics allows one to hope that henceforth Bell inequalities will be part of all physics cursus.

One major step towards a better appreciation of Bell inequalities came from a young Polish PhD student at Oxford University, Artur Ekert. In 1991, he realized that non-local quantum correlations are nothing but cryptographic keys! Indeed, in both cases, the correlation is private and, after some error correction, the bits on both sides are identical. This proposal to exploit non-local correlations for cryptographic applications changed everything (though it took several years to prove Ekert's intuition correct [6,7]). Moreover, just a few years later, Peter Shor showed how one can exploit entanglement to break the commonly used public key cryptography system RSA. Thus, in the 1990s, non-locality and entanglement were in the spotlight, at last.

But that would not have sufficed. The entanglement source used so far was too complex. Leonard Mandel, at Rochester University, realized that a humble non-linear crystal could provide highly entangled photons when pumped by a simple diode. Moreover, the entangled photons could easily be coupled into optical fibers, opening thus the road to quantum cryptography using existing infrastructure, *e.g.* our demonstrations of quantum non-locality over the Swisscom network and quantum cryptography under Lake Geneva [8], illustrated in Fig. 1.

The focus thus changed from foundations of quantum physics to quantum information science and technologies. New ideas emerged, like quantum teleportation and quantum error correction, in addition to fast experimental progress. Anton Zeilinger had been interested in foundations since his early days as a physicist in neutron interferometry. He quickly joined the quantum information community and became a leading figure. His demonstration of quantum teleportation, immediately after the one in Rome, by De Martini and Popescu, attracted enormous attention, both within the scientific community and from the public at large. Soon thereafter, Zeilinger went further and demonstrated the teleportation of entanglement. Generally, quantum teleportation is the resource behind quantum computation and long-distance quantum communication. Zeilinger also improved on Aspect's experiments in fast choices of the measurement settings (though with low detection efficiencies, hence much simpler experiments were possible [10]). Next, the so-called detection loophole was closed in an optical experiment by Paul Kwiat's group at Ilinois University [11], before a series of "final" loophole-free experiments, one of which was carried out by Zeilinger's group. Zeilinger continued with a long series of remarkable experiments, including dense coding, and the demonstration of 3 and 4 photon entanglement, culminating with the long-distance free-space communication in the Canary Islands, making him a clear leader of the new field of experimental quantum information.

The next step was the understanding that entanglement is actually not necessary for point-to-point quantum cryptography, though it remains essential for the security proofs. Indeed, while in tests of Bell inequalities one sets the source about half way between the measurement devices, in applications it is much more practical to put it on one side. Hence, a mere single photon travels to the receiver. This, and a few additional tricks - especially the move to wavelengths compatible with standard telecom optical fibers, which we initiated in Geneva with the development of specific single-photon detectors, made it possible to not only demonstrate quantum cryptography, but to industrialize and commercialize it. Today, there are many small companies selling quantum cryptography equipments, some quite advanced as illustrated in Fig. 2. Development efforts will continue, but no longer with the aim of excluding local variables satisfying (1); the goals now are to make the equipments cheaper, faster and able to cover longer distances, probably by exploiting quantum teleportation.

On the conceptual side, the violation of Bell inequalities dramatically revolutionized our world-view. Interestingly, Newton's theory of gravity was also non-local, even signaling. But Einstein improved on it, making gravity local. It is thus not surprising that he strongly objected to quantum non-locality, not fully appreciating that it is of a very different sort: without any action at a distance, just non-local randomness without any possibility to use it for signaling [12,13]. In contrast to Newton's non-locality, quantum non-locality is here to stay; the experimental evidence is clear on that point. Today, non-local quantum correlations are explored for device-independent quantum information processing

[7], in particular device-independent quantum cryptography, a truly fascinating research field unthinkable before Bell's work. Another timely and exciting conceptual goal is to take non-locality beyond the simple Bell scenario and place it in the context of quantum networks with several independent sources of entanglement [14]; this already led to the remarkable result that some quantum networks can't be described using only real-number Hilbert spaces [15].

