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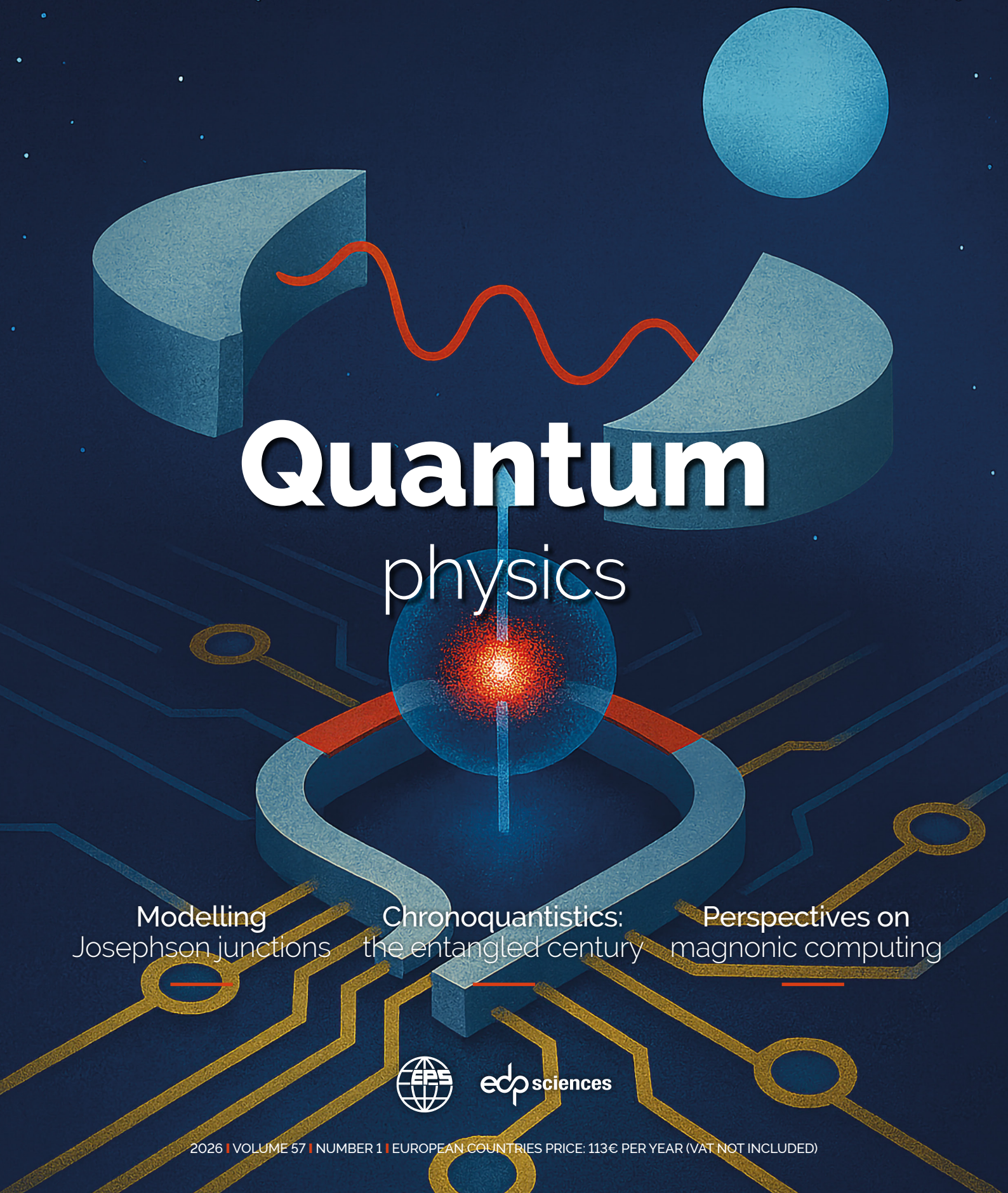

Quantum physics

Modelling Josephson junctions

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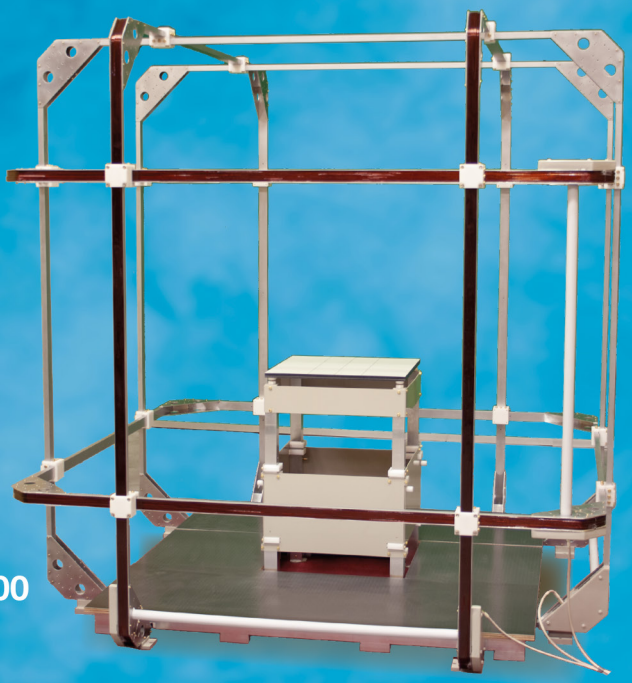

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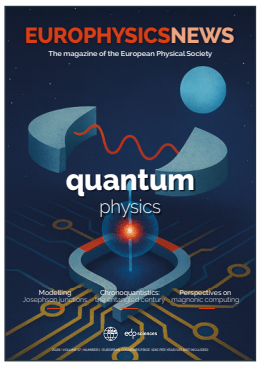

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Cover picture: AI-generated image of macroscopic quantum physics (© Ádám Gali).

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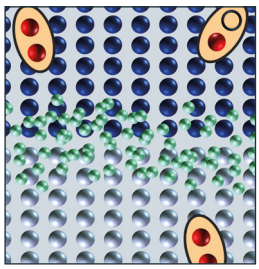
From macroscopic quantum circuits to scalable quantum systems



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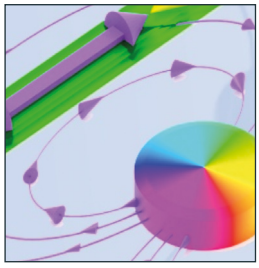
Modelling Josephson junctions for superconducting quantum computing



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Perspectives on magnonic computing

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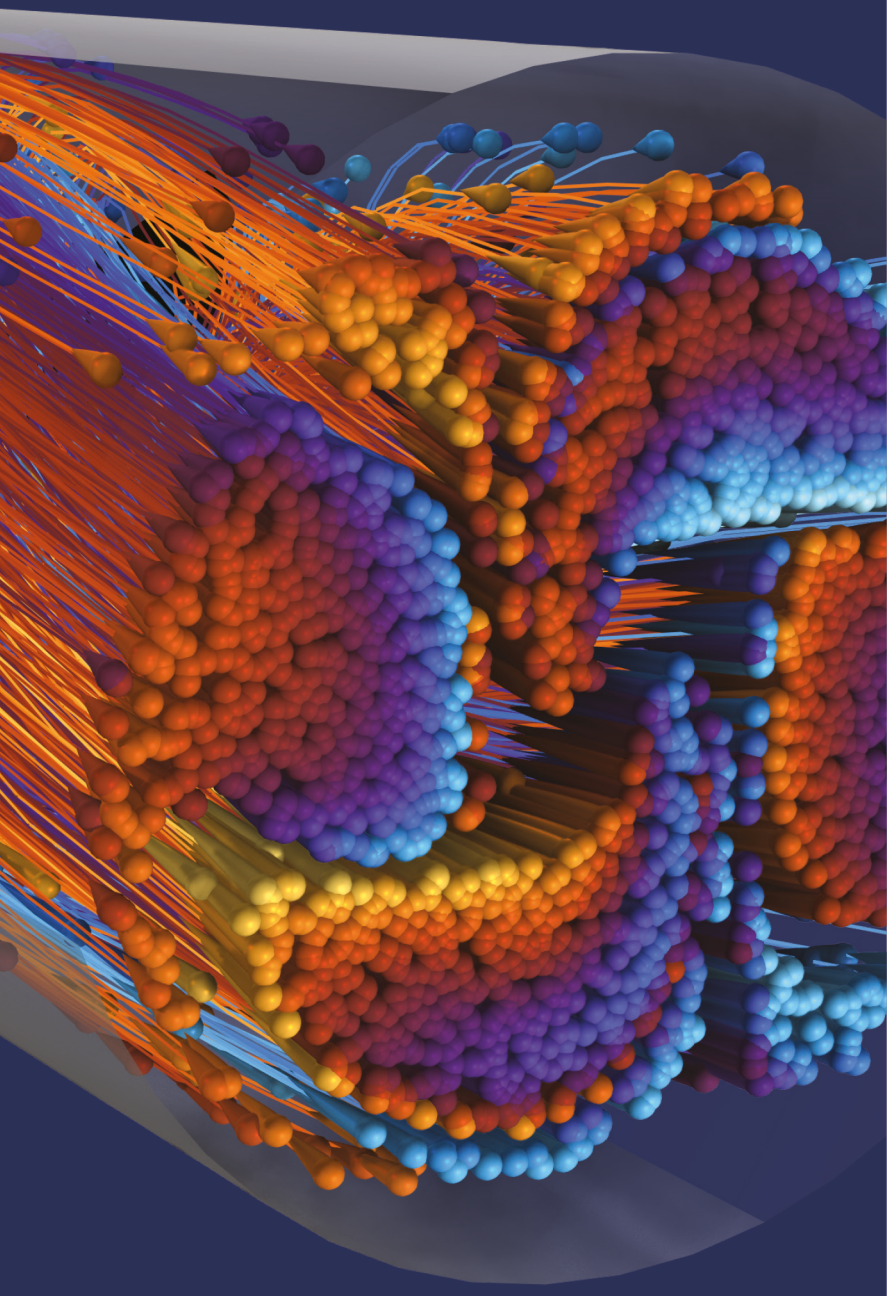

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[EPS EDITORIAL]

What is the size of Schrödinger's cat?

DOI: https://doi.org/10.1051/2026101

The 2025 Nobel prize in Physics was awarded to John Clarke, Michel H. Devoret, and John M. Martinis *"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"*.

The core discovery celebrated by the 2025 Prize bridges one of the most persistent boundaries in physics: the demarcation between the quantum domain—characterised by probabilities, superposition, and tunnelling—and the classical world of everyday experience. Quantum mechanics traditionally governs phenomena at the atomic and subatomic scales. The work of Clarke, Devoret, and Martinis demonstrated unequivocally that quantum phenomena can emerge in systems large enough to be manipulated and measured directly as engineered electrical circuits.

The experiments date from the early 1980s, using Josephson junctions (an insulating interface separating two superconductors), and the tunnelling effect (see their publication *"Measurements of Macroscopic Quantum Tunnelling out of the Zero-Voltage State of Current-Biased Josephson Junction"*, *Phys. Rev. Lett.* **55**, 1908 – Published 28 October 1985). Classically, a particle like a low energy electron cannot pass the insulating barrier. In contrast, quantum mechanics permits tunnelling despite insufficient energy.

Although the early studies of quantum tunnelling focused on single particles, macroscopic systems composed of many particles can also exhibit tunnelling through the coherent dynamics of a collective quantum variable. Such coherence is normally destroyed by environmental noise. Clarke, Devoret, and Martinis demonstrated that a superconducting circuit could be sufficiently isolated to preserve macroscopic quantum coherence, enabling tunnelling of a collective degree of freedom.

Clarke, Devoret and Martinis were able to experimentally answer the question raised by A.J. Legget, himself a recipient of the Nobel Prize for Physics in 2003 for pioneering contributions to the theory of superconductors and superfluids: could a smaller version of the Schrödinger's cat thought experiment be performed in superconducting or superfluid systems? (see the publication "Prospects in Ultralow Temperature Physics", *J. Phys. Colloq.* **39** C6-1274 (1978)].

Clarke, Devoret and Martinis showed that tunnelling and energy quantisation can happen at a macroscopic level. This completely reshapes our understanding of the limits of quantum mechanics.

The work of Clarke, Devoret, and Martinis paves the way for practical applications, in particular to quantum computing, even if this is still to be made effective. Their result established the physical basis of superconducting qubits, in which information is stored and manipulated using coherent quantum states of macroscopic electrical circuits.

There are promising implementations, notably technologies based on superconducting qubits, including transmons and fluxoniums, the latter offering longer coherence, higher anharmonicity, and lower frequencies, thus allowing better stability and error control.

We may also recall that this Nobel prize is awarded during the "International Year of Quantum Science and Technology" (IYQ) – https://quantum2025.org/ – celebrating the first centenary of the invention of Quantum Mechanics and raising public awareness of the importance and impact of quantum science and applications on all aspects of life.

Once again, the Nobel prize confirms that fundamental research remains the driving force of technological revolutions: by a better understanding of the fundamental laws of physics, research opens concrete perspectives. ■

Mairi Sakellariadou,
EPS President

From everyday light to quantum horizons: celebrating the International Day of Light with RAU young minds in Yerevan

G. Khachatryan and A. Avetisya – Russian-Armenian University (Yerevan, Armenia) – DOI: https://doi.org/10.1051/epn/2026102

A full day celebration of the International Day of Light (IDL) was organized at the Russian Armenian University (RAU) in Yerevan, Armenia, within the QWAVE initiative (Quantum World: Advancements, Visions, and Exploration), launched in the context of the Quantum Year 2025. "IDL with QWAVE: From Photons to the Stars" is the name of the event that brought together high school students, university students, educators, and early career researchers for a program that connected everyday optical phenomena with modern photonics and emerging quantum technologies.

The RAU Young Minds (YM) Section is a student-led initiative operating under the umbrella of the European Physical Society (EPS) YM Program. Its mission is to foster an active and inclusive physics community among students and early career researchers at RAU. Through outreach, educational events, and international engagement, the section aims to bridge the gap between classroom learning and cutting-edge research, while connecting local students to the wider European and global physics network. Created in 2023 is one strong section of the YM network that organizes several events throughout the years.

In this event that RAU YM organized, the main aim was to raise public awareness of how deeply light-based science influences both fundamental research and real-world applications, from spectroscopy and laser technologies to astronomy and quantum optics. The event was designed as an outreach platform to introduce participants to the mission and activities of the EPS YM Program and the Radiant Minds Student Chapter at RAU, and to encourage students to see themselves as part of a broader scientific community that extends well beyond national borders. The program was intentionally structured to serve audiences with different backgrounds while keeping a clear narrative: from intuition to experimentation, and then to research level perspectives.

The goals of the YM initiative, the role of the student chapter, and the value of joining international scientific networks were explained in a welcoming session. This introduction set an inspiring tone and helped participants understand how student driven communities can create real opportunities for learning, collaboration, and growth.

The morning session focused on accessible popular science talks for school students. These lectures introduced core ideas in optics, photonics, lasers, and astronomy through clear examples and engaging stories. "Light Detectives: How We Know What Stars Are Made Of" highlighted how light becomes a tool for reading the universe, and how spectroscopy reveals the composition and physical conditions of distant stars. "Recursion: Acquaintance and Love at First Sight" was a lecture that particularly resonated with younger attendees by combining scientific ideas with an approachable narrative style, sparking lively questions and discussion. Together, the morning session built a conceptual foundation and demonstrated how the same physical principles can connect daily observations to advanced scientific exploration.

In the middle of the day, selected participants took part in hands on optical experiments and laboratory demonstrations. This segment was a core strength of the event, moving from listening to doing. Students explored optical effects and measurement ideas in a guided setting, observing how light behaves in real setups and learning how to describe and interpret what they see.

The practical component reinforced scientific methodology, encouraged critical thinking, and gave students the confidence that physics is not only something to read about, it is something they can test, question, and understand.

After the experimental session and lunch, the event continued with advanced scientific lectures aimed at university students and early career researchers. "Taming Light with Tiny Crystals: The Magic of Quantum Materials," showed how engineered materials and nanoscale structures can offer precise control of light and open pathways toward novel photonic and quantum enabled technologies. The highlight of the entire day was the keynote lecture by Assoc. Prof. Ebrahim Karimi (University of Ottawa), a globally recognized researcher in structured light and quantum information. In "Beyond Vision: The Hidden Powers of the Human Eye", he delivered a compelling and interdisciplinary perspective linking optics, quantum concepts, biology, and human perception. The talk combined depth with remarkable clarity and left a strong impression on the audience, showing how fundamental research in light can reshape our understanding of both technology and the human experience.

