A Nobel prize
for Alain Aspect, John Clauser and Anton Zeilinger

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The Nobel committee announced on October 4th that Alain Aspect, John Clauser and Anton Zeilinger were awarded the Nobel prize *"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"* [1]. In this article, we want to put the Nobel Prize in perspective, and replace the three laureates' contribution in their historical context.

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The development of Quantum Physics during the 20th century is certainly one of the most extraordinary intellectual adventures of mankind. This theory has deeply modified our conception of the world, and it has had in parallel a strong impact on our life with its numerous applications: transistors, lasers, integrated circuits. One cornerstone of quantum science is the concept of photons, introduced in 1905 (see [2]) and one of the most prominent features of the quantum formalism is *entanglement* (a term coined by Schrödinger). Einstein, Podolsky and Rosen pointed out its subtle and paradoxical character in a celebrated paper. They used this notion to demonstrate the conflict between quantum mechanics and a realistic local theory of the physical world. Moreover, to the question "Can a quantum-mechanical description of physical reality be considered complete?" the answer of Einstein and co-authors was negative, and their conclusion was incompatible with the "orthodox" point of view, advocated in particular by N. Bohr. This conflict between Einstein and Bohr lasted until the end of their lives; it remained a philosophical question until the work of J.S. Bell in 1964. Bell proved that the correlations between any pair of physical quantities, when calculated within a realistic local theory, are constrained by a specific inequality, which can be violated by quantum mechanics. From this moment, the above-mentioned conflict was no longer a matter of taste, but it became a quantitative question that could be settled experimentally.

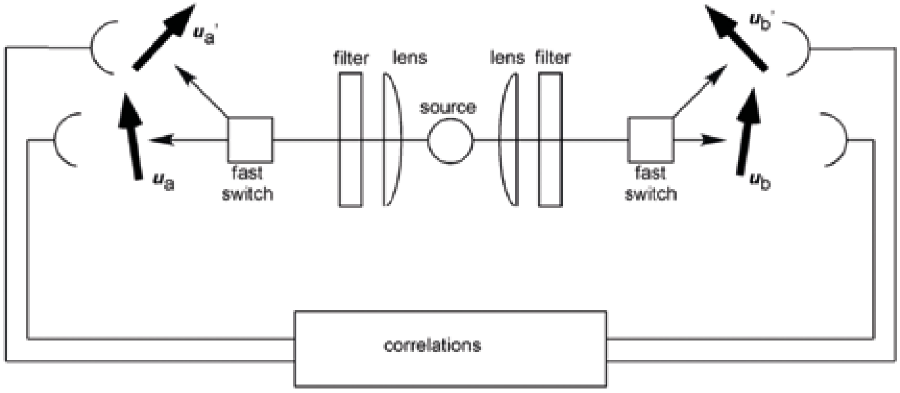

Figure 1: Concept of the Bell Inequality violation experiment designed by Aspect: a source of entangled photons (center) distributes each photon of the pair to four detectors (left and right), where fast switches enable measurements over different sets of polarizations.

This is when **John Clauser** enters into the story : first, as a graduate student at Columbia University, when he found a modified version of Bell's theorem with an inequality that can be applied to practical experiments (using pairs of entangled photons and measurement over various polarizations), then in 1972 when he performed with Stuart Freedman at the University of Berkeley the first experiment that conclusively showed a violation of Bell's inequality by more than 5 standard deviations [3]. This experiment, which was using a lamp to excite the atoms (pre-laser era!) was a tour-de-force with a data acquisition time of 200 hours. The result of Clauser was later confirmed with a similar experiment by Fry and Thompson in 1976.

In the meantime, starting in 1974, **Alain Aspect** engaged in a program in which the independence between the polarization measurements on each photon of the pair was enforced by a relativistic argument. In these experiments realized at Institut d'Optique in Orsay, the setting of each polarizer was changing rapidly in time, so that there was no possibility that an information about this setting is exchanged between the two detection channels: The choice of the measurement basis for the photons polarization was done well after the pair of entangled photons was created and the locality condition, which is an essential hypothesis of Bell's theorem, becomes a consequence of Einstein's causality that prevents any faster-than-light influence. This resulted in the publication in 1982 of two key articles [4], to which one of us (JD) was lucky to be associated, together with Philippe Grangier and with Gérard Roger -a skilful engineer. **Anton Zeilinger** realized in Innsbruck in 1997 the first quantum teleportation experiment, followed in 1998 by the third key experiment on Bell inequality violations with photons, by using ultrafast and random settings of the analyzers, thus enforcing so-called *"strict Einstein locality conditions"* [5]. As a postdoc in Vienna, where the group of Anton Zeilinger moved in the early 2000, one of us (SG) was at one of the epicenters of this revolution, and witnessed the vitality of the field, and the breadth of its application, spanning also well beyond optics, to atoms, superconductors and mechanical systems. Although very little doubts remain about local realism, the quest to experimentally close all potential loopholes continued, and remains to date an important topic, both as a fundamental subject, but also of practical importance, as pointed out by Alain Aspect in his 2015 perspective paper [6].

Beyond their crucial contributions for which the prize was awarded, one can also stress the importance and diversity of the three Laureates's other contributions to quantum science, for instance for Alain Aspect, the Bose-Einstein condensation of Helium or the Anderson localization of Atoms, to name just two salient examples. Another