Sincere congratulations John, Alain and Anton, you made me so happy. Congratulations also to the Nobel Committee for recognizing, finally, the game-changing findings of the late John Stewart Bell, with whom, along with his wife Mary, I had the pleasure of sharing several cheese raclettes in downtown Geneva. ■

About the Author

Nicolas Gisin was born in Geneva, Switzerland, in 1952. His interests cover a wide range of topics, from the foundations of quantum physics and philosophy, to applications in quantum communications. He authored a popular book on Quantum Chance and Non-locality, is a co-founder of the company IDQ.

Aknowledgement

Many thanks to Benjamin Feddersen for polishing my English.

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TOWARD A GLOBAL QUANTUM NETWORK

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About 90 years ago, Albert Einstein complained about the "spooky action at a distance" of quantum entanglement and questioned the completeness of quantum mechanics [1]. This year, the Nobel Prize is awarded to three pioneers that put Einstein's curiosity under experimental tests based on Bell's inequality [2]. The fundamentals of quantum mechanics are not of just theoretical or philosophical interest. Rather, worldwide efforts are harnessing these quantum weirdness to develop emerging technologies.

The goal is to build a large-scale and fully functional quantum networks both for the exploration of new frontier of physics and the implementations of quantum computation, communication, and metrology.

The near-term application of such a quantum network is to establish secure quantum-encrypted communications, because privacy and security rooted in human being since the ancient time. Traditional public-key cryptography usually relies on the perceived computational intractability of certain mathematical functions. However, history has shown that nearly all advances in classical cryptography were subsequently defeated by advances in cracking. It has long been suspected that, "Human ingenuity cannot concoct a cipher which human ingenuity cannot resolve".

It might come as a surprise that the very fundamental principle of quantum mechanics was exploited to solve this long-standing problem on information security which the mathematicians have struggled with for centuries. In the 1980s, Bennett and Brassard presented a feasible protocol of quantum key distribution (QKD), known as BB84 [3]. Independently, in 1991, Ekert discovered that quantum entanglement can be used for unconditionally secure information transfer [4]. Their invented quantum cryptography is a fundamentally new way—and the only known approach—that allows distant parties to communicate safely under the nose of an eavesdropper endowed with unlimited computational power.

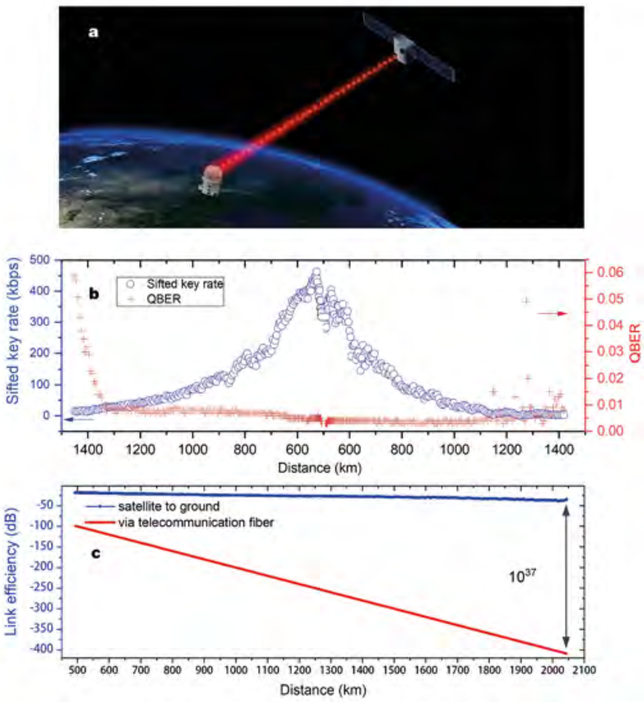
The first table-top proof-of-concept QKD experiment was done in 1989 by Bennett and his co-workers using an attenuated LED with a distance of 32 cm, followed by many similar small-scale demonstrations in optical fibres or terrestrial free space up to a distance of a few tens of kilometres. However, these communication distances, which were within half an hour drive, were far from a practical scale. More importantly, there existed serious loopholes in the early work, which can be used for eavesdropping. For example, Brassard recalled that in their work they "could literally hear the photons as they flew, and zeroes and ones made different noises".