A creative photo competition further enriched the event by inviting participants to submit images of optical phenomena together with short scientific explanations. In addition to local participants, the competition received an international submission (from Dr. Mohamed Aboushelib, Egypt), whose work was awarded the "Most Unique Photo" recognition by the jury. His photo captured sunlight scattering through clouds, revealing the stunning dance of light and atmosphere. The awarded photos can be seen in Figure 1, including the three main places: the close-up of a CD surface reflecting a vivid rainbow, a composition of Mount Ararat reflected in a car mirror and a beam of light illuminating ancient frescoes in an Armenian Monastery. The contest format, combining visual creativity with scientific reasoning, proved especially effective in helping students learn through observation and explanation.

The day concluded with an awards ceremony in a warm and celebratory atmosphere, where winners shared the stories behind their photos. Participant feedback was notably strong. Students were highly engaged not only during the experiments and contest, but also throughout the lectures, asking thoughtful questions and expressing genuine excitement. Many participants later reached out to ask about future events and how to stay involved, a clear sign that the initiative succeeded in motivating the next generation.

Support from EPS YM played an important role in strengthening visibility and logistics. Transportation support helped ensure participation from regional students, and during the lunch and coffee break, participants enjoyed pastries featuring the EPS YM logo, a small detail that created a memorable visual identity and reinforced the connection between outreach and the wider European physics community. Huge thanks to the RAU YM section for the organization of this remarkable event and to all the speakers, attendees and participants.■

Exploring the full-stack design space of quantum computing

– DOI: https://doi.org/10.1051/epn/2026103

In-depth analysis shows that co-designing hardware and software is essential for optimising quantum performance.

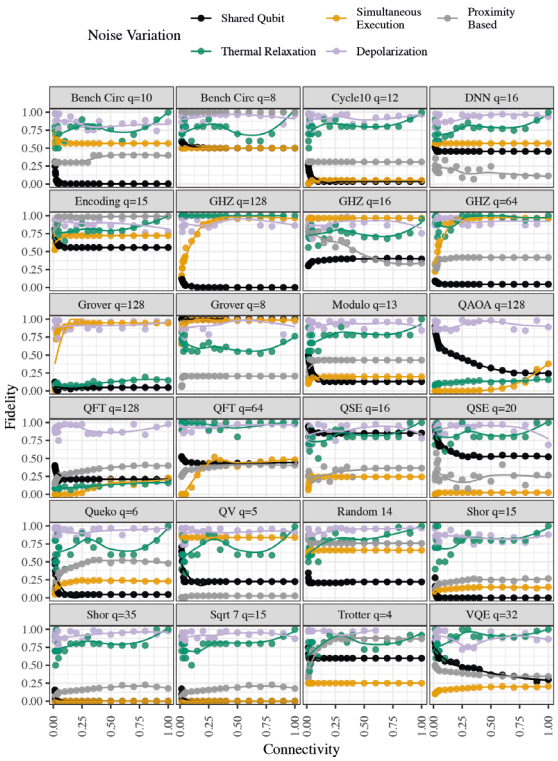
Over the past few years, advances in quantum computing have pushed it steadily closer to practical, real-world applications. But before this goal can be reached, greater standardisation will be needed across the entire quantum 'stack' – from user-facing software, all the way down to the underlying hardware.

In new research published in *EPJ Quantum Technology*, a team led by Hila Safi at the Technical University of Applied Sciences Regensburg investigates how this full-stack design challenge might be addressed. By systematically exploring the interplay between software hardware, the researchers show that improving quantum performance will depend on carefully co-designing both layers together.

Compared with classical computers, quantum hardware operates according to fundamentally different physical principles, meaning established design approaches can't simply be reused when building full-stack quantum systems. As well as being highly sensitive to noise, which can rapidly destroy fragile quantum information, quantum states also cannot be copied, placing strict limits on how information is processed and moved through a system.

At the same time, current quantum devices face severe practical constraints, including unavoidable noise and restricted qubit connectivity, which limits how many qubits can directly interact. As a result, quantum computing architectures must be rethought to integrate seamlessly with existing classical infrastructure, overlapping where possible but diverging where quantum-specific requirements demand it.

To work within these constraints, developers of quantum systems need to adapt classical design ideas wherever possible. In practice, this means carefully choosing how qubits are arranged and how operations are routed between them. Ideally, this would ensure that limited quantum resources are used as efficiently as possible, while still operating within a largely classical computing infrastructure. Practically, however, configurations of possible designs are often vast – presenting a daunting challenge for developers.



▲ Illustration of fidelity vs. connectivity across benchmarks as facets comparing three crosstalk models, thermal relaxation, and depolarisation noise for the heavy-hex back-end topology.

In their study, Safi's team tackled this problem using a technique known as design space exploration (DSE). Widely used in engineering and computer science, DSE involves systematically testing many different system configurations to understand how design choices affect the performance of the overall system. Here, the approach allowed the researchers to explore a wide range of ways to compile and execute quantum circuits, using methodologies inspired by classical system design.

Using computationally noisy simulations, the researchers varied both software-level decisions – such as qubit placement and routing strategies – and hardware-related features, including noise levels and connectivity patterns. This systematic approach revealed which combinations of choices led to the most accurate execution in the final circuit configuration.

The results show that by carefully selecting software strategies and hardware configurations, developers can substantially improve quantum circuit fidelity, even beyond what standard error mitigation techniques can achieve on their own. Importantly, these gains persist when quantum error correction schemes are included, rather than replacing their benefits.

Overall, the study highlights the critical role of a full-stack approach to optimising quantum systems, where hardware and software are designed in tandem with each other. By building on these insights, Safi and colleagues hope future work will further improve the accuracy and scalability of quantum computing architectures, potentially bringing widespread use a step closer to our everyday lives. ■

Reference

[1] S H. Safi, M. Bandic, C. Niedermeier *et al.*, *EPJ Quantum Technol.* **12**, 117 (2025). https://doi.org/10.1140/epjqt/s40507-025-00413-7

Magnetic skyrmion as Schrödinger's cat

– DOI: https://doi.org/10.1051/2026104

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The studies of quantum tunneling of subatomic particles began almost immediately after Schrödinger wrote his seminal equation in 1926.

The alpha-decay of the uranium nucleus is one example. According to quantum mechanics, before catching the alpha-particle, one must assume that it exists in a superposition of two states: inside and outside the nucleus. This inspired Schrödinger to propose in 1935 a mind-boggling thought experiment in which the Geiger counter, detecting the alpha particle, triggers the action that kills a cat. Before observing the cat, one would have to assume that it exists in a superposition of two states: alive and dead. It raised a question whether quantum mechanics applies to macroscopic objects. Experiments on Josephson junctions performed in the 1980s, for which the 2025 Physics Nobel Prize was awarded, answered it positively. These experiments opened a path to building quantum computers whose elements – qubits are in a quantum superposition of two states. In superconductors, the macroscopic variable is the phase difference across the Josephson junction, which determines the macroscopic electric current across the junction.

Similar suggestions have been made for magnetic systems. In the last 50 years, macroscopic quantum tunneling (MQT) of the magnetic moment has been studied theoretically and experimentally. Magnetic relaxation observed at low temperatures has been attributed to quantum tunneling of the magnetic moment between energy minima in small magnetic particles and to quantum tunneling of domain walls in the potential landscape created by defects in the crystal. Unlike experiments on Josephson junctions, a direct comparison of experiments on magnetic tunneling with theory has been hindered by difficulties in measuring the quantum tunneling of the magnetic moment in a single, sufficiently small magnetic particle at millikelvin temperatures, or conducting a similar experiment with a domain wall of sufficiently small area. This is one reason why magnetic qubits lag superconducting qubits.

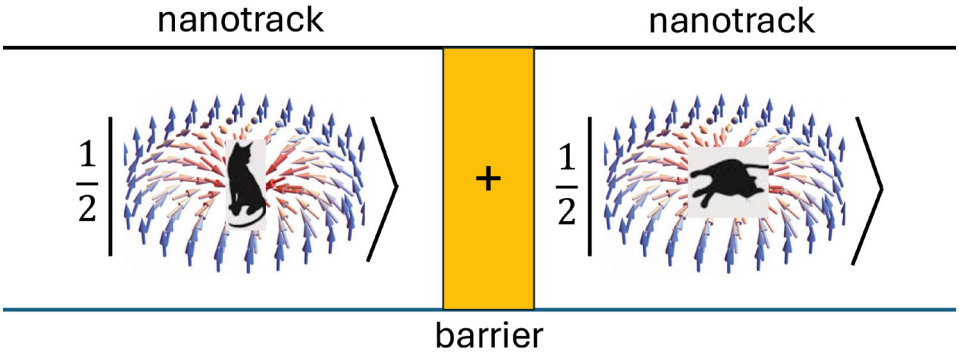
In our EPL-2025 [1], we proposed to use magnetic skyrmions for testing the theory of macroscopic quantum tunneling and exploring the possibility of building skyrmion-based qubits. A skyrmion is a topological defect in a uniformly magnetized background of a ferromagnetic film. While the structure of magnetic particles prepared by various technological methods is difficult to control, the structure of a skyrmion is fixed by topology. Conservation of the topological charge would provide an additional level of protection for skyrmion-based computer memory, whether classical or quantum. We computed the effective mass of a skyrmion in a nanotrack and demonstrated that the de Broglie wavelength of such a skyrmion can easily be of the order of one nanometer. This makes it plausible that such a skyrmion, despite consisting of hundreds or even thousands of individual atomic spins, would exhibit wave properties in diffraction and interference experiments like those with light and electrons. A defining MQT experiment would be observation of quantum tunneling of a skyrmion through a classically impenetrable barrier inside a nanotrack, see Fig. 1. We showed that the probability of such a tunneling could be sufficiently large to observe it at low temperature when the thermal overbarrier transition is ruled out. ■

This work has been sponsored by the U.S. Air Force Office of Scientific Research.

Reference

[1] E. M. Chudnovsky and D. A. Garanin, Magnetic skyrmion as Schrödinger's cat, *EPL* **151** (2025) 46001

▼ Quantum tunneling of a skyrmion formed by many spins through a classically impenetrable barrier inside the nanotrack. Schrödinger's cat is realized through a quantum superposition of skyrmion states on the left and on the right from the barrier. Such states of a skyrmion in a nanotrack can be used to develop topologically protected qubits.



Nobel Prize (Quantum Physics in Action)

by Jose Lado,
Aalto University, Finland – DOI: https://doi.org/10.1051/epn/2026105

Several of our most transformative established technologies rely on controlling energy, electric currents, and electromagnetic waves. These physical effects are everywhere in nature, but it is when we learn to extract, control, and engineer them, and only then, that we can create technologies that shift the boundaries and what we can do. Quantum effects are also everywhere, and we do know that they govern the microscopic world for more than 100 years. However, it is only when we can extract, control, and engineer quantum effects that a whole range of possibilities will open up. Quantum technology relies on extracting the quantumness hidden everywhere in nature, enabling us once again to create a technology to push once again the boundaries of what is possible.

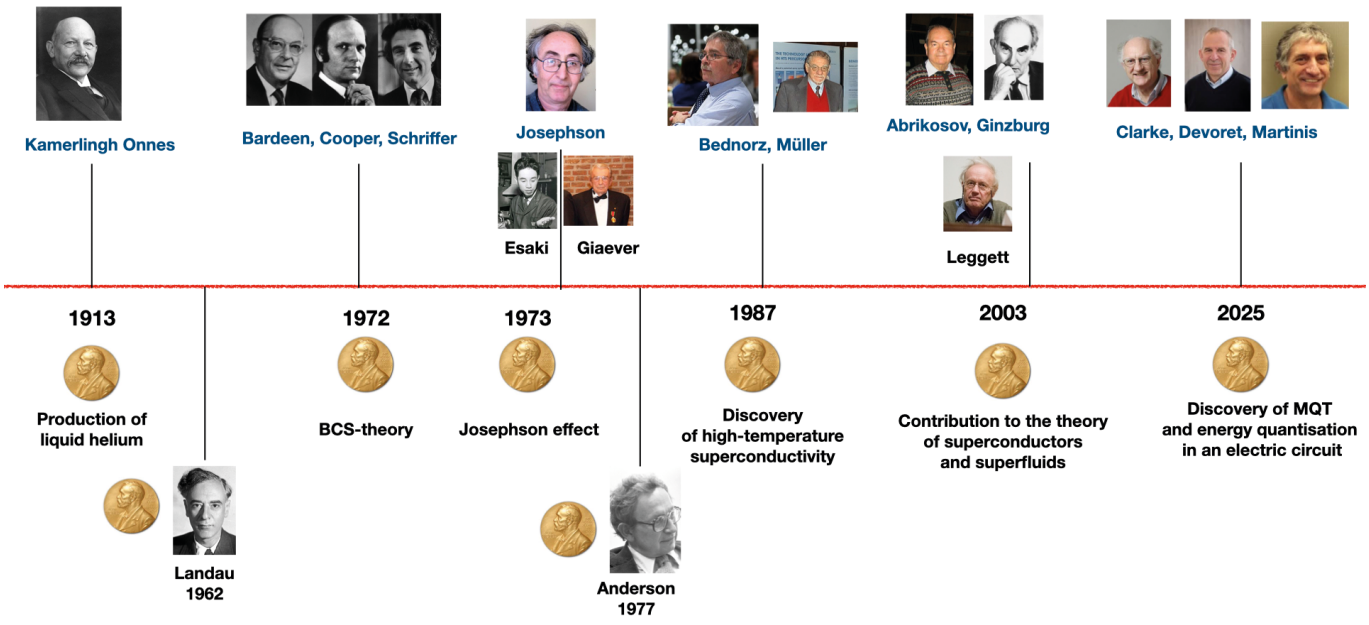
Quantum effects are hiding in plain sight. Quantum mechanics governs the dynamics of the world that surrounds us, and yet the most paradigmatic quantum effects including interference, tunneling and superposition do not seem to be present at our human scale. Quantum mechanics becomes unavoidably present when going to the atomic scale. And yet, at macroscopic scales, those effects are washed away, and classical physics appears. Somehow, nature has a tendency to hide quantum effects as we go to bigger scales. A crucial step to unleash quantum technologies relies on out-engineering nature, exploiting quantum materials and quantum devices in which quantum effects are not lost, but survive up to macroscopic scales.

Superconductivity is one of those examples in which a quantum effect, the coherence of the collective electron wavefunction, survives up to macroscopic scales. Superconductivity itself started as a fascinating and unexpected fundamental physical phenomena, and established a whole quantum state of matter we did not know before. Fast forward to the present, and superconductors have become a keystone of some of our most important quantum technology. Crucially, superconducting quantum materials provided a key strategy to bring quantum effects all the way up to our human scale, becoming the building blocks for controllable macroscopic qubits, and enabling the current breakthroughs in quantum detectors and quantum computers. The Nobel Prize in physics 2025 demonstrated how quantum phenomena in the microscopic world, quantum tunneling and superposition, can be brought up to our macroscopic world.

The current issue explores the path that superconducting quantum technology has taken in the last century, exploring potential future strategies to enable boundless, scalable quantum technologies. Sebastian Bergeret discusses the path that started with the discovery of superconductivty and led us to superconducting qubits, cornerstones of current quantum technology. Martin Weides explores what our current challenges in scaling quantum computers based on superconducting circuits are. Matti Silveri analyzes complementary potential strategies to create error-corrected quantum computers, scaling up quantum circuits, and improving qubits. Gianluigi Catelani and Giampiero Marchegiani discuss the role of theoretical modeling in understanding and mitigating some of the errors of conventional qubits. Finally, Antigone Marino and Paola Belardini discuss the outlook that quantum technology can provide to our future.

