Editorial

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Pioneering quantum information science

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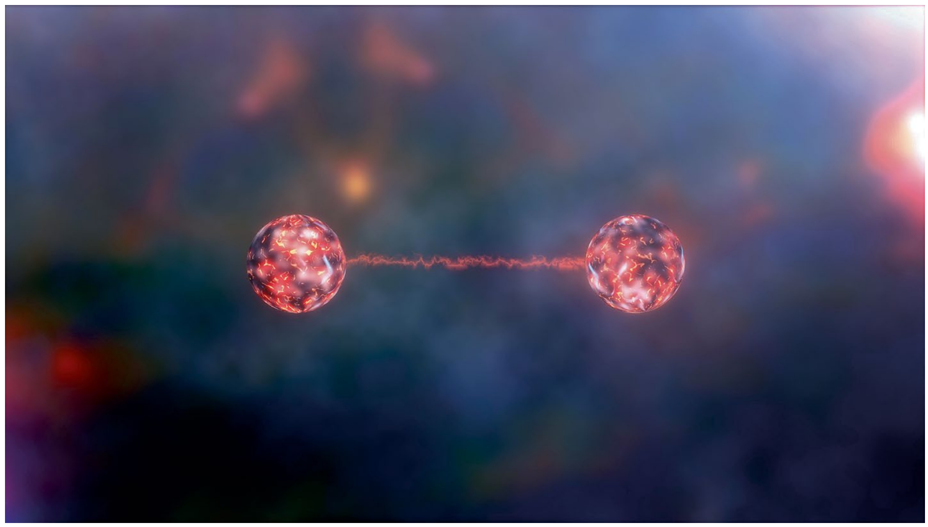

We discuss the research recognized by the most recent Nobel Prize in Physics, which has had important implications for quantum technologies.

On 4 October 2022, the Royal Swedish Academy of Sciences announced that the 2022 Nobel Prize in Physics would be awarded to three scientists — Alain Aspect, John F. Clauser and Anton Zeilinger — "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." While the implications of this research might not be immediately straightforward to the computational science community, the groundbreaking experiments — namely Bell tests — provided concrete evidence regarding the existence of non-local quantum correlations between distant particles, also known as quantum entanglements, which are key components in state-of-the-art quantum technologies, including quantum cryptography and quantum communication.

Quantum entanglement, a notable phenomenon from quantum theory, is valid independent of the physical distance between the particles: experimentally determined properties of one particle are correlated with the properties of its counterpart, even when there is a large distance between them. Such non-local effects predicted from quantum mechanics are at odds with our view of the world, as the entangled particles seem to be non-separable. Albert Einstein did not believe this, and termed this non-separability "spooky action at a distance". This was followed by the development of the hidden-variable theory by various scientists at that time who tried to explain such unusual non-local interactions from a completely different perspective. If Einstein was right, quantum mechanics would be incomplete, and there would be a counter proposal to it[1].

In 1964, John Stewart Bell proposed a theorem — Bell's theorem[2] — to address the debate between the hidden-variable theory and quantum mechanics[3]. This theorem is founded on the Bell inequality, which proves the existence of an upper bound (≤2) for a classical correlation function based on the hidden-variable assumption. However, quantum entanglement-based correlations break this inequality by yielding a higher value up to $2\sqrt{2}$: such a violation of the Bell inequality indicates that the "spooky action at a distance" is real.

The main contribution from this year's laureates in physics was to carry out this mathematical theorem in the laboratory. Aspect, Clauser, and Zeilinger each designed practical experimental settings and apparatus, and the results from their research were able to verify the violation of the Bell inequality using entangled states. In other words, their results clearly indicated that nature does allow such non-local effects, and that quantum mechanics cannot be replaced by classical theories when describing quantum entanglements.

The pioneering work from these three scientists provided a solid scientific ground for quantum theory, which was a major achievement for the development of quantum technologies; quantum entanglement, for instance, is at the heart of quantum computing. In addition, their work provided an important resource — entangled pairs, or Bell pairs — for quantum information science. The first direct application using a Bell pair was the teleportation of quantum information proposed by Charles H. Bennett et al.[4]. In 1997, Zeilinger experimentally demonstrated that quantum information encoded in the polarization states of a pair of entangled photons can be teleported at distance[5].

Another noteworthy application is quantum cryptography. In 1991, Artur K. Ekert proposed the use of the Bell inequality theorem in the key distribution task in cryptography[6]. In such quantum-encrypted key distribution, if an eavesdropper attempts to intercept the distributed key, this interference will destroy quantum entanglement, which is detectable by conducting a Bell inequality test. Three parallel studies published this year further demonstrated that a quantum key is secure even if the distribution device is hacked by the eavesdropper[7–9]. Bell inequalities also inspired developments in random number generation, which is widely used in statistical sampling, computer simulation, and cryptography: the non-local correlations of entangled quantum states can be used to certify the genuine randomness in cryptographically secure random number generators[10].

In 1922, the Nobel Prize in Physics was awarded to one of the founding fathers of quantum mechanics — Niels Bohr — who proposed the use of quantum theory for modeling a hydrogen atom, a groundbreaking approach for solving challenges in fundamental sciences. This year, the Nobel committee recognized yet another essential building block in quantum information science, but today's scientific progress drastically differs from that of a century ago. Quantum science has recently had many disruptive developments, and we have started to see more advancements to practical applications of quantum

CREDIT: VICHAI VIRIYATHANAPORN / ALAMY STOCK PHOTO technologies; the quantum entanglement distribution, for instance, has increased from 0.4 kilometers back in 1998 in Zeilinger's experiment[11] to over 1,200 kilometers in 2017[12]. While it is unclear whether or not there are further limitations on entangled Bell pairs, we do know that Bell pairs at larger distances and larger scales could lead us to a deeper understanding of our Universe, as well as to potentially faster and more secure communication networks resourced on modern quantum technologies.

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