Quantum cryptography is ideally secure only when perfect single-photon sources and detectors are employed. Unfortunately, ideal devices never exist. To solve the problems related to source and detector, respectively, decoy-state and measurement-device-independent QKD was proposed and experimentally realized. These works made QKD a viable technology under realistic conditions and kick-started worldwide engineering efforts of practical QKD networks.

The most important challenge of quantum networks is to go long distance to be useful at a global scale. In both fiber optics and terrestrial free space, there is inevitable photon loss exponentially at an increasing channel length. At 1000 km, even with a perfect GHz rate single-photon source, ideal photon detectors and the best commercial optical fibres, one can detect only 0.3 photons per century. Moreover, the quantum no-cloning theorem, which underpins the security of QKD, also excludes the possibility of simply amplifying quantum signals as in classical repeaters.

Due to these problems, quantum repeaters will play a key role in future quantum network to extend to a scalable range, by combining the functionalities of entanglement swapping, entanglement purification, and quantum memory. While these key parameters keep improving in ongoing experiments, significant engineering efforts remain to be done for • • •

▼ **FIG. 1:** (a) Establishing a reliable space-to-ground link for the quantum state transfer; (b)&(c) Performance of satellite-to-ground QKD during one orbit. QBER: quantum bit error rate.



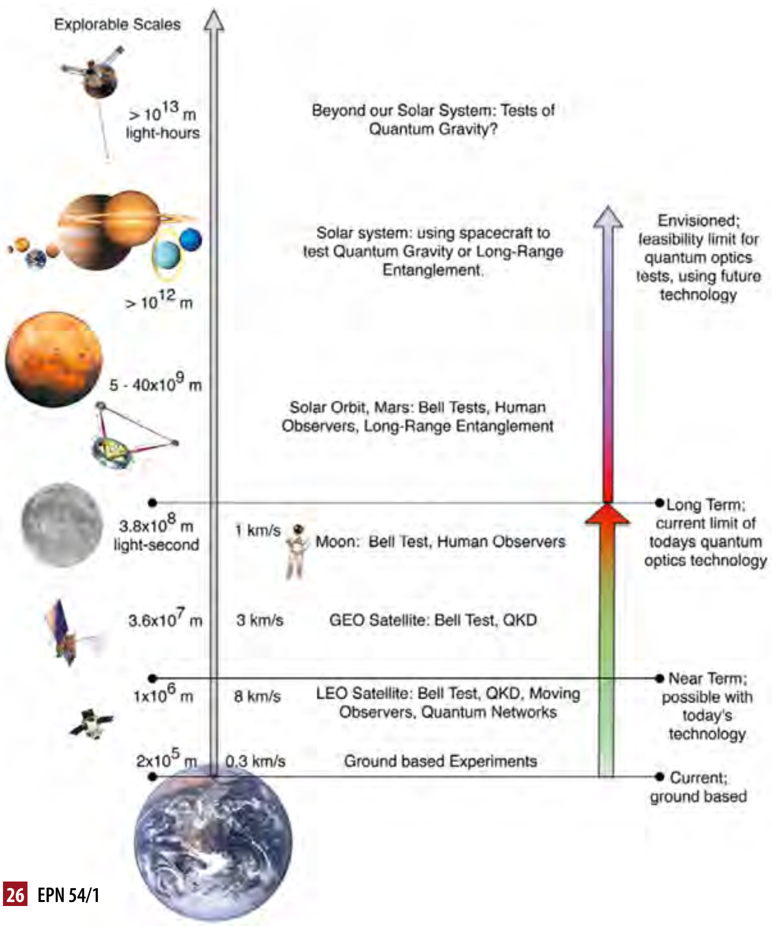
the quantum repeaters to go to 1000 km scale.

On the other hand, satellite-based free-space quantum link offers a unique and more efficient approach for global quantum networks, by taking advantage of the negligible photon loss in the atmosphere. The first quantum satellite, Micius, was successfully launched in August 16, 2016, in Jiuquan, China, orbiting at an altitude of ~500 km.