Unlocking quantum effects in macroscopic systems opens a door to shifting the boundaries of knowledge and technology, and what we believe to be possible and impossible. Superconducting qubits are now a central piece of quantum technology and provide a crucial building block for many strategies for quantum detection, quantum metrology, and quantum computing. Quantum materials realizing macroscopic quantum states, beyond superconductivity, can fuel the next breakthroughs in quantum technology, potentially opening subareas that we are not even aware of. Quantum technologies are in their infancy, and we yet do not understand their ultimate impact. We, however, do know one thing: its steady, rapid, and unstoppable progress will unavoidably enable us to address some of the technological and global challenges that we currently consider impossible to solve. ■

Superconductivity: A Nobel Prize Perspective



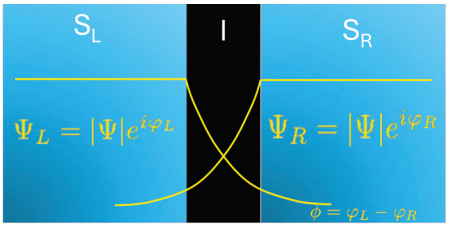
FROM SUPERCONDUCTIVITY TO MACROSCOPIC QUANTUM PHENOMENA: A PATH MARKED BY NOBEL PRIZES

Sebastián Bergeret – DOI: https://doi.org/10.1051/epn/2026106
Centro de Física de Materiales (CFM-CSIC), San Sebastián, Spain and Donostia International Physics Center (DIPC), San Sebastián, Spain

Is it possible to create a Schrödinger's cat in a laboratory - that is, to make a macroscopic object obey the laws of quantum mechanics? The 2025 Nobel Prize in Physics recognizes experiments showing that this is indeed possible, using superconducting electrical circuits.

The path to this achievement can be traced through the history of superconductivity marked by key Nobel Prizes (Fig. 1). From the prize awarded to Kamerlingh Onnes for the discovery of superconductivity itself, through the theoretical breakthroughs of Ginzburg, Landau, and Bardeen, Cooper, Schrieffer, and Josephson for theory achievements, to the 2025 laureates - John Clarke, Michel Devoret, and John Martinis - who demonstrated quantum behaviour in macroscopic superconducting electric circuits.

Surely, when Heike Kamerlingh Onnes discovered in 1911 that certain metals lose all electrical resistance below a critical temperature, he could not have imagined that this phenomenon would capture the attention of scientists for more than a century. It also took some time before superconductivity began to be properly understood. A major step forward came in 1950, when Vitaly Ginzburg and Lev Landau proposed an insightful and intuitive phenomenological theory which introduced a complex order parameter $\Psi=|\Psi|e^{i\phi}$ - a kind of pseudo wavefunction - whose squared amplitude ● ● ●



First Josephson relation

$$I_J = I_c \sin\phi$$

Second Josephson relation

$$\dot{\phi} = \frac{2e}{\hbar} V$$

▸ **FIG 1:** Schematic view of a Josephson junction formed by two superconductors (S_L, S_R) separated by an insulating layer. A supercurrent (I_J), proportional to the sine of the phase difference (ϕ), can flow without a voltage drop, due to the overlap of the collective electron wave functions. The two Josephson relations are shown below.

● ● ● represents the density of electrons participating in superconductivity. This simple description already anticipated one of the profounds aspects of the phenomenon: superconductivity is characterized by a global quantum phase shared by all participating electrons, *i.e.*, they act collectively as a single coherent quantum system.

Seven years later, John Bardeen, Leon Cooper, and Robert Schrieffer presented the first microscopic theory of superconductivity, known as the BCS theory. The BCS theory confirms that superconductivity is a macroscopic quantum state in which electrons near the Fermi surface form bound pairs, known as Cooper pairs. Actually, these pairs condense into a single collective state. All superconducting properties - such as zero electrical resistance, perfect diamagnetism, and quantum transport in macroscopic quantum devices - can be understood within BCS theory.

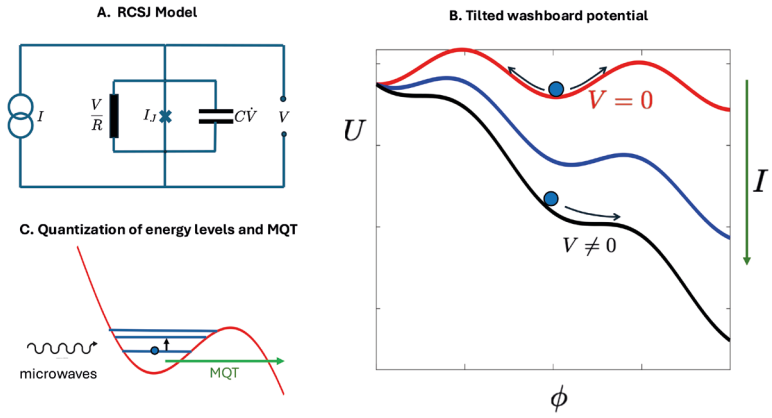
A subsequent fundamental link to the Nobel Prize of 2025 - and another Nobel Prize in this story - was the prediction of the Josephson effect. In 1962, Brian D. Josephson, then a PhD student at the University of Cambridge, predicted that two superconductors separated by a thin insulating barrier could sustain a supercurrent with no applied voltage, and that this current would depend on the macroscopic phase difference, $\varphi=\phi_L-\phi_R$, between the superconductors forming the junction (Fig. 1). In simple terms, this can be understood as the overlap of the two macroscopic "wave functions" of the superconductors, coupled through the tunnelling barrier. Such an overlap leads to a supercurrent, that is a current without dissipation. Josephson also showed that the time derivative of the phase difference is proportional to the voltage across the junction.

Josephson's predictions were confirmed within a year by P.W. Anderson and J.M. Rowell (1963), and the interest in using the Josephson effect in real devices grew rapidly. It soon became clear that in order to understand the current - voltage characteristics of a Josephson junction, one had to take into account the electrical circuit and electromagnetic environment seen by the junction. In this context, between 1966 and 1968, the so-called RCSJ (Resistively and Capacitively Shunted Junction) model was introduced.

The RCSJ model, which underlies the experiments by Clarke, Devoret and Martinis, represents a Josephson junction and its surrounding circuitry as a simple LCR circuit (Fig. 3a), with the Josephson junction itself acting as a nonlinear inductor L. The resistance R accounts for dissipation when a finite voltage develops across the junction, while C accounts for both the junction's and circuit's capacitance. An applied current I is shared by the three branches, providing a complete picture of the junction's dynamics.

From this simple circuit one can derive the equations for the phase dynamics, recalling that the second Josephson relation connects the voltage across the junction to the time evolution of the phase (Fig. 1). The resulting equation admits a very intuitive mechanical analogy: it is equivalent to the motion of a particle with an effective mass proportional to the capacitance, moving in a one-dimensional tilted "washboard" potential $U(\phi)$ (Fig. 2b), with the phase difference playing the role of the particle's position. For example, if the particle is confined in one of the minima of the potential, it remains there, *i.e.*, the phase does not change in time and, according to Josephson's second relation, this corresponds to a zero-voltage state. As the bias current increases, the tilt of the potential grows (Fig. 2b). When the bias current exceeds I_c - the maximum supercurrent the junction can sustain without dissipation - the particle escapes from the minimum and slides down the potential, producing a finite voltage across the junction. This simple model provides a rather accurate description of the phase dynamics, and consequently of the current–voltage characteristics of Josephson junctions. But how does this classical model relate to quantum mechanics and to the Nobel Prize of 2025?

▾ **FIG 2:** (a) Schematic circuit of the RCSJ model describing the dynamics of a Josephson junction. The bias current (I) is distributed among the three branches. (b) Tilted washboard potential. When the "particle" is in a potential minimum, it corresponds to a zero-voltage state. Increasing the bias current (I) increases the tilt, allowing the particle to escape and generates a finite voltage across the junction. (c) Quantization of the junction's energy levels is analogous to the quantization of a particle in a quantum well. The system's state can be changed by microwave irradiation. According to quantum mechanics, there is also a finite probability of escape via macroscopic quantum tunneling (MQT). Both properties were demonstrated in the experiments by Clarke, Devoret, and Martinis in the mid-1980s.



Although the superconducting phase is a collective phase of many Cooper pairs, the RCSJ model treats it as a classical variable. So where does quantum mechanics enter? To answer this question, let us push the analogy a bit further and assume that the particle is trapped in one of the potential wells. Classically, it could escape only with the help of thermal fluctuations, which allow it to hop over the potential barrier. Quantum mechanics, however, offers another route to escape, namely tunnelling.

Already in the late 1960s, Y.M. Ivanchenko and L.A. Zil'berman realized that even when thermal fluctuations are suppressed - *e.g.*, at very low temperatures - the phase may still undergo quantum fluctuations. In the mechanical analogy, this means that the "particle" can escape from a potential minimum by tunnelling through the barrier even at zero temperature. This phenomenon is known as macroscopic quantum tunnelling (MQT), a term coined by Anthony J. Leggett in the late 1970s. The word macroscopic is crucial here, as it recalls that the "position" of the particle in the RCSJ analogy, is nothing but the collective superconducting phase difference across the junction. This single variable emerges from the coherent behaviour of an enormous number of electrons. MQT will result in a transition from a zero to a finite voltage state.

There is another key aspect borrowed from quantum mechanics: when the particle is confined in one of the wells of the washboard potential (Fig. 3B), it no longer has a continuous range of energies but instead has discrete energy levels. Translated back to our circuit, this means that the Josephson junction can reside in different quantized energy states.

These ideas directly inspired John Clarke, Michel Devoret, and John Martinis in designing a carefully controlled experiment to demonstrate the two quantum effects described above. They embedded a Josephson junction in an experimental setup designed to mimic the conditions of the RCSJ model. By biasing the junction with a current below the critical current, corresponding to the zero-voltage state, *i.e.*, the particle being in a minimum of the potential, they could probe the dynamics of the phase in a controlled way. The "escape" of the particle from the potential well was detected as the sudden appearance of a finite voltage across the junction, providing a direct signature of the phase leaving the potential well. By repeating this measurement many times and varying the temperature, they could study the escape rate. At sufficiently low temperatures, the escape rate became essentially temperature independent, in agreement with the predictions for macroscopic quantum tunnelling (MQT), a clear demonstration that the phase behaves as a macroscopic quantum variable.

To further reveal the quantized nature of the phase, they applied microwaves to the junction. When the microwave frequency matched the spacing between the quantized energy levels of the well (Fig. 2c), the escape rate increased resonantly. This provided direct evidence that the macroscopic phase also exhibits discrete energy states, just like a quantum particle in an atom. These experiments unambiguously demonstrated the quantum nature of a macroscopic degree of freedom. In effect, Clarke, Devoret, and Martinis created the first "macroscopic artificial atom", or, if one prefers, a circuit-level realization of Schrödinger's cat: a macroscopic object obeying the laws of quantum mechanics.

Their work opened a new field of research. It provided the foundation for later developments such as the Cooper pair box, a device that exploits the variable conjugate to the superconducting phase - the electric charge - ultimately leading to the transmon qubit used in state-of-the-art quantum computers. More broadly, it invigorated the field of mesoscopic physics by demonstrating that a single macroscopic degree of freedom can be coherently manipulated and measured, thereby bridging condensed matter physics and quantum information science.

Beyond its applications, as John Clarke noted in a recent interview, their discovery had technological consequences that could not have been anticipated at the time it was made. It serves as a powerful reminder of the importance of supporting and funding fundamental research, whether or not it leads to immediate technological applications. ■

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References

[1] J. M. Martinis, M. H. Devoret and J. Clarke, *Phys. Rev. Lett.* **15**, *1543 (1985); Phys. Rev. B* **35**, 4682 (1987)

[2] Anderson P.W. and Rowell J.M., *Phys.Rev.Lett.***10**, 230 (1963)

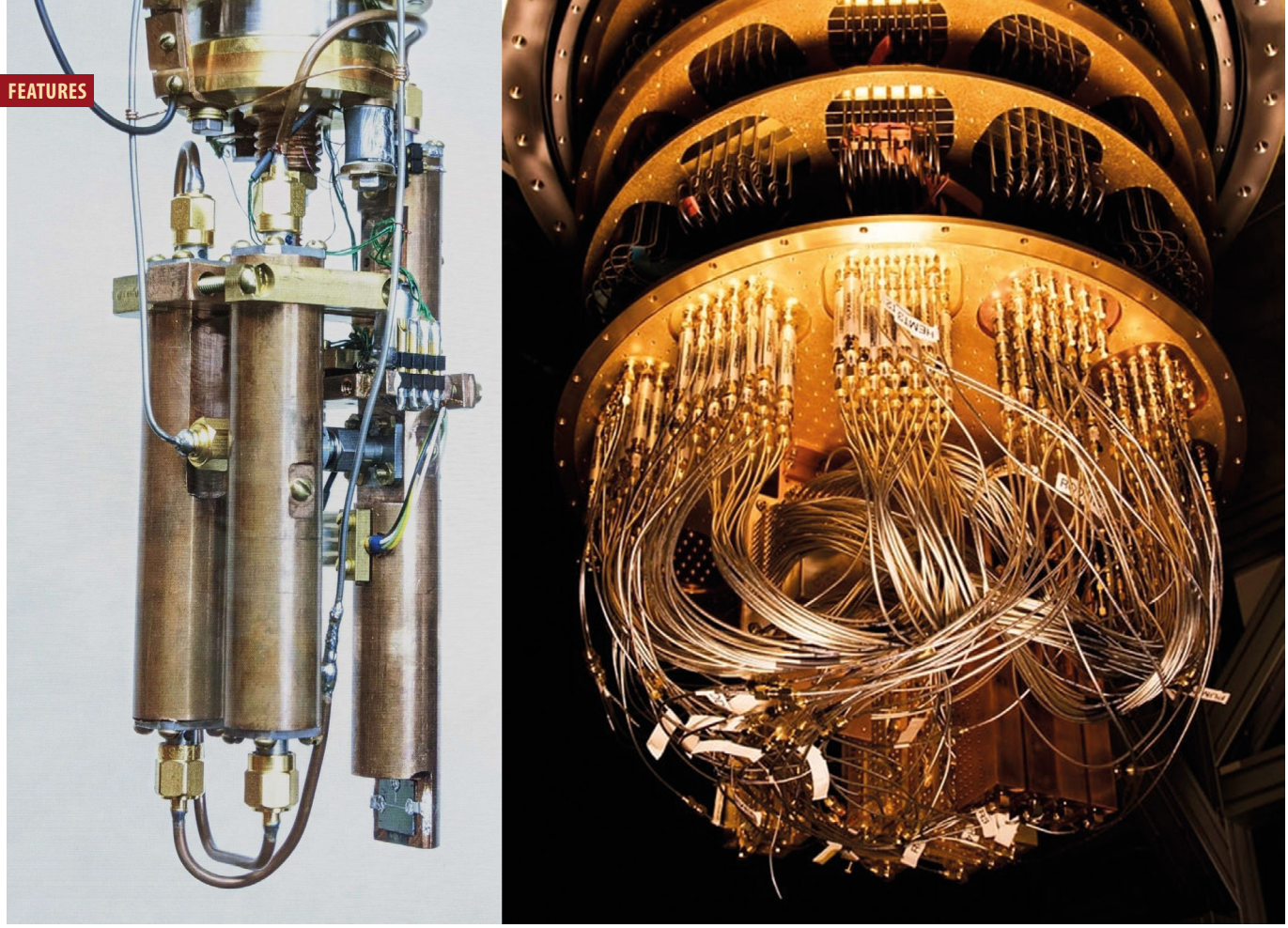
[3] Leggett A. J., *Prog. Theor. Phys. Supp.* **69**, 80 (1980)

[4] Ivanchenko, Yu. M. and L. A. Zil'berman, *Sov. Phys. JETP* **28**, 1272 (1969)

On the Cooper Box and the Transmon:

[5] V. Bouchiat, D. Vion, P. Joyez, D. Esteve, M. H. Devoret, *Physica Scripta T***76**, 165 (1998); Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, *Nature* **398**, 786 (1999)

[6] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, R. J. Schoelkopf, *Phys. Rev. A* **76**, 042319 (2007); M. H. Devoret and R. J. Schoelkopf, *Science* **339**, 1169 (2013)



FROM MACROSCOPIC QUANTUM CIRCUITS TO SCALABLE QUANTUM SYSTEMS

Songyuan Zhao and Martin Weides
James Watt School of Engineering, University of Glasgow – DOI: https://doi.org/10.1051/epn/2026107

Superconducting quantum circuits have reached impressive performance, with individual qubits and operations working extremely well. This maturity was recognized by the 2025 Nobel Prize in Physics, awarded for demonstrating that genuinely quantum phenomena – such as energy quantization and tunnelling – can occur in macroscopic electrical circuits. Yet building large, reliable quantum processors remains challenging. The limitation is no longer a single flaw, but the combined effect of many small imperfections spread across the hardware. Subtle losses in materials, tiny variations in components, unwanted heat, and constraints imposed by wiring, packaging, and control electronics all accumulate as systems grow in size. This article explains how such device-level effects ultimately limit the performance of entire quantum processors, and why understanding this link is essential for turning today's high-quality quantum devices into scalable and reliable quantum technologies.