The satellite sends two entangled photon beams from two telescopes in the satellite to separate ground stations, with two independent satellite-to-ground quantum links established simultaneously. As the entangled photons propagate from the flying satellite (with a speed of 8 km/s) through the atmosphere to the two ground stations thousands of km apart, extremely demanding techniques are needed to be developed to overcome the detrimental effects of beam diffraction, pointing error, atmospheric turbulence and absorption. To put it in a non-technical way, the necessary technical ability is equivalent to: clearly seeing and tracking a moving single human hair at a distance of 300 meters away (in terms of pointing and tracking ability), and detecting a single photon in the Earth from a single match's fire lighted at the Moon (in terms of single-photon detection sensitivity and isolation from background noise).

Three key milestones have been in a few months after the launch: satellite-to-ground decoy-state quantum key distribution over a distance of 1200 km generating a final key rate of 1.1 kbits/s [5], which was recently improved to 47.8 kbits/s; satellite-based entanglement distribution to two locations on the Earth separated by 1200 km and test of Bell inequality [6], and ground-to-satellite quantum

▾ **FIG. 2:** Overview of the distance scales and the corresponding conceived quantum experiments reviewed in ref. [8].



teleportation over 1400 km [7]. Remarkably, the effective link efficiency of the satellite-based channel is ~37 orders of magnitudes larger than direct transmission through optical fibres at the same length of ~2000 km.

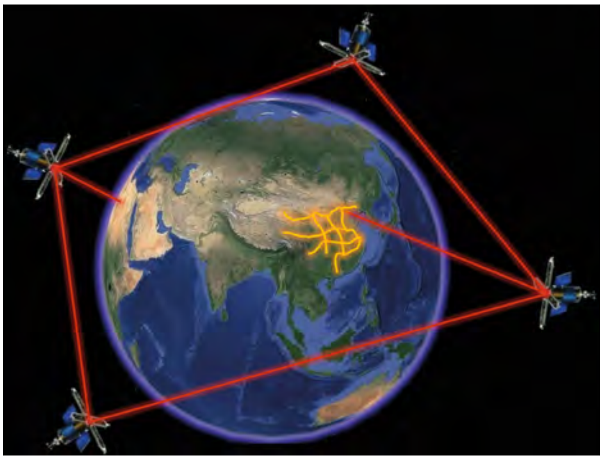
The two-link efficiency was further improved in 2020, and the satellite was utilized to perform quantum cryptography between two ground stations over 1120 km based on Ekert's entanglement-based protocol, where the unconditional security is ensured even if the satellite is controlled by an adversary. The satellite has now been combined with metropolitan fibre networks to form a space-ground integrated quantum network. Using the satellite as a trustful relay, two team achieved intercontinental quantum communications between Beijing and Vienna with a record distance of 7600 km.

Meanwhile, the methods developed in the quantum science satellite opens new paths to high-precision measurement and foundational tests. For instance, using satellite-based entanglement distribution, it is possible to entangled remote N atomic clocks and improve the time measurement accuracy by $\sqrt{N}$ times, as proposed by Lukin and Ye *et al.* Combining the quantum teleportation with the distributed telescopes will create an effective aperture with the size of Earth and an enormous resolution that would allow in principle reading licence plates on Jupiter's moons as pointed by Kwiat.

In general, the space-based platform is also a first step toward fundamental quantum optics experiments at distances that are inaccessible previously on the ground. A wide variety of potential tests have been conceived using increasingly distant satellites, as sketched in Fig. 2. Examples include probing the gravity-induced decoherence and the interface between gravity (the theory of very large) and quantum (the theory of very small). These tests have the potential to determine the applicability of quantum theory at larger length scales, eliminate various alternative physical theories, and place bounds on phenomenological models motivated by ideas about spacetime microstructure from quantum gravity.