▲ **FIG 1:** Left: dilution refrigerator system used by Devoret, Martinis, and Clarke in their 1985 experiments on macroscopic quantum tunnelling and energy quantisation. Right: dilution refrigerator system hosting Google Quantum AI's Sycamore processor used in the 2019 quantum supremacy experiment.

Between the everyday world of wires and switches and the abstract realm of wavefunctions, quantum mechanics found a new voice. The 2025 Nobel Prize in Physics celebrates the moment when quantum behaviour ceased to be confined to atoms and particles, and instead revealed itself in something far more tangible: electrical circuits made from superconductors.

The prize was awarded jointly to John Clarke, Michel H. Devoret, and John M. Martinis for demonstrating macroscopic quantum tunnelling [1] and energy quantisation [2] in electrical circuits. Their experiments showed, with remarkable clarity, that quantum mechanics does not end at the microscopic scale — provided we build systems carefully, cool them deeply, and isolate them from the noisy classical world.

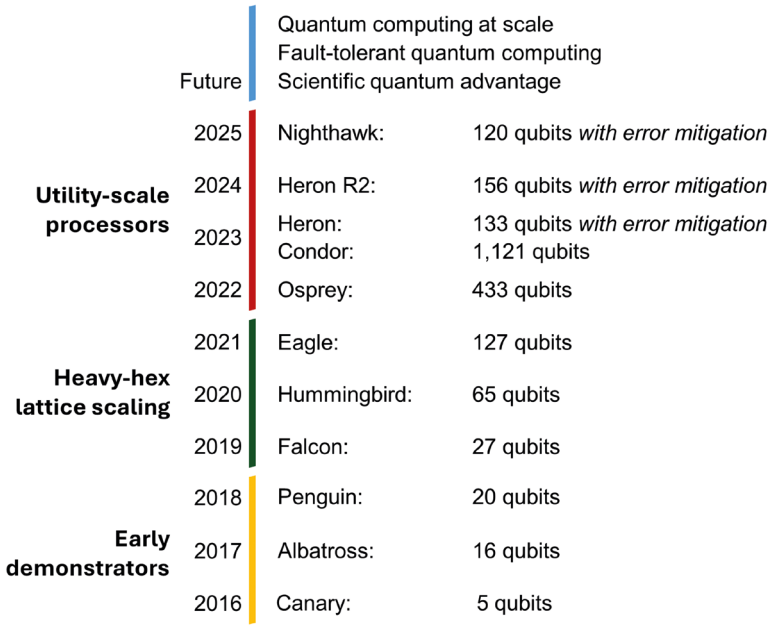
At the heart of this story lies superconductivity, a phenomenon discovered more than a century ago but still central to modern quantum physics. When certain materials such as aluminium and niobium are cooled below a critical temperature, their electrical resistance vanishes entirely. Currents can flow without dissipation, circulating indefinitely without energy loss. Superconductivity is a collective quantum state: electrons bind into Cooper pairs, and the entire system is described by a single macroscopic wavefunction with a well-defined quantum phase. This collective coherence, extending over micrometres or even millimetres, allows superconductors to support quantum behaviour on scales vastly larger than atoms.

To observe delicate quantum effects in such systems, thermal motion must be suppressed almost completely. The experiments recognised by the Nobel Committee were performed at temperatures around 10 millikelvin, more than 100 times colder than outer space. At these temperatures, achieved using dilution refrigerators, thermal energy becomes negligible compared to quantum energy scales. Random excitations freeze out, and quantum mechanics is allowed to speak clearly.

Cooling alone, however, is not enough. At millikelvin temperatures, even a faint electromagnetic disturbance or a barely perceptible vibration can overwhelm the signal. These experiments demanded an extraordinary level of experimental discipline: careful filtering of every electrical line, shielding against stray radiation, meticulous grounding, and mechanical isolation. The success of the work lay not in forcing a signal out of nature, but in removing everything that obscured it.

The crucial element enabling these discoveries is the Josephson junction [3], itself associated with an earlier Nobel Prize. A Josephson junction consists of two superconductors separated by an ultra-thin insulating layer of only a few nanometres. Classically, such a barrier would block current completely, but quantum mechanics allows Cooper pairs to tunnel coherently through the insulator while preserving their phase across the junction.

Quantum tunnelling is familiar at the microscopic level. Electrons tunnel through barriers in semiconductors; ● ● ●



▲ **FIG 2:** Timeline of major IBM Quantum processor generations over the past decade, showing the progression from early few-qubit demonstrators to utility-scale systems with over a thousand qubits.

atoms tunnel in chemical reactions. What Clarke, Devoret, and Martinis demonstrated was that an entire electrical circuit can tunnel. In their experiments, the phase difference across a Josephson junction behaves like a particle trapped in a potential well defined by the circuit design. Classically, escaping such a well requires sufficient thermal energy to climb over the barrier. As the temperature was lowered, a striking transition occurs: the escape rate became temperature independent, reflecting the collective tunnelling of many Cooper pairs as a single quantum object. This was macroscopic quantum tunnelling, observed directly and unambiguously.

The same systems demonstrated another defining feature of quantum mechanics: energy quantisation. Rather than occupying a continuous range of energies, the circuits could exist only in discrete energy levels. Using microwave spectroscopy, transitions between these levels were observed as sharp resonances. The circuit behaved like an artificial atom, with properties determined not by chemistry, but by lithography and design.

This marked a turning point in experimental physics. Quantum systems were no longer merely discovered in nature — they were engineered. Energy levels could be shaped, coupling could be tuned, and quantum states could be prepared, measured, and controlled within an electrical circuit.

The path from these foundational experiments to today's quantum computers is unusually direct. In the 1980s and 1990s, macroscopic quantum tunnelling and quantisation established that superconducting circuits obey quantum mechanics. In the early 2000s, these insights were used to design superconducting qubits, where two quantised energy levels encode quantum information [4]. Over the following decades, control techniques improved, coherence times lengthened, and multi-qubit systems became possible. Today, superconducting quantum processors containing tens to hundreds of qubits operate routinely in laboratories around the world.

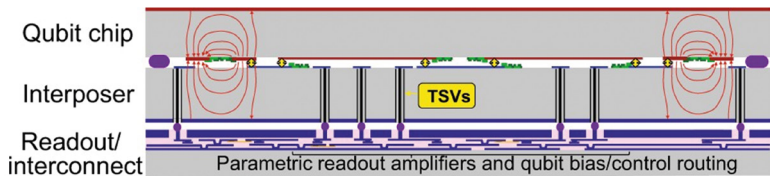
The move from a handful of qubits to processors with tens or hundreds of elements marks a transition into the noisy intermediate-scale quantum (NISQ) regime. At and beyond this scale, the central question is no longer whether individual qubits can behave quantum mechanically, but how well many such elements can work together as a single quantum system.

In today's quantum processors, performance is shaped by the collective influence of many device-level effects distributed across the hardware. Materials that are nearly lossless still host minute dissipation at surfaces and interfaces. Josephson junctions can be fabricated with extraordinary precision, yet each junction still exhibits sub-nanometre-scale variations. Even at millikelvin temperatures in a well-shielded cryostat, residual disturbances such as stray electromagnetic radiation, energetic particle excitation, or even cosmic ray can occasionally disrupt delicate quantum states. These effects are subtle and well understood individually, but their accumulation across many qubits can significantly complicate and limit overall processor performance.

As systems grow, performance also becomes increasingly shaped by the interplay between qubits and the supporting infrastructure required to operate them as a coherent whole. Wiring, packaging, filtering, and control electronics must connect hundreds of quantum elements to the outside world while preserving coherence and stability. These classical components are not mere auxiliaries: they shape how qubits are addressed, how densely they can be arranged, and how reliably operations can be repeated over time. Understanding this dynamic interplay, from materials, devices, and components to full systems, is now a key step toward scalable quantum computing.

State-of-the-art superconducting quantum processors developed by groups such as IBM and Google already comprise hundreds to over a thousand qubits, embedded within large dilution refrigerators and connected by thousands of control and readout lines. IBM's Condor processor, for example, integrates 1,121 qubits and requires over a mile of high-density cryogenic wiring within a single cryostat. At this scale, scalability becomes a tangible constraint: each additional qubit brings added wiring, heat load, calibration complexity, and opportunities for cross-talk and interference. The effort to scaling up quantum computing is as much about managing cryogenics, interconnects, and system integration as it is about improving individual qubit performance.

▼ **FIG 3:** Schematic of a modern 3D-integrated qubit control and readout scheme proposed by MIT Lincoln Laboratory [7], in which qubit, interposer, and readout/interconnect chips are vertically stacked and connected using indium bump bonds and through-silicon vias (TSVs).



This perspective is reflected in the remarkable breadth of the current research landscape [5]. Efforts spanning materials optimisation, cleaner interfaces, and improved fabrication processes aim to reduce noise, extend quantum coherence, and improve fabrication scalability. In parallel, new qubit designs explore increased protection against environmental disturbances, while error correction and error mitigation have now been demonstrated on working quantum processors. Scaling strategies extend beyond qubit count alone, encompassing higher operating temperatures and frequencies, modular architectures, and the integration of cryogenic control electronics [6].

The present generation of quantum processors has enabled landmark results, including the demonstration of quantum advantage [8] and error-corrected operations [9]. At the same time, a broader ecosystem is taking shape, spanning algorithms, software stacks, cloud platforms, and an expanding user community [10]. Looking forward, roadmaps from major academic and industrial efforts outline a staged progression toward scalable, fault-tolerant quantum computing, where reliable quantum processors will be used to address real-world problems such as quantum chemistry and materials simulation, drug discovery, large-scale combinatorial optimisation, cryptography, security, and machine learning. Accordingly, scalable, fault-tolerant quantum computing is not a single breakthrough, but the sustained alignment of device physics, system engineering, and application-driven development across the entire quantum community.

Designated as the International Year of Quantum Science and Technology, 2025 highlighted how quantum physics is reshaping technology beyond the laboratory. The challenge in the decade ahead is to translate this momentum in research and development into reliable, scalable technological capabilities. ■

References

[1] M. Devoret, J. M. Martinis and J. Clarke, Physical Review Letters, Oct. 1985, doi: https://doi.org/10.1103/physrevlett.55.1908

[2] J. M. Martinis, M. H. Devoret and J. Clarke, Physical review letters, Oct. 1985, doi: https://doi.org/10.1103/physrevlett.55.1543

[3] B. D. Josephson, Physics Letters, Jul. 1962, doi: https://doi.org/10.1016/0031-9163(62)91369-0

[4] J. Clarke and F. K. Wilhelm, Nature, Jun. 2008, doi: https://doi.org/10.1038/nature07128

[5] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, Applied Physics Reviews, Jun. 2019, doi: https://doi.org/10.1063/1.5089550

[6] J. Brennan *et al.*, APL Quantum, Dec. 2025, doi: https://doi.org/10.1063/5.0273490

[7] D. Rosenberg *et al.*, npj Quantum Information, Oct. 2017, doi: https://doi.org/10.1038/s41534-017-0044-0

[8] F. Arute *et al.*, Nature, Oct. 2019, doi: https://doi.org/10.1038/s41586-019-1666-5

[9] R. Acharya *et al.*, Nature, Dec. 2024, doi: https://doi.org/10.1038/s41586-024-08449-y

[10] J. Preskill, Quantum, Aug. 2018, doi: https://doi.org/10.22331/q-2018-08-06-79

QUANTUM ERROR CORRECTION WITH SUPERCONDUCTING CIRCUIT BASED QUBITS:

IS IT BETTER FIRST SCALE-UP AND THEN CORRECT OR FIRST CORRECT AND THEN SCALE-UP?

Matti Silveri – University of Oulu, Finland – DOI: https://doi.org/10.1051/epn/2026108

Superconducting electric circuits have now qubits and operations with excellent fidelities. Unfortunately, this is not yet enough for the stringent requirements of quantum computation. To go beyond, one needs to realize quantum error correction. Which is the best way to reach it? Is it first correct errors in individual devices and then scale up or first scale up and then correct errors?

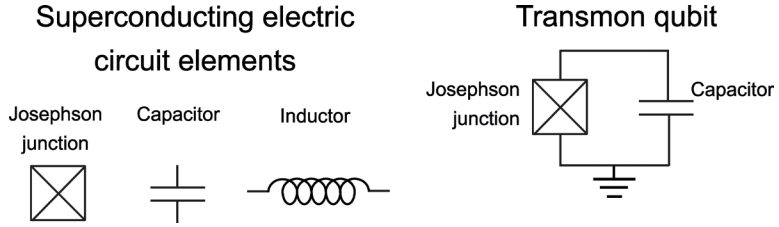
Superconducting qubits

The Nobel prize in physics 2025 celebrates pioneering quantum physics experiments and the following major fundamental and technological advancements of superconducting electric circuits. The experiments by Nobel laureates in 1984-85 convinced the scientific community that simple superconducting electric circuits exhibit clear and pure quantum mechanical concepts in circuit-scale, such as energy level quantization and quantum tunneling. Macroscopic quantum phenomena of superconductivity and accurate control and measurement techniques of electric circuits create the basis of modern high-performance quantum technologies. Indeed, the elementary circuit elements are just superconductor-insulator-superconductor junctions (Josephson junction), capacitors and inductors, see Fig. 1.

The essential concept here is a qubit, a quantum mechanical two-level system. The quantum state of a qubit needs to be highly controllable, measurable and long-lived. In addition to that, qubits need to have on-demand interactions between each other to realize rich quantum operations utilized in computing, communication and sensing applications. To build a good qubit, the old rule 'the simpler the better' still holds in many occasions. For example, the most-used superconducting qubit, named as the transmon qubit, is made just of a Josephson junction and a parallel capacitor (Fig 1).

The first qubit quantum state realized in a superconducting electric circuit had only a nanosecond lifetime in 1999 [1]. Over 25 years later, the lifetimes have been pushed to millisecond range [2,3]. Actually, the single qubit lifetimes themselves are not anymore the most limiting factor for the potential of superconducting quantum technologies. The current-day challenge is to implement high-accuracy qubit operations. In practical terms, this means electric control pulses that change the state of qubits. The fundamental reason for the challenge for realizing accurate gate operations is the fact that a quantum state is an analog concept, not discrete, not digital. This means that quantum state amplitudes and phases are continuous variables and they all need to be transformed exactly under qubit operations.

▼ **FIG 1:** (a) Elements of superconducting electric circuits are a Josephson junction, a capacitor and an inductor. A Josephson junction is a superconducting wire interrupted with a thin insulating layer, creating a superconductor-insulator-superconductor junction. A transmon qubit is made of a Josephson junction in parallel with a shunting capacitor.



Quantum error correction: Creating a few less-faulty qubits out of many flawed qubits and faulty operations

How to go beyond? Is it just enough to keep improving devices, materials and controls of superconducting circuits and in some point we have good enough qubits and qubit operations? The consensus answer is 'no'. In addition to material and device engineering, we need to implement also 'quantum error correction'. This is a software method for actively removing effects of errors from qubits and their operations while simultaneously keeping them fully operational [4].

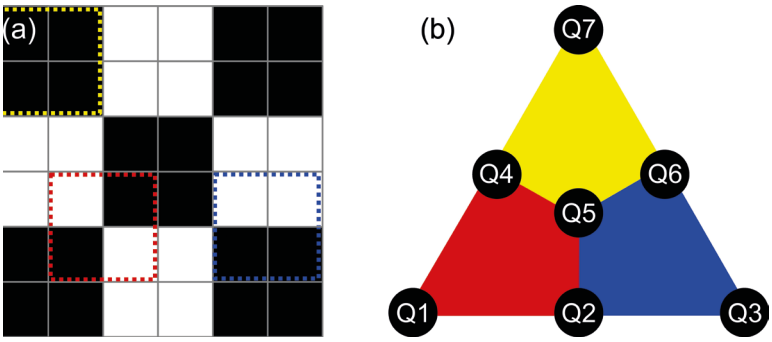
In quantum error correction, an error-corrected qubit, denoted as the logical qubit, is built out of a physical system that is bigger than just a two-level system. Here bigger means that it has more than two quantum states. The extra states are used to detect errors and recover from their effects. In other words, the system has useful redundancy and structure. This is a bit similar to error correction in regular reading. We can read text despite few errors. Wörds and sentences have strukture which helps detecting possible errors and parsing them without losing essential information. In quantum error correction, useful structure and redundancy are created with entanglement.