Micius only marks the beginning. For the Chinese quantum satellite plans, there are two goals in the next 5 to 10 years. The first one is to develop 3 to 5 small LEO satellites dedicated to QKD missions, which will provide more practical and efficient QKD services. The second goal is to develop a medium-Earth-orbit to geosynchronous-orbit satellite, which can provide longer service time and wider coverage. The combination of a high-orbit satellite and multiple LEO satellites can form a quantum constellation for global services, as shown in Fig. 3. Furthermore, with such a new generation space platform, we plan to realize the high-precision satellite-ground time-frequency transfer and GEO satellite-based optical clocks to verify the technology of wide-area optical frequency standard.

Another important element in quantum networks is quantum computers, with various qubit candidates including



▲ **FIG. 3:** Road maps for the global quantum communication network. Intracity metropolitan networks will be created using fibers. Quantum repeaters can connect the metropolitan networks. Long-distance and intercontinental quantum communication will be realized via satellite-based quantum channels.

superconducting circuits, trapped ions, atom arrays in optical tweezers, and single photons. To link the distant qubits, quantum interface is required to coherently mapping a single photon qubit in and out of the stationary qubits. Optical quantum computers have the unique advantage to be naturally integrated in the photonic networks. As a non-universal model of quantum computing, boson sampling has been demonstrated with up to 113 photon clicks out of a 144-mode interferometer, which yields a Hilbert state space dimension of 1043 and a sampling rate ten order of magnitudes faster than using the state-of-the-art simulation strategies on supercomputers [9]. Just as Bell experiments refute Einstein's local hidden variable models, the quantum computational experiments have provided strong evidence against the Extended Church-Turing Thesis. These work marks the dawn of the quantum era in computation. ■

About the Author

Jian-Wei Pan received his Bachelor (1992) and Master (1995) in Physics from the University of Science and Technology of China, Hefei, and his PhD (1999) from the University of Vienna. He is currently a Professor of Physics of the University of Science and Technology of China.

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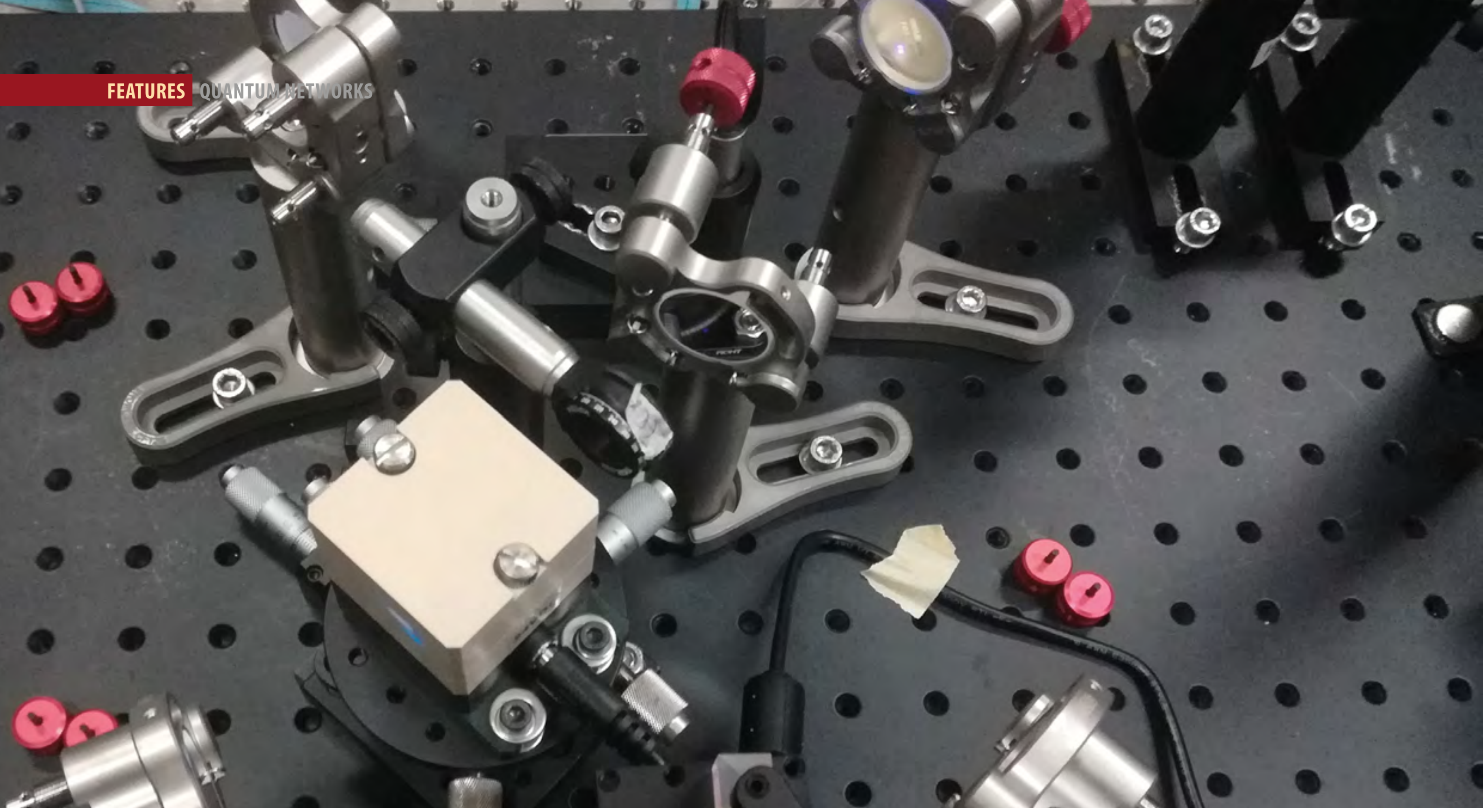

ENTANGLEMENT, CAUSALITY AND QUANTUM NETWORKS

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Quantum nonlocality, generated by strong correlations between entangled systems, defies the classical view of nature based on standard causal reasoning plus physical assumptions. The new frontier of the research on entanglement is to explore quantum correlations in complex networks, involving several parties and generating new striking quantum effects. We present recent advances on the realization of photonic quantum networks.

Entanglement and quantum nonlocality

In 1935 Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) challenged the completeness of quantum theory in its standard formulation, presenting the famous EPR paradox [1]. The scientists showed that the assumption of completeness of quantum mechanics, contradicts at least one among two natural assumptions: the locality of influences and a fundamental criterion of reality. At the root of the EPR paradox there is entanglement, the most distinctive phenomenon emerging from quantum mechanics and departing from a classical interpretation of the world. Entangled states of multipartite systems exhibit strong correlations that are maintained regardless of the distance between the parties. Einstein and his coworkers believed that these nonlocal correlations were incompatible with the principle of locality, which states that an influence cannot be transmitted faster than the speed of light. They argued that quantum mechanics should be considered an incomplete description of reality and should be integrated by a more complete theory that incorporates hidden variables leading to a deterministic and local description of physical systems.

Three decades later John Bell demonstrated the impossibility of formulating local hidden variable (LHV) theories that are consistent with all predictions of quantum mechanics [2]. His theorem led to the development of Bell inequalities, which can be experimentally tested to determine whether nature can be described by LHV theories. If Bell inequalities are violated, no LHV theory can provide an adequate description of the observed data. A large number of experimental tests have been conducted so far to verify the predictions of quantum mechanics. These experiments have consistently shown that the predictions of quantum mechanics violate Bell inequalities, demonstrating that LHV theories, satisfying Bell's assumptions, are incompatible with nature.

Causal inference and quantum nonlocality

Quantum nonlocality manifests itself through the violation of Bell inequalities that are derived from classical assumptions. Recently, it has been realized that these assumptions can be cast in the classical causal framework. More specifically, Bell theorem requires the so-called freedom of choice in which the measurement choices are statistically independent from the source of the subsystems and the local causality assumption. Local causality is the factorization of probabilities implied by the classical causal model of the Bell scenario, where the correlations of the two systems are required to be entirely explained by the common cause. In this way, Bell theorem can be seen as a particular case of the general causality framework [3]. Here, causal models are mathematically formalized by Bayesian networks, able to treat probabilistic causal relations. They are based on Directed Acyclic Graphs (DAGs) that describe the causal relationships between the variables of the considered scenario [3].