Quantum error correction is really challenging to realize in practice for two fundamental reasons. First, it is created by the physical operations that are themselves erroneous. That is to say quantum error correction is a process where one purifies a few less-faulty qubits and operations out of many flawed qubits and faulty operations. The second challenge originates in inherent quantum mechanical properties, especially those related on quantum measurements. The quantum error correction measurements need to be delicately tailored so that they just reveal the effects of errors but nothing about the logical qubit state itself. To realize this one needs to utilize again entanglement.

An error-corrected superconducting circuit-based quantum computer has two types of blueprints that can be described as: (a) first scale-up and then correct, (b) first correct and then scale-up. The difference between them is that what is considered as the big system to create the error-correction in the first place. In the scale-up and correct approach, the big system is a grid of qubits [5]. In the correct and scale-up method, the big system is a resonator and a qubit [6].

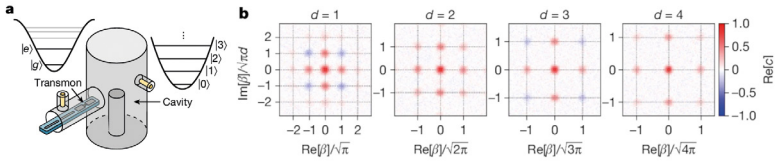
First scale-up and then correct?

Let us take a qubit grid that has in total N physical qubits and let us build one logical qubit out of it. The total number of different physical multi-qubit states is 2^N and the basic idea is to choose two of these multi-qubit states as the logical qubit states. It is easy to see that there are many ways of choosing these. What is a good approach then?



▲ **FIG 2:** (a) Visualization of a 2D tiling where X shape is the non-local tiling pattern. Colored squares visualize different almost-local tile coloring checks: If the parity of colors is even no tiling coloring error has occurred. (b) Schematic of a qubit grid quantum error correction code consisting of seven physical qubits, one logical qubit and three error check "tiles".

First, the physical errors are local. For example, a material defect may accidentally flip a local physical qubit state. The logical qubit states should be chosen so that single localized errors are correctable. In other words, the logical states must have highly non-local character so that local perturbations do not destroy them. Second, errors must be detectable with nearly-local measurements. This restriction comes from the fact that in practical terms it is possible to make physical qubits to interact with • • •



▲ **FIG 3:** (a) Schematic of a cavity (resonator) and a transmon qubit for creating a logical error-correctable qubit. (b) Visualization of different Gottesman-Kitaev-Preskill -type error-correctable logical states. Adapted from B.L Brock et al., *Nature* **641**, 512 (2025).

• • • other only in short-range. It is practically possible to realize measurements that simultaneously measure common properties of nearby-qubits only.

The scale-up and correct approach is like making a 2D tiling, where there is a non-local tiling pattern representing the logical state and local rule for detecting coloring errors. For example, the local rule can be that four nearby tiles must have even number of different color. To detect errors, here to detect that a color has flipped, it is enough to look nearby-tiles and this measurement does not reveal anything about the non-local tiling pattern, see Fig. 2.

First correct and then scale-up?

The approach denoted as 'first correct and then scale-up' is based on utilizing the quantum eigenstates of a single harmonic oscillator [6]: the ground state $|0\rangle$, the first excited state $|1\rangle$, the second excited state $|2\rangle$,... In theory, a single harmonic oscillator has infinite number of eigenstates, constituting the big system needed for quantum error correction. In practice, though, coherence and controllability limit the number of states to a finite but sufficiently large. Also, in practice, one needs a qubit coupled to the harmonic oscillator to efficiently control and measure the states.

The idea is to construct two logical states out of the eigenstates of the harmonic oscillator. One of the simplest examples is to select the physical states $|2\rangle$ and $(|0\rangle+|4\rangle)/\sqrt{2}$ as the logical states [7]. Here it is important to notice that they are made of even parity states. With harmonic oscillator, the dominant error is an energy loss error, that means that the logical states become as the states $|1\rangle$ and $|3\rangle$ under a loss of single excitation. One notices that the error states are of odd parity. The way to detect if an error has occurred is to measure parity of the physical states, which only reveals whether or not an excitation loss error has occurred but does not distinguish between the logical states or the error states. Parity plays the same role as the non-local structure in the qubit grid states. Similarly as in the qubit grid approach, one can select the logical states in a many different ways, see Fig 3.

Both of the approaches have their strengths and weaknesses. The qubit grid approach, where one first need to scale-up the number of qubits and then correct the errors, provides in theory strong protection against local errors. However, the weaknesses is that one first needs to push the error levels of physical qubits, operations, and measurements to low enough values to benefit on the error correction in large qubit grid [8]. As the number of physical qubits increases also the number of different errors increases. This yields a decoding challenge: How to decide efficiently what was the error that occurred and how to correct it quickly before other errors appear?

The resonator and qubit approach is simple and efficient in hardware. Another positive feature is also that harmonic oscillators have generally much lower intrinsic error rates than corresponding qubits [9]. Also the resonator approach is quite well free from the decoding challenge as its errors are simpler, essentially different number of excitation losses. The main challenges lie in realizing accurate and quick operations and measurements for the resonator logical states.

As in many cases, good solutions can be found by hybridizing, combining the benefits of both approaches. Here it would mean taking an error-corrected resonator as the physical qubit of the qubit grid approach, truly realizing the first correct and then scale-up scenario [10]. Currently several laboratories and quantum technology companies are exploring several variants of these error correction approaches. It will be interesting to see which approach or combination of them is the first one to reach a fully error-corrected and scalable superconducting quantum computer. ■

About the Author

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References

[1] Y. Nakamura, Yu. A. Pashkin, J. S. Tsai, *Nature* **398**, 786 (1999)

[2] M. Tuokkola *et al.*, *Nat. Commun.* **16**, 5421 (2025)

[3] M. P. Bland, F. Bahrami *et al.*, *Nature* **647**, 343 (2025)

[4] D. Gottesman, *An introduction to quantum error correction and fault-tolerant quantum computation*, arXiv:0904.2557 (2009)

[5] A. G. Fowler, M. Mariantoni, J. M. Martinis, A. N. Cleland, *Phys. Rev. A* **86**, 032324 (2012).

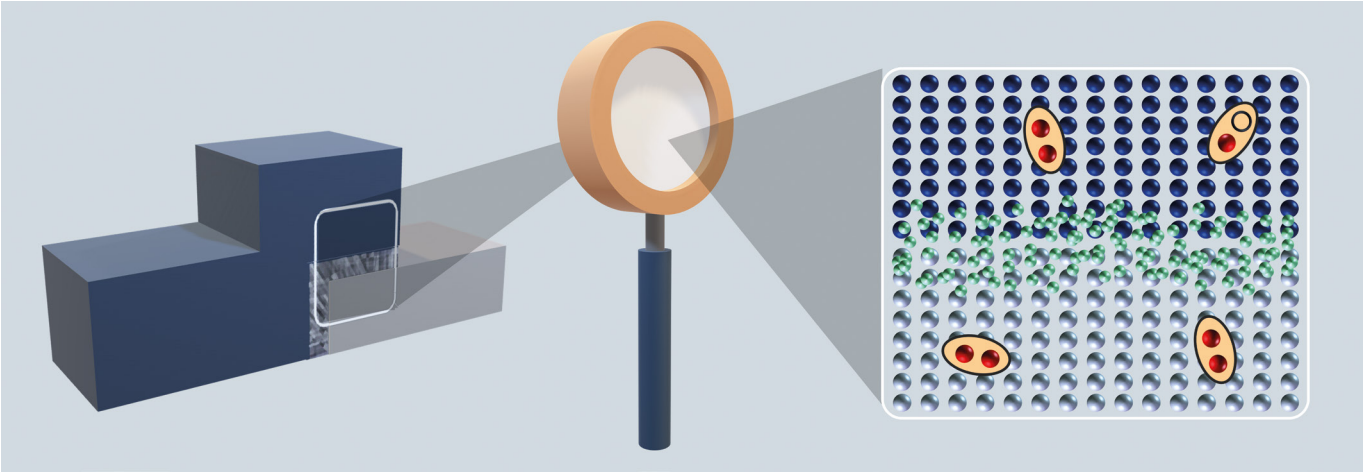
[6] D. Gottesman, A. Kitaev, J. Preskill, *Phys. Rev. A* **64**, 012310 (2001)

[7] M. H. Michael *et al.*, *Phys. Rev. X* **6**, 031006 (2016)

[8] R. Acharya *et al.*, *Nature* **638**, 920 (2025)

[9] V. V. Sivak *et al.*, *Nature* **616**, 50 (2023)

[10] H. Putterman *et al.*, *Nature* **638**, 927 (2025).



MODELLING JOSEPHSON JUNCTIONS FOR SUPERCONDUCTING QUANTUM COMPUTING

Gianluigi Catelani[1,2] and Giampiero Marchegiani[2] – DOI: https://doi.org/10.1051/epn/2026109

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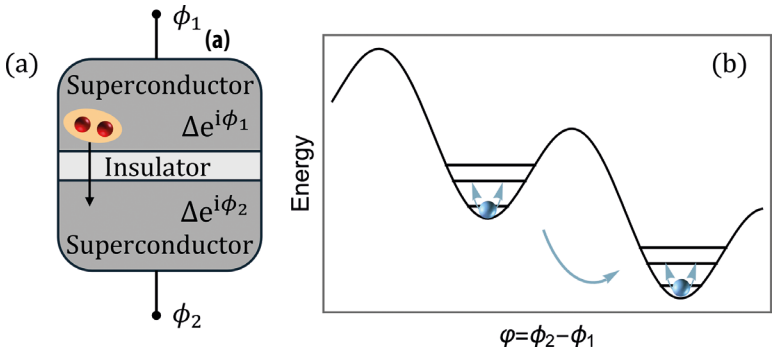
Josephson junctions are non-linear circuit elements with low dissipation, which makes them suitable building blocks for artificial atoms: macroscopic objects which display quantum behavior. Despite significant progress, the error rates achieved when using these atoms as qubits are still too high for the most useful applications of quantum computing. Accurate theoretical modelling can indicate the way to mitigate some of these errors.

From superconductivity to qubits

In the superconducting state, an electric current can flow without dissipation, which is why it is called a supercurrent. Superconductivity, discovered in 1911 by Kamerlingh Onnes (1913 Nobel Prize in physics) is arguably one of the most fascinating states of matter: electrons join into so-called Cooper pairs and condense into a new state. This state is characterized by a complex order parameter having both a phase φ and an amplitude Δ, the latter related to a finite gap for excitations and changes in the former to supercurrents. The theoretical explanation of superconductivity, published in 1957 by Bardeen, Cooper and Schrieffer (1972 Nobel Prize in Physics) took more than 40 years. Just a few years later, in 1962, Josephson (1973 Nobel Prize in Physics), predicted that a supercurrent could flow even through a junction, a device in which the superconductor is interrupted by a thin insulating barrier; this phenomenon is now known as the DC Josephson effect, see Fig. 1(a).

The main prediction by Josephson, initially doubted by Bardeen, was quickly verified experimentally, and it led Leggett (2003 Nobel Prize in Physics) to propose [1] that, thanks to their low dissipation, superconducting circuits comprising Josephson junctions could be used to explore a fundamental question: do macroscopic objects obey quantum mechanics? This question motivated the experiments that earned Clarke, Devoret, and Martinis the 2025 Nobel: they showed that the phase difference across a Josephson junction behaves like a quantum particle that displays quantized energy levels [2] and can tunnel through a barrier [3], see Fig. 1(b).



▲ **FIG. 1:** (a) schematic depiction of a Josephson junction: two superconductors (with order parameter amplitude Δ and phase φ) are separated by a thin insulating barrier. When a phase difference is present, a non-dissipative current, carried by Cooper pairs, can flow across the structure (Josephson effect). (b) Potential energy landscape of a current-biased Josephson junction (tilted-washboard potential). The phase difference behaves like a particle in a potential well. The 2025 Nobel Prize in Physics was awarded for demonstrating two macroscopic quantum effects: quantization of the energy levels and quantum tunnelling between wells.

Based on their measurement, the three Nobelists expected that a quantum superposition of the ground and excited state of this "phase particle" would have a lifetime (coherence time) in the nanosecond range. The verification of this expectation had to wait more than a decade, when the first superconducting qubit, known as the "Cooper pair box", was demonstrated [4]. Over the years, many alternative qubit designs have been proposed, most notably the transmon, whose coherence time has been recently pushed to the millisecond regime, an improvement of over 5 orders of magnitude.

The above historical summary shows how important the low dissipation of Josephson junctions is. Interestingly, Josephson also predicted a peculiar dependence of dissipation on phase difference: dissipation should be minimized when the phase difference is π. This dependence arises from the properties of Bogoliubov quasiparticles, the fundamental excitations in superconductors that are a coherent superposition of electrons and holes; at phase difference π, the destructive interference between these two components suppresses dissipation. Efforts to check experimentally this second prediction in the 1970s and 80s were inconclusive. The high sensitivity of qubits to all dissipation mechanisms finally enabled the measurement of this interference effect in the group of Devoret in 2014 [5].

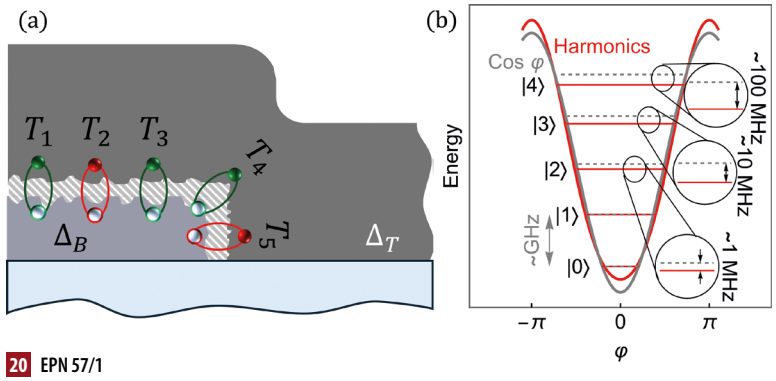
Probing the current-phase relationship

The DC Josephson effect generally happens between two weakly connected superconductors, but the relationship between current and phase depends on the details of the connection. In the case of a thin insulating barrier, the current is proportional to the sine of the phase difference, with the proportionality constant being the critical current, the maximum supercurrent that can flow across the junction. The sinusoidal dependence is obtained in the theoretical limit in which the barrier is modeled as comprising an infinitely large number of transmission channels of infinitesimally small transparency. In real devices, the number of channels is of course finite, typically in the millions for junctions used in qubits, and their transparencies are small but finite. More importantly, the barrier growth is a stochastic process that leads to its thickness being non-uniform and hence to a distribution in the channel transparency, see Fig. 2(a).

The precise shape of the current-phase relation determines the exact energies of the quantized levels first detected by Martinis, Devoret, and Clarke. Modern qubits enable much more precise spectroscopic measurements of the energy levels of the "phase particle" and stringent comparison to theory [6]. In a transmon, which is made of a Josephson junction shunted by a capacitor, measuring the energies of the first two excited states should be enough to determine both the critical current and the charging energy, and consequently enable the calculation of the energies of the higher levels. This simple procedure does not work, as the energies are found to significantly deviate from expectations [Fig. 2(b)]. By including in the model the fluctuations in the barrier thickness, good agreement between theory and experiment can be obtained.

The properties of the barrier are not the only possible source influencing the energies of the levels: an inductance inserted between the junction and the capacitor has similar effects. Quantifying the respective roles of barrier and stray inductance is the subject of ongoing research [7].

▼ **FIG. 2:** (a) Lateral view schematic of a typical nanofabricated superconductor–insulator–superconductor junction. Bottom and top film have order parameter amplitudes Δ_B and Δ_T. We depict a distribution of transmission channels T_1, …, T_N, most (green) of low and few (red) of high transparency. (b) Energy levels for a purely cos(φ) potential (grey) vs realistic potential including higher-harmonics (red). There is a discrepancy between the energy levels in the two models, which generally increases at higher levels. Adapted from [6].