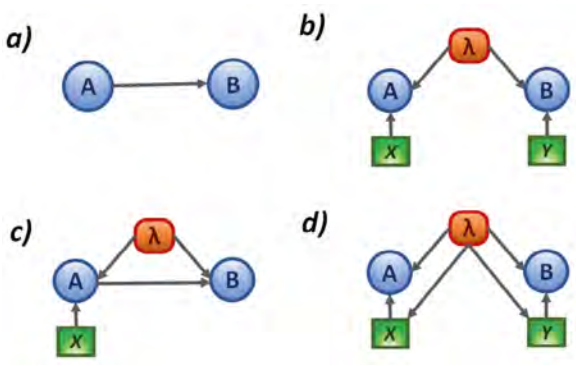
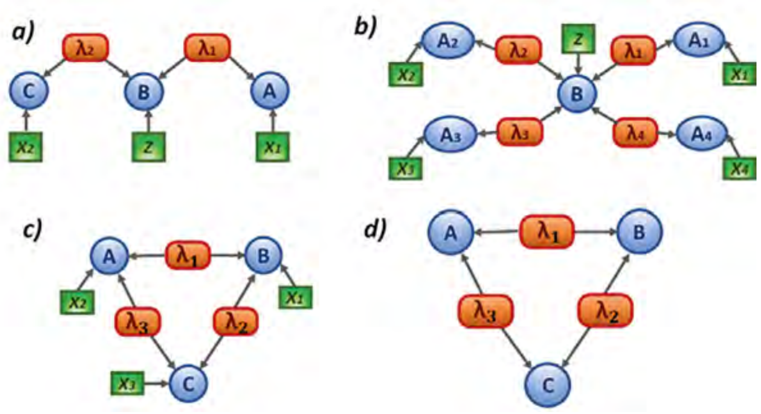


FIG. 1: Causal structures. a) Causal arrow between two variables. b) Bell scenario. c) Instrumental scenario. d) Bell scenario without freedom of choice assumption.

The relevant variables, observable or latent, are represented by nodes. Conversely, causal relationships between variables are represented by arrows (Fig. 1a). DAGs are both an explicit graphical representation and a mathematical description of causal modeling. From any causal model, one can directly extract the classical constraints on the probabilities relative to the observable nodes by means of a general factorization rule called Markov condition. For instance, in the Bell bipartite scenario (Fig. 1b), the Markov condition corresponds exactly to local causality. Notably, these constraints depend only on the causal structure and not its specific implementation and the inner structure of the • • •



▲ **FIG. 2:** Causal structures. a) Bilocal scenario. b) Star-shaped network. c) Triangle network with external inputs. d) Triangle network without inputs.

experimental devices. In Bell's scenario the absence of causal arrows between the source and the measurement choices corresponds to the free-choice assumption. Experimental tests try to enforce this assumption using quantum random number generators or even human choices [4] for choosing the measurement settings. When such an assumption is not used, possible influences between the source and the measurements choices (Fig. 1c) could explain Bell inequalities violations. In this case, one can extend the causal structure to demonstrate quantum violation of classical causal constraints [5]. On the other hand, if one allows for causal influences between the two parties, considering the so-called instrumental scenario (Fig. 1d), quantum-classical gaps can be nevertheless found [6,7].

In this way, causal modeling has a twofold utility. First, it helps to clarify the assumptions behind classical models that are violated by quantum correlations. Hence, it represents a powerful tool to study the testable boundaries between classical and quantum realms. Second, it allows the study of classical constraints in general arbitrary causal structures composed by several nodes and sources. Hence, several networks, beyond the bipartite Bell scenario, can be studied in this framework.