Gap asymmetry

The precise measurement of the energy levels shows that more detailed modeling of the DC Josephson effect is needed to reconcile experiments with theory. This also holds true for the lifetime of qubits. In this case, the additional ingredient needed in the model has to do with how Josephson junctions are typically fabricated: first, an aluminum film a few tens on nm thick is deposited. Then the film is oxidized, and finally a second, thicker film is deposited on part of the first one to form the junction

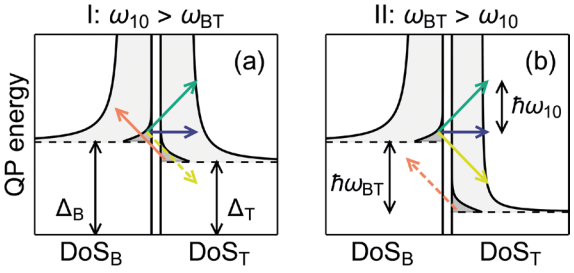
[*cf.* Fig. 2(a)]. Aluminum is peculiar among superconductors in that its superconducting gap (the minimum energy for quasiparticles, see Fig. 3) grows with the inverse thickness for films thinner than a few hundred nm. Therefore, the top film in the junction has a lower gap than the bottom one, $\Delta_T<\Delta_B$, leading to "gap asymmetry" between the two sides of the junction.

Recent works [8,9] showed that this gap asymmetry influences the qubits lifetime. This happens because a quasiparticle that tunnels through the junction can exchange energy with the qubit [10]. If the gap asymmetry is smaller than the qubit energy, the quasiparticle can absorb that energy when tunneling. However, if the gap asymmetry is larger than the qubit energy, a quasiparticle in the top film cannot tunnel into the bottom one (Fig. 3): a mechanism of qubit relaxation is blocked, and hence the qubit lifetime becomes longer. Conversely, at low temperatures the quasiparticles are maintained in a nonequilibrium state whose signature can be revealed by careful measurements of qubit transition rates [11].

The protection of qubit from relaxation relies on the fact that quasiparticles accumulate in the low gap film. More generally, additional protection can be obtained by adding, far from the junction, quasiparticle traps: superconducting regions with even lower gap [12, 13] or normal-metal islands [14]. Crucially, the protection afforded by gap asymmetry has been shown effective also during "quasiparticle bursts" [15]: when a high-energy particle passes through the substrate hosting the qubits, it can deposit a large energy into it in the form of phonons. These phonons can rapidly reach many qubits, break Cooper pairs and hence generate quasiparticles. These quasiparticles then relax multiple qubits in a manner correlated in space and time. These correlations are especially bad news for quantum computation, since quantum error correction is much less effective in their presence.

Qubits with large gap asymmetry have been recently used by Google to demonstrate quantum error correction [16]. Even more recently [17], they showed that a residual effect of the bursts is still limiting quantum error correction. This residual effect arises from the fact that in addition to causing relaxation, quasiparticles also lower the qubit frequency [10]. This frequency shift takes place also when tunneling is hindered, as the gap is suppressed when adding quasiparticles. This means that additional protection from quasiparticles is needed, beyond that provided by gap asymmetry. One approach is to "capture" the phonons before they reach the qubits [18, 19].

We have focused here on the effort to exploit the Josephson effect for quantum computing, but other devices based on it, such as SQUID magnetometers, are already in practical use. Even though more than 60 years have passed since Josephson's initial prediction, the effect that bears his name is still the focus of both fundamental and applied research. ■



◂ **FIG. 3:** Quasiparticle density of states (DoS) schematic (light shaded regions) for the bottom and top superconducting films in a junction, characterized by the energy gaps $\Delta_B>\Delta_T$. The states occupied by quasiparticles (QP) are identified by darker color. The arrows denote the quasiparticle tunneling events for two choices of gap asymmetry ω_{BT} exemplifying (a) non-protected design with qubit frequency ω_{10} larger than asymmetry, and (b) gap-engineered design. The dashed arrows represent the suppressed transition rates due to the gap asymmetry. Adapted from [8].

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Giampiero Marchegiani is senior researcher at the Technology Innovation Institute (UAE). His research focuses on quasiparticle physics and thermal transport in superconducting devices based on Josephson junctions.

References

[1] A.J. Leggett, *Prog. Theor. Phys. Suppl.* **69**, 80 (1980)

[2] J.M. Martinis, M.H. Devoret, and J. Clarke, *Phys. Rev. Lett.* **55**, 1543 (1985)

[3] M.H. Devoret, J.M. Martinis, and J. Clarke, *Phys. Rev. Lett.* **55**, 1908 (1985)

[4] Y. Nakamura, Yu.A. Pashkin, and J.S. Tsai, *Nature* **398**, 786 (1999)

[5] I.M. Pop, K. Geerlings, G. Catelani, R.J. Schoelkopf, L.I. Glazman, and M.H. Devoret, *Nature* **508**, 369 (2014)

[6] D. Willsch, D. Rieger, *et al.*, *Nat. Phys.* **20**, 815 (2024)

[7] J. Kim, M. Hays, *et al.*, arXiv:2507.08171 (2025)

[8] G. Marchegiani, L. Amico, and G. Catelani, *PRX Quantum* **3**, 040338 (2022)

[9] S. Diamond, V. Fatemi, *et al.*, *PRX Quantum* **3**, 040304 (2022)

[10] G. Catelani, R.J. Schoelkopf, M.H. Devoret, and L.I. Glazman, *Phys. Rev. B* **84**, 064517 (2011)

[11] G. Marchegiani and G. Catelani, *Commun. Phys.* **8**, 120 (2025)

[12] R.-P. Riwar and G. Catelani, *Phys. Rev. B* **100**, 144514 (2019)

[13] X. Pan, Y. Zhou, *et al.*, *Nat. Commun.* **13**, 7196 (2022)

[14] R.-P. Riwar, A. Hosseinkhani, *et al.*, *Phys. Rev. B* **94**, 104516 (2016)

[15] M. McEwen, K.C. Miao, J. Atalaya, *et. al. Phys. Rev. Lett.* **133**, 240601 (2024)

[16] Google Quantum AI and Collaborators, *Nature* **638**, 920 (2025)

[17] V.D. Kurilovich, G. Roberts, *et al.*, arXiv:2506.18228 (2025)

[18] F. Henriques, F. Valenti, *et al.*, *Appl. Phys. Lett.* **115**, 212601 (2019)

[19] J.M. Martinis, *npj Quantum Inf.* **7**, 90 (2021)

CHRONOQUANTISTICS: THE ENTANGLED CENTURY

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Chronoquantistics invites us to reflect on a century of discoveries that have reshaped not only physics but the human experience. From the probabilistic revolutions of 1925 to the dawn of quantum computing and sensing, the quantum world has evolved into a chronicle of intertwined timelines — scientific, technological, and philosophical. This article traces the temporal symmetries that link Planck's quanta to today's quantum networks, exploring how our understanding of time, causality, and measurement has deepened alongside our tools for manipulating the quantum realm. Beyond circuits and algorithms, Chronoquantistics proposes a unifying lens through which to view the next era of quantum innovation: one where humanity's mastery of uncertainty becomes its most powerful technology for shaping the future.

1900

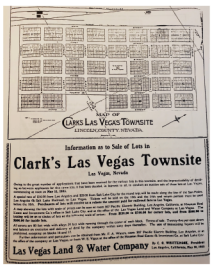
Paris hosted the first Universal Exhibition of the 20th century. The Eiffel Tower and the Paris Metro are inaugurated.

Max Planck correctly interpreted the spectrum of a black body by assuming that electromagnetic radiation was emitted and absorbed by atoms only in discrete packets, or quanta, of energy proportional to the frequency of the electromagnetic wave.

1905

Albert Einstein explained the photoelectric effect by proposing light consists of quanta with energy equal to Planck's constant times their frequency.

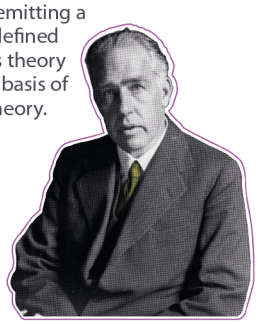
The city of Las Vegas was founded in Nevada.



1913

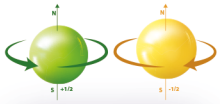
Henry Ford's company introduced the first moving assembly line for mass producing the Model T.

Niels Bohr published his model of atomic structure, introducing the theory that electrons move in well-defined orbits, corresponding to different energy levels around the nucleus of the atom. Bohr also introduced the idea that an electron can fall from a high-energy orbit to a lower one, emitting a photon of defined energy. This theory formed the basis of quantum theory.



1922

Otto Stern and **Walther Gerlach** devised an experiment to determine whether particles have an intrinsic angular momentum. Like a planet orbiting a star, the electron has angular momentum given by its revolution around the nucleus and its rotation about its own axis — its spin.

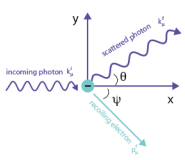


The British Broadcasting Company (BBC) was founded.

1923

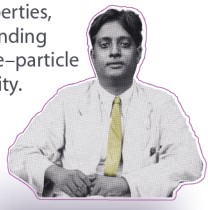
Walt and Roy Disney found The Disney Brothers Cartoon Studio in Hollywood, which would later become The Walt Disney Company.

Arthur Compton described the scattering of photons that collide with electrons, transferring part of their energy and increasing the wavelength of the scattered radiation. This phenomenon, which cannot be explained by classical electromagnetism, confirmed the quantum nature of light according to Einstein's theory, which regards photons as particles possessing momentum.



1924

Satyendra Nath Bose rederived Planck's law for photons, and Einstein extended it to atomic gases, creating Bose–Einstein statistics, one of the two quantum statistics alongside Fermi–Dirac, which refined the classical Maxwell–Boltzmann model. In the same year, de Broglie proposed that matter also has wave properties, extending wave–particle duality.



The first-ever Winter Olympic Games were held in Chamonix, France.

1925

Scottish inventor John Logie Baird successfully transmitted the first televised images in London.

F. Scott Fitzgerald's iconic novel The Great Gatsby, a tale of wealth, decadence, and the American Dream, was published.

1926

Erwin Schrödinger formulated the equation that bears his name. With it, he described the wave-like behavior of particles, introducing the concept of the wave function, which allows us to calculate the probability of finding a particle in a certain state or position. In the same year, he published a series of seminal articles that laid the foundations of wave mechanics, one of the two original formulations of quantum theory (along with Heisenberg's matrix theory).

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi$$

The McGraw Electric Company introduced the Toastmaster, the first pop-up toaster, promising perfect toast every time.

1927

Lindbergh completed the first solo, nonstop flight across the Atlantic Ocean in the Spirit of St. Louis.

Werner Heisenberg formulated the Uncertainty Principle, stating that one cannot precisely know both the position and momentum of a particle. This fundamental feature of quantum nature reflects the inherently probabilistic behavior of the microscopic world.

1935

Two famous paradoxes were proposed that challenged the interpretation of quantum mechanics.

Schrödinger imagined a thought experiment in which a **cat** was locked in a box with a mechanism linked to the decay of a radioactive atom. If the atom decays, a poison is released and the cat dies; if it doesn't decay, the cat stays alive. According to quantum mechanics, until the box is opened and observed, the atom has both decayed and not decayed, so the cat is simultaneously alive and dead. The paradox shows how difficult it is to apply quantum logic—valid for microscopic particles—to macroscopic objects, and calls into question the role of the observer in determining reality.

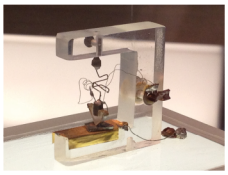
Einstein, along with Boris Podolski and Nathan Rosen, proposed another thought experiment (known as **EPR Paradox**) to criticize quantum mechanics. It describes two particles entangled, that is, linked in such a way that the state of one immediately determines the state of the other, even if they are far apart. According to quantum theory, measuring one particle instantly determines the state of the other, an effect Einstein called "spooky action at a distance". The paradox showed that quantum theory was incomplete, as it appeared to violate the principle of locality of relativity.

Kodachrome film, a subtractive color reversal film, was first marketed by Eastman Kodak for 16 mm movies.

1947

U.S. Air Force Captain Chuck Yeager became the first person to fly faster than the speed of sound in the Bell X-1 rocket plane.

At Bell Labs, **John Bardeen**, **Walter Brattain**, and **William Shockley** invented the first germanium point-contact transistor, which amplified and switched signals without vacuum tubes—ushering in modern electronics with smaller, more efficient, and reliable devices.



1948

Richard Feynman introduced the path integral formulation, a new way of describing quantum mechanics in which the behavior of particles is determined by summing over all possible paths they can take between two points. This revolutionary idea became a cornerstone of quantum electrodynamics (QED) and much of modern theoretical physics.

The first commercial instant camera, the Polaroid Land Camera Model 95, was sold in Boston. Invented by Edwin H. Land, it produced a finished photograph in about 60 seconds.

1952

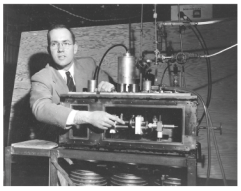
Princess Elizabeth was proclaimed Queen of the United Kingdom and the Commonwealth.

Joseph Woodland and Bernard Silver patented the barcode, though it would be many years before it was put into wide commercial use.

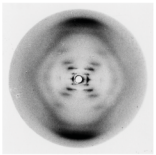
David Bohm developed the Bohmian interpretation of quantum mechanics, where particles have definite positions and trajectories guided by a "pilot wave" described by the Schrödinger equation. Unlike the Copenhagen interpretation, Bohm's theory is deterministic: quantum randomness stems from unknown initial conditions rather than true indeterminacy, offering a realist, deterministic alternative that reproduces all quantum predictions.

1953

Charles H. Townes invented the Microwave Amplification by Stimulated Emission of Radiation (MASER), the first device to produce coherent electromagnetic waves through the process of stimulated emission, a principle later extended to visible light in the Light Amplification by Stimulated Emission of Radiation (LASER).



First image showing X-ray diffraction pattern of DNA is taken.



Sir Edmund Hillary and Sherpa Tenzing Norgay became the first people confirmed to have reached the summit of Mount Everest.

1955

Civil rights activist Rosa Parks was arrested for refusing to give up her seat to a white passenger on a segregated bus in Montgomery, Alabama.

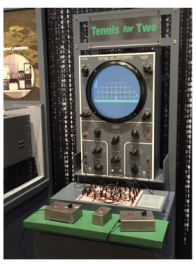
The first Disneyland theme park opened in Anaheim, California, introducing a new era of family entertainment.

Atomichron, the first commercially available atomic clock, was invented. It was developed by Harold Lyons and his team at the National Bureau of Standards (NBS) in the United States and later commercialized by the National Company. The Atomichron used cesium atoms to keep time with unprecedented precision, accurate to within one second in millions of years, and became crucial for applications such as navigation, telecommunications, and time standardization.

1958

John Bardeen, **Leon Cooper,** and **Robert Schrieffer** formulated the BCS theory of superconductivity. Named after their initials, the theory explains how, at very low temperatures, electrons in a metal can form pairs (called Cooper pairs) that move through the lattice without resistance, thus giving rise to superconductivity.

Physicist William Higinbotham created Tennis for Two at the Brookhaven National Laboratory. The game used an analog computer and an oscilloscope screen to simulate a game of tennis and was a huge hit at the lab's visitors' day.



1962

The first James Bond film, "Dr No," is released, marking the secret agent's cinematic debut with Sean Connery in the lead role.

Brian Josephson described how a supercurrent, a current that flows without any voltage, can pass between two superconductors separated by a very thin insulating barrier. This led to the invention of the Josephson junction, a key component in superconducting electronics, quantum computing, and extremely sensitive magnetic field detectors known as SQUIDs (Superconducting Quantum Interference Devices).

John S. Bell formulated Bell's theorem, showing that no theory of local hidden variables can reproduce all the predictions of quantum mechanics. Bell's theorem provides a way to test whether the world behaves according to quantum mechanics or classical local realism, through what are now called Bell's inequalities, which have been experimentally violated, confirming the nonlocal nature of quantum entanglement.

1964

The first jar of Nutella is produced, the best-selling spread in the world, with an annual production of 365,000 tons.

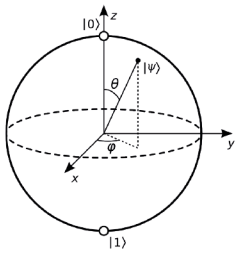
John Lennon is assassinated in New York.

The video game Pac-Man is released.

1980

Klaus von Klitzing discovered the quantum Hall effect: when a two-dimensional electron gas is placed in a strong magnetic field at very low temperatures, the Hall resistance takes on quantized values. This discovery provided a new standard for measuring electrical resistance and deepened our understanding of quantum physics in solid-state systems.

Richard Feynman proposed the idea of using a controllable quantum system to model or simulate another, more complex quantum system. This idea laid the theoretical foundation for quantum computing and today drives research in quantum simulators and quantum algorithms for chemistry, condensed matter, and particle physics.



1981

The first Personal Computer (IBM Model 5150) was released, featuring a 4.77 MHz Intel 8088 processor and the MS-DOS operating system.

The 24-hour music video channel Music Television (MTV) launched on August 1. The first video aired was "Video Killed the Radio Star" by The Buggles.

MUSIC TELEVISION®

NASA's Mars Pathfinder lander and its rover, Sojourner, landed on Mars, transmitting thousands of images and scientific data.

IBM's Deep Blue became the first computer to beat a reigning chess world champion, Garry Kasparov, in a six-game match.

1997

Anton Zeilinger's team performed the first experimental demonstration of quantum teleportation.

The **Quantum Manifesto** is published, setting out a vision and roadmap for the development of quantum technologies in Europe. The Manifesto called on the European Commission to launch a large-scale and long-term initiative which later became the European Quantum Flagship.

Main Goals of the 2016 Quantum Manifesto:

- Create a strong European quantum technology ecosystem, linking research, industry, and education.
- Develop practical quantum technologies in 4 key areas:
  - Quantum communication
  - Quantum computing
  - Quantum simulation
  - Quantum sensing and metrology
- Accelerate innovation and translate scientific results into market applications.
- Train the next generation of quantum scientists and engineers.

2016

The United Kingdom voted to leave the European Union in a historic referendum, triggering political upheaval and economic uncertainty.

The longtime Cuban revolutionary leader Fidel Castro died at the age of 90.

Queen Elizabeth II dies. Her reign, which lasted more than 70 years, was the longest in British history.

The global population officially crossed the 8 billion mark.

2022

John Clauser, **Alain Aspect** e **Anton Zeilinger** were awarded the Nobel Prize in Physics "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science". Their work turned what was once a philosophical debate (Einstein's "spooky action at a distance") into the basis of modern quantum technologies, including quantum computing, cryptography, and communication.

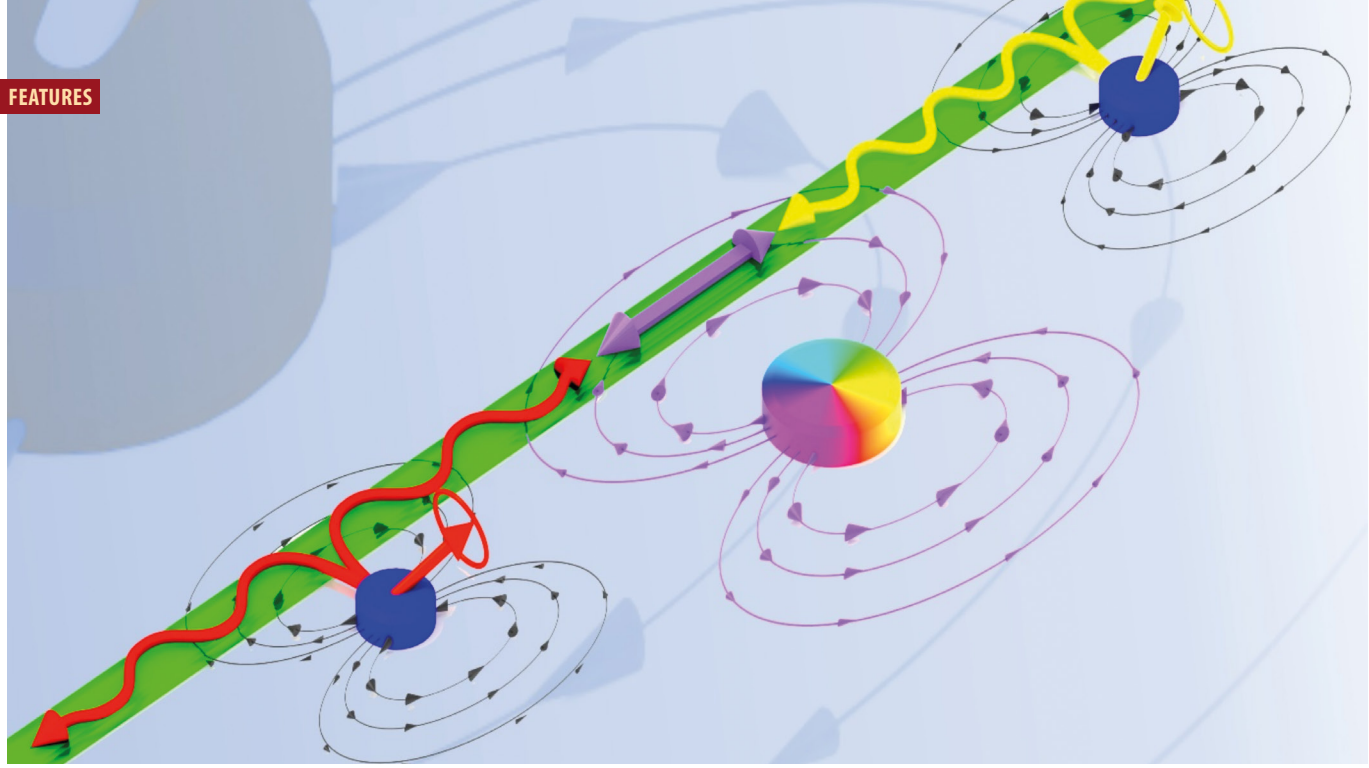
John Clarke, **Michel H. Devoret** and **John M. Martinis** were awarded the Nobel Prize in Physics "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit".

UNESCO declared 2025 the **International Year of Quantum Science and Technology** (IYQ 2025) to celebrate the centenary of quantum mechanics and highlights its crucial role in scientific and technological innovations.

INTERNATIONAL YEAR OF
Quantum Science and Technology

2025

You are reading Euro Physics News (EPN).



PERSPECTIVES ON MAGNONIC COMPUTING

Burkard Hillebrands, Philipp Pirro and Alexander A. Serga

Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität (RPTU) Kaiserslautern-Landau, Erwin-Schrödinger-Strasse 56, 67661 Kaiserslautern, Germany – DOI: https://doi.org/10.1051/epn/2026111

We live in a time of intensifying transformations and innovations in the information technology field. So far, computing power has steadily increased due to miniaturisation, multi-core and graphics processor development, and more. Currently, we are observing that new computing concepts, that go beyond two-state Boolean logic, are considered and implemented. Quantum computing is among the best known of these concepts, but to date neural-like neuromorphic systems such as artificial neural networks and annealers are already widely implemented with large use in artificial intelligence applications.

However, with these new advents, a gap opens up between the algorithms and the available hardware. We need to search for new hardware solutions, both in pushing existing technology further forward, as well as searching for radically new concepts.

The currently fast-developing field of magnonics could offer such a new approach. The field is still in the very fundamental domain, but potential applications are increasingly being discussed. We will address the potential and the perspectives of magnonic computing in this article.

Magnonics deals with waves in magnetically ordered materials [1]. They are called spin waves, with their quanta, magnons. These waves exist because of the quantum-mechanical exchange interaction, as well as the dipole-dipole interaction between magnetic dipoles, which are provided by the spins in a magnetic material. Other phenomena, such as a full plethora of magnetic anisotropies, also contribute to the spin-wave properties, making spin-wave-based functionalities extremely versatile and shapeable. Spin waves are highly nonlinear, allowing for low-threshold nonlinear wave formation and interaction. The group velocity is of the order of kilometres per second, comparable to the phonon group velocity. Since it is much smaller than the speed of light, the wavelength can be made very small at electronically addressable frequencies in the GHz range, favouring small structure sizes down to the nanometre range. Nowadays, most magnonic demonstrators are based on ferromagnetic or ferrimagnetic materials using spin waves in the GHz range with wavelengths from micrometres down to several tens of nanometres.

Most wave-based computing concepts build on linear and nonlinear wave interference, wave confinement in waveguide structures, and the formation of wave packets as information carriers [1]. Compared to many other physical systems, magnonics is distinguished by the fact that it enables wave-based computing concepts in a very natural manner. Many concepts developed in the field of integrated and fibre optics can be realised in magnonics, often with the added value of better scalability towards small feature sizes, larger wave interaction strength due to the stronger nonlinear interactions, and low energy consumption. On the other hand, the low group velocity and the damping of magnons do not allow for long-distance transport, and the data processing rate of logic devices working in the GHz range is limited. Working with high-frequency magnons in the THz range, such as those present in antiferromagnetic materials, looks promising with regard to processing speed. The inclusion of hybridized excitations, as produced by coupling to (guided) phonons, holds a lot of still unexplored potential, especially for longer-distance transport [2].

Magnonic wave computing

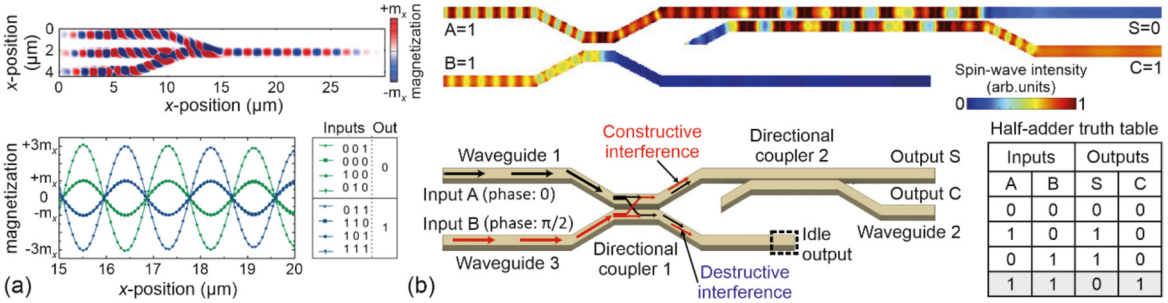
Many concepts for magnonic wave computing have been presented. Most are based on the excitation and propagation of spin waves – for an overview see, *e.g.*, [1, 3, 4]. An early realised prototype device [5] is a majority gate based on the interference of waves at the three input terminals with phases of either 0 or π to code binary information – see Fig. 1a. The phase at the output terminal is the majority phase of the three input terminals. Using this, and a phase shifter of phase π as an implementation of a NOT gate, all functions of Boolean logic can be performed. From this example, it becomes immediately clear that logic functionalities can be realised with structures much less sophisticated compared to conventional transistor-based logic. Challenges remain to create large functional logic circuits consisting of many of these devices interlinked only in the spin-wave domain [4]. For example, such implementations need to be augmented with spin-wave amplifiers to compensate for losses and to achieve the needed fan-out [1, 4].

This exemplary early and simple device illustrates several properties of magnonic implementation: First, the concept of linear-wave interference can be easily expanded towards multi-wave interference, the so-called frequency multiplexing approach. Second, for implementation in ferro- or ferrimagnetic materials, such as the currently widely-used material Yttrium-Iron-Garnet [1], the frequencies are in the GHz regime and thus the energy quantum per magnon (1 GHz corresponds to 4.14 μeV) is very low. A half adder (see Fig. 1b) [4], working at room temperature, consumes about 16 million magnons per logic operation, so it has excellent low-power performance in the attojoule range [6]. A major issue still is the energy-efficient conversion of electric signals to magnonic signals and vice versa. Nowadays, this conversion often relies on dynamic magnetic fields generated by antennas carrying microwave currents; however the excitation efficiency is low. Much research is underway to increase the efficiency, *e.g.*, by involving piezoelectric and magnetoelastic or, more generally, multiferroic degrees of freedom [4].

There is no requirement to stick with one-dimensional magnonic waveguide structures. 2D devices have been proposed, which are further enhanced by the availability of caustic radiation effects for magnons. In general, 2D magnon optics is well advanced including Fourier filters, frequency splitters and multiplexers, and more [1]. Potentially, waveguide structures can be realized in 3D [3] and might help to solve the von Neumann interconnectivity bottleneck, see also the Outlook section. The fabrication process is a challenge, but there is no fundamental limit imposed by the physics on which magnonic computation relies.

Magnonic neuromorphic computing

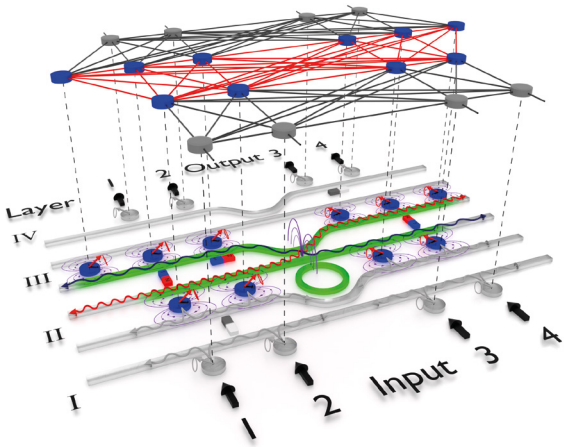
Technologies based on concepts of neuromorphic computing are advancing fast. Out of the many approaches, magnonic techniques could provide pathways to direct hardware implementation for artificial neural networks (ANN). Neurons can be efficiently created using magnonic nonlinearities, *e.g.*, by using nonlinear resonators, and by magnonic bistabilities [7]. Both provide nonlinear activation functions, *i.e.*, they emit magnons at their output only when a certain input amplitude is overcome. Using different spin-wave frequencies, magnetic ground states or bias fields, these activation functions can be manipulated, which is an important feature to adapt the magnonic ANN during its training process or ●●●



Half-adder truth table

Inputs		Outputs	
A	B	S	C
0	0	0	0
1	0	1	0
0	1	1	0
1	1	0	1

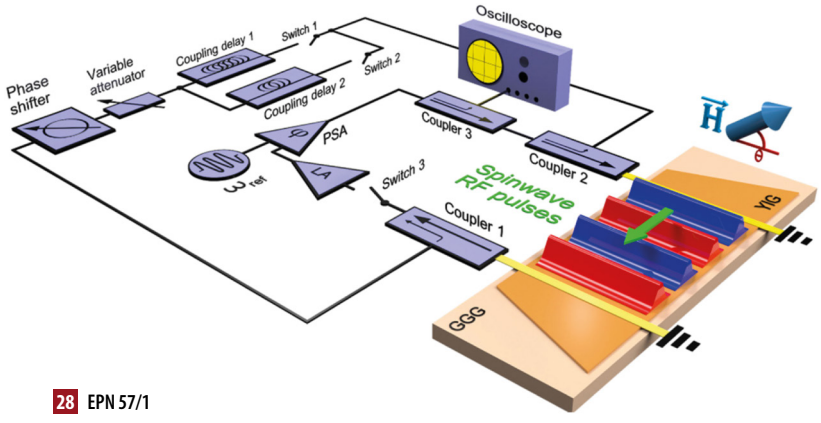
◂ **FIG 1:** Micromagnetic simulations of (a) magnonic majority gate (adapted from [5]), (b) half adder (adapted from [4,6]) which uses two magnonic directional couplers.



▸ FIG 2: Artificial neuronal network based on spintronic auto-oscillators (blue) connected by coherent spin waves, which are emitted into nanoconduits (green).

● ● ● to reconfigure it for new tasks. The synaptic connections between the magnonic neurons are provided by magnonic transport. They have the functionality of synaptic weights – during the training process, they can be configured by many means, such as using magnetic memory cells or tuneable amplifiers. A more advanced approach in this context is the combination of magnonic networks with spintronic auto-oscillators, which have already been successfully used as artificial neurons, see Fig. 2. In addition to controllable nonlinearity, this platform offers high interconnectivity of the neurons, since spin-wave frequency multiplexing can be used.

A variant of neuromorphic computing is reservoir computing – here, a recurrent neural network maps input signals into higher-dimensional computational spaces through the dynamics of a fixed, non-linear system called a reservoir. Compared to traditional ANN, these systems are easier to realize since they do not change the weights of the individual connections. One interesting example, which does not rely on data transport in real space via magnonic currents, is to use nonlinear interactions of magnons and transport in reciprocal space ("modal multiplexing") to demonstrate functionalities such as pattern recognition [8]. The challenge of this approach is the comparably difficult readout of the computational result from the reciprocal space. Other magnonic reservoir approaches use spin-wave-based ring oscillators with time-multiplexing, which are comparably slower but benefit from an efficient connection to the electronic periphery [9].



▾ FIG 3: Schematics of a hybrid magnonic-microwave Ising machine, which uses the phase of spin-wave pulses in a YIG delay line to represent the state of the annealer system [10].