Quantum networks beyond bell scenario

The simplest form of nonlocality can be demonstrated in the standard bipartite Bell scenario, where a single source shares subsystems among two distant measurement stations (Fig.1b). There are at least two motivations for considering more general and complex causal scenarios composed of several parties and sources. The first is fundamental: complex networks are able to show new forms of nonclassicality. The second reason is practical: the advantages for quantum communication, brought by quantum nonlocality, will lead to the realization of the future quantum internet connecting several dislocated users. It is then crucial to study which kind of nonclassicality can arise from these scenarios, in order to exploit it for communication tasks. Accordingly, during the last years, an intensive and growing research has been dedicated to face the challenges posed by complex networks coming from both theoretical and experimental sides [8]. We briefly review recent advances on the development of photonic platforms able to show quantum nonclassicality, violating causal constraints in complex networks composed by independent sources.

Bilocal and star-network scenarios

The simplest complex network with more than one source is the bilocal scenario [8]. Here, two independent sources share subsystems among three measurement stations, with a central one receiving subsystems from both the sources, and the two peripheral ones each receiving a subsystem from a source, respectively (Fig. 2a). From the causal constraints, explicit nonlinear Bell-like inequalities can be devised in this scenario. Entangled states and suitable measurements can violate these inequalities contradicting the predictions of bilocal models, that are those models satisfying the causal constraints in the bilocal scenario. Different photonic experiments reached a violation of classical limits using entangled states of light. The first experiments were performed using pairs of polarization entangled photon pairs from two sources pumped by the same laser [9,10]. To enforce the independence of the sources, a demonstration using fully independent sources was realized, also performing the measurements in a space-like configuration [11].

A generalization of the bilocal scenario to an arbitrary number of independent sources is the star-network scenario where n sources share subsystems between a common central node and n peripheral nodes (Fig.2b). A photonic implementation of a quantum star-network has been demonstrated using up to four independent sources and five measurement stations [12].

Triangle scenario

One of the most interesting causal scenarios is the triangle network. Here, three independent sources share pairwise pairs of subsystems among three measurement stations in a triangle configuration (see Fig.2c-d). This seemingly simple scenario shows rich features.

When each node of the network is provided with an external input, requiring the freedom of choice assumption, the nonclassicality of quantum correlations can be demonstrated performing three parallel Bell tests among each pair of nodes of the network. This configuration has been experimentally realized using three entangled photon sources in [13]. The most striking feature of the triangle network is that quantum correlations can show nonclassicality without the use of external input. In this way, the freedom of choice assumption is not needed and is replaced with the independence of the sources. The first experimental demonstration of this new kind of nonclassicality has been recently implemented in [14].

Discussion and perspectives

The nonclassicality arising from entangled states is the most radical departure of quantum theory from classical physics. This nonclassicality can be cast in the violation of classical causal modeling. The causality framework allows to formalize quantum nonclassicality in arbitrary scenarios and in the last years several quantum networks were realized in photonic systems violating classical causal constraints. Several challenges remain to be faced in this research area. From a theoretical point of view, the characterization of the classical-quantum gap in complex networks is a hard task with several open points. From an experimental perspective, networks with different causal structures have to be explored, in particular those in which entangled measurements on subsystems from different sources are performed. ■

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Citizen science in the next EPN issue

Citizen science is research conducted with participation from the interested public. It is a concept already well known from astronomy, where a large community of amateur-astronomers is involved in the classification of astronomical objects observed by telescopes. Also in physics projects, the public is often invited to help classifying 'events'. Important drivers of modern citizen science are the large increase in open data and the possibility to analyse the data by using an app on a smartphone.

In the next EPN issue we will highlight several citizen science projects. One of them is the EPS Citizen Science Competition 2022, organised last year in September. Participants in the competition took part in research projects in the fields of particle physics and gravitational wave astronomy. We will introduce you in the objectives of the competition. The buzz word is Zooniverse. EPS offered the winners a travel grant to visit CERN in Geneva and the gravitational wave observatory VIRGO in Italy.

We will update you on the results of the EU-funded REINFORCE project that realised more Citizen Science projects in the field of frontier physics, bridging the gap between large research infrastructures and society. In addition we will introduce you in the citizen science tools of EUROVOLC, the European network of observatories and research infrastructures for Volcanology.

This and more in the next issue of EPN, which will come on-line around 19 April 2023 as a flipbook at www.epn.eps.org and as registered document at www.europhysics.org. ■