Magnonic systems for optimisation tasks

An important class of computing applications consists of optimisation tasks. Among them are many problems, which scale unfavourably with system size when being realized with conventional logic, especially hard combinational optimization problems. Annealing techniques provide a pathway to their solution. Here, the problem is mapped onto finding the (absolute) minimum of an objective function.

Ising machines provide an elegant solution. They are based on a combinatorial approach: each state of an Ising machine – often called a "spin" for obvious reasons – is binary, and the challenge is that each state must interact with many other states. A matrix of the interaction strengths between all possible spin combinations represents the input. The Ising machine delivers the solution to the problem, which is the respective wavefunction. This has been realized in optics using optical delay lines and nonlinear interactions. Recently, a magnonic version has been demonstrated, which has the charm of a small footprint due to the rather slow group velocity of magnons [10]. Figure 3 shows the setup and the principle of function. For applications like this, the inherent advantages of a magnonic implementation, such as nonlinearity and small group velocities, come into their own.

Outlook

On the bottom line, regarding the balance of unique favourable properties in a magnonic environment and also considering existing disadvantages, magnonics could prove to be an excellent option for computing in the next generations. The concepts are under development. Apart from low power consumption and the realisation of specific devices, where the advantage of coherence is immediately evident (such as frequency splitters and combiners), we see a significant advantage when it comes to advanced computation schemes, especially those which benefit most from a wave-based approach.

Magnonics is currently advancing very fast. Many novel concepts have been reported, such as the use of magnonic Bose-Einstein condensates and transport mechanisms based on them [1, 11]. Magnonics can be implemented in the quantum regime [1, 2], but more likely applications in the classical regime are foreseen due to favouring room-temperature operation.

In particular, magnonics is very flexible to adapt, if it comes to new challenges. We would like to conclude with a simple example: if large-scale neuromorphic computing is considered, we are faced with the connectivity problem – in the human brain each neuron is connected to 10 000 others via synapses. Such a structure can only be realized in three-dimensional hardware. Out of the foreseeable technologies, magnonics might present here the

best chances to provide a platform for realization. In the long run, it might become a major direction to develop such 3D-magnonic concepts. ■

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Burkard Hillebrands is a senior professor of experimental physics at RPTU University Kaiserslautern-Landau, where he has established a research group addressing experimental magnetism, in particular magnonics.

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References:

[1] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, *Nat. Rev. Mater.* **6**, 1114 (2021)

[2] Y. Li, W. Zhang, V. Tyberkevych, W.-K. Kwok, A. Hoffmann, and V. Novosad, *J. Appl. Phys.* **128**, 130902 (2020)

[3] G. Gubbiotti *et al.*, *J. Phys.: Condens. Matter* **37**, 143502 (2025)

[4] A. Mahmoud, F. Ciubotaru, F. Vanderveken, A. V. Chumak, S. Hamdioui, C. Adelmann, and S. Cotofana, *J. Appl. Phys.* **128**, 161101 (2020)

[5] S. Klingler, P. Pirro, T. Brächer, B. Leven, B. Hillebrands, and A. V. Chumak, *Appl. Phys. Lett.* **106**, 212406 (2015)

[6] Q. Wang, M. Kewenig, M. Schneider, R. Verba, F. Kohl, B. Heinz, M. Geilen, M. Mohseni, B. Lägel, F. Ciubotaru, C. Adelmann, C. Dubs, S. D. Cotofana, O. V. Dobrovolskiy, T. Brächer, P. Pirro, and A. V. Chumak, *Nat. Electron.* **3**, 765 (2020)

[7] Q. Wang, R. Verba, B. Heinz, M. Schneider, O. Wojewoda, K. Davídková, K. Levchenko, C. Dubs, N. J. Mauser, M. Urbánek, P. Pirro, and A. V. Chumak, *Sci. Adv.* **9**, eadg4609 (2023)

[8] L. Körber, C. Heins, T. Hula, J.-V. Kim, S. Thlang, H. Schultheiss, J. Fassbender, and K. Schultheiss, *Nat. Commun.* **14**, 3954 (2023)

[9] S. Watt, M. Kostylev, A. B. Ustinov, and B. A. Kalinikos, *Phys. Rev. Appl.* **15**, 064060 (2021)

[10] A. Litvinenko, R. Khymyn, V. H. González, R. Ovcharov, A. A. Awad, V. Tyberkevych, A. Slavin, and J. Åkerman, *Commun. Phys.* **6**, 227 (2023)

[11] M. Mohseni, V. I. Vasyuchka, V. S. L'vov, A. A. Serga, and B. Hillebrands, *Commun. Phys.* **5**, 196 (2022)

Soft Matter:
Concepts, Phenomena, and Applications

Wim van Saarloos, Vincenzo Vitelli, Zorana Zeravcic

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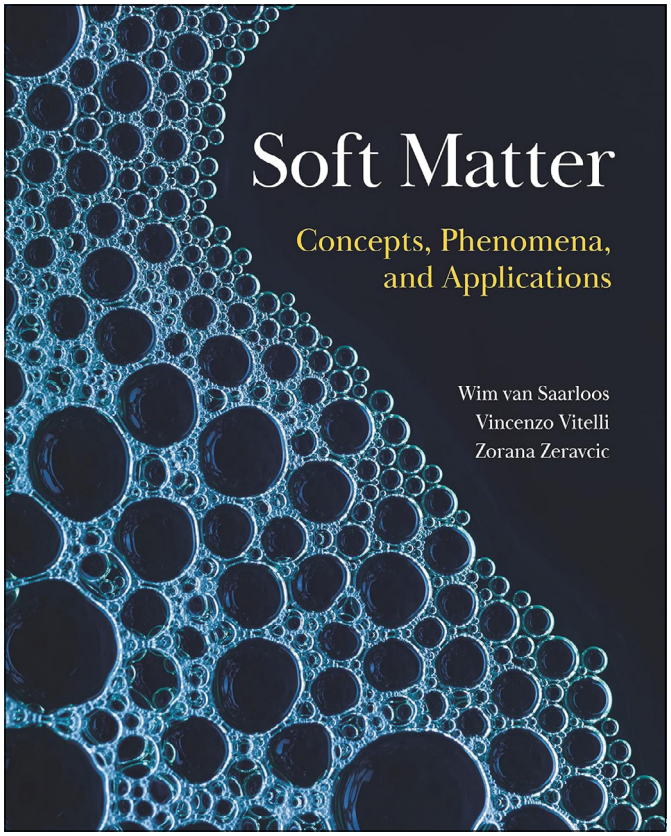

Imagine you find yourself in the middle of a giant jig-saw puzzle. Some of its pieces you have probably seen before, others are entirely new to you. Then, miraculously, all of the pieces start falling together, revealing an artwork full of unexpected connections. And in a perfect illustration of the maxim that the whole is more than the sum of its parts, even the pieces that looked familiar to you acquire an extra dimension – and new things to discover – when you suddenly see the bigger picture. That is how I felt while reading "Soft Matter" by Van Saarloos, Vitelli, and Zeravcic. It is a wonderful book, kaleidoscopic in its design, combining in a riveting and seemingly effortless way the many diverse topics that together form the fascinating new field called Soft Matter.

The phenomenal diversity of the field, with its conceptual framework that spans multiple disciplines including physics, biology and chemistry, naturally constitutes a huge challenge to anyone who sets out to teach the subject. What to include? What to leave out? And how to blend everything together in a consistent way? The book by Van Saarloos, Vitelli, and Zeravcic – which grew out of lectures given at the Universities of Leiden and Chicago to a variety of students at different levels – answers these questions in a superb way. The authors start with an engaging introduction on the scientific challenges, the strong societal relevance, as well as the sheer fun of Soft Matter. After this compelling opening chapter, Part I lies the foundations of the field: Fluid Dynamics, Elasticity and key elements of contemporary Statistical Physics, such as how to deal with fluctuations. Depending on the prior knowledge of the students, teachers can make their own choice about which topics need to be covered here. Part II contains the heart of the matter: Colloids, Polymers, and Liquid Crystals (three topics that will certainly be covered in any course) and a captivating chapter on Interfaces, Surfaces, and Membranes. Part III moves on to the advanced topics of Active Matter and Pattern Formation out of Equilibrium, providing excellent material for a graduate course or a series of state-of-the-art seminars in a summer school. Last but not least, Part IV gives a survey of new frontiers such as Designing Matter, Neural Network Architecture, Artificial Intelligence, and Artificial Life. This final part can be studied independently and forms a rich source for end-of-term assignments and student presentations. Thus, the authors offer the whole spectrum from the fundamental theoretical background to the forefront of current research.

Unifying themes throughout "Soft Matter" are its focus on the hydrodynamic approach and its open eye for applications in biological systems. Both of these themes are great strengths in themselves, and moreover make the book remarkably consistent given the enormous breadth of the field.

Apart from getting acquainted with a treasure trove of knowledge, the reader is also treated to an excitingly fresh and flexible way of thinking about Soft Matter: creative, out-of-the-box, and thorough at the same time. Written in a crystal-clear and friendly style – with scientific elegance, dexterity, and exceptional acumen throughout – this is a marvelous textbook which will take students and teachers alike on an intellectual adventure of the first order.

Mathematical modeling and physical insight go hand in hand on every page and I found it a delight to follow the authors from one eye-opener to the next, many of which happened to be (to my surprise and enthusiasm) on topics of my own expertise. Van Saarloos, Vitelli, and Zeravcic have the open-mindedness to address questions that are usually brushed aside and fully succeed in giving convincing answers.

The well-balanced choice of the core material, the uniquely accessible approach throughout, the thought-stimulating notes in the margin, the worked-out examples, the beautiful illustrations, the guided step-by-step exercises at the end of each chapter, the website that accompanies the book with videos and valuable extra material; all of these contribute to give "Soft Matter" the makings of an instant classic. A truly amazing accomplishment, which deserves a prominent place in every physics curriculum around the world. ■

Ko van der Weele, *University of Patras, Greece*

Bart van Tiggelen - 1965-2025

Bart van Tiggelen passed away on December 20, 2025, leaving us stunned by the void his untimely departure left behind.

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Bart was an outstanding theorist whose scientific contributions have left their mark on Modern Physics. He was a builder who did not shy away from taking on important collective responsibilities. He also made a major contribution to the evolution of scientific publications by defending the values of quality and integrity. Bart had strong convictions and defended them with determination, never with malice and always with sharp humor. Those who worked alongside him at the CNRS remember his boundless energy. His frequent bursts of laughter and rare outbursts made the walls shake.

Born in the Netherlands in 1965, Bart defended his doctoral thesis in Amsterdam in 1992 on multiple scattering and the localization of light in disordered media. He joined the CNRS in 1996. His major scientific contributions include the introduction of the concept of wave transport velocity in disordered media, the theory of multiple scattering of seismic waves, the theory of multiple scattering of light in anisotropic media and in the presence of an external magnetic field, and the generalization of the self-coherent theory of localization to media of finite size. These scientific achievements have been recognized with numerous awards and distinctions, including the Anatole and Suzanne Abragam Prize (2002) awarded by the French Academy of Sciences and the Paul Langevin Prize (2004) awarded by the French Physical Society.

Bart has also been heavily involved in important collective responsibilities. He was director of the Laboratory of Physics and Modeling of Condensed Matter (2007-2012); director of the Research Group entitled "Waves in Complex Media: Propagation in Soft Matter and Granular Media" from (2003-2008); member of the "Comité National de la Recherche Scientifique" from (2004-2008); and deputy scientific director of the CNRS Institute of Physics (2012-2018), in charge of theoretical and numerical physics, interdisciplinarity, training, and scientific publishing.

Bart was a great advocate of summer schools. Schools lasting more than three days were an incomprehensible model for the CNRS administration. Thanks to Bart, summer schools lasting several weeks still exist today in Les Houches or Cargèse.

Bart was also very active at French Physics Society (SFP), as member of its board, and then of its executive committee. He chaired the SFP's publications committee for many years. As a strong advocate for the free dissemination of scientific information, Bart has been involved in promoting "open science." Thanks to his teachings, we gave a strong impetus to the CNRS's policy in this area, modifying significantly recruitment and evaluation practices. This is bearing fruit today, and it is thanks to Bart.

Bart has long collaborated with "Europhysic Letter", serving as member of the editorial board (2012-2017), and then as editor-in-chief (2018-2021). Beyond his daily work as editor-in-chief, he made a real contribution to issues such as impact factors and the ever-increasing demands placed on reviewers. Bart has also been an advocate for an ecosystem that supports the most original and high-quality science, rather than more incremental contributions.

To those who have had the good fortune to work alongside you, you have taught them boldness, curiosity, and generosity. You have taught them to accept neither hypocrisy nor compromise. You have challenged us, made us think, and reminded us that science is, above all, a human adventure. ■

Alain Schuhl,
Previous director of CNRS Physics Institute

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The upcoming issue of Europhysics News, the magazine of the European Physical Society, will explore one of the most transformative developments in contemporary science: Artificial Intelligence for Physics. The issue is dedicated to understanding how AI is reshaping the way physics is conceived, practiced, and communicated, how it is becoming an active partner in scientific discovery.

The issue will also reflect on a deeper question: is AI merely enhancing physics, or is it changing its epistemology? As algorithms begin to identify patterns beyond intuitive human reach, physicists are called to rethink interpretation, validation, and the very nature of explanation.

By bringing together researchers across disciplines, this issue of Europhysics News aims to stimulate discussion within the European and global physics community, highlighting both the extraordinary opportunities and the critical challenges that AI introduces into the scientific method.

Artificial Intelligence is not replacing physics — it is expanding its horizons. Stay tuned for a deep reading of EPN 57/2, on-line around 19 May 2026 as a flipbook at epn.eps.org and as registered document at europhysicsnews.org. ■

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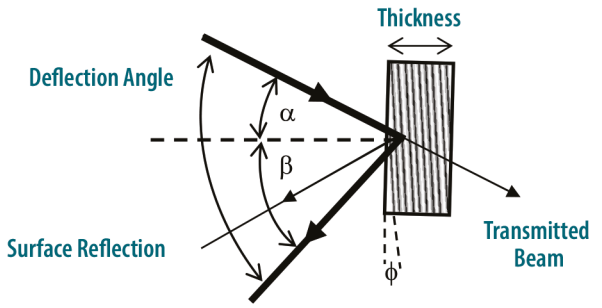

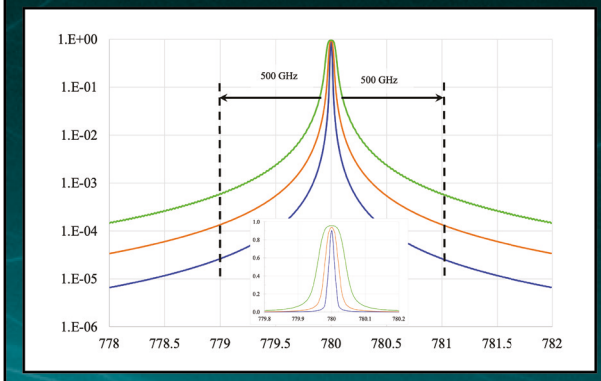

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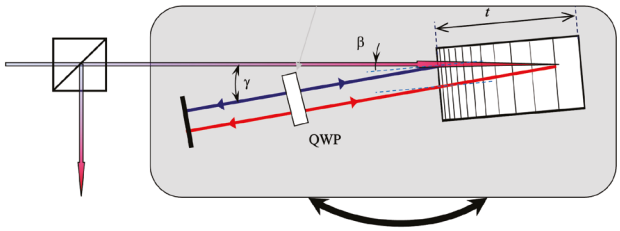
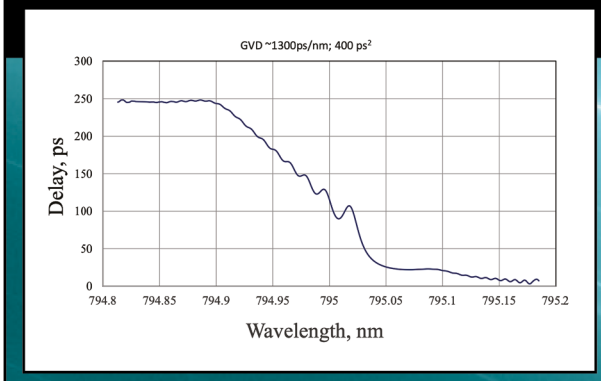


Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



PTR glass based highly dispersive CBGs enabled passively stable, efficient, method of fast amplitude modulation compatible for high power laser sources. *[H. Levine at al. "Dispersive optical systems for scalable Raman driving of hyperfine Qubits," Phys. Rev. A 105, 032618 (2022)]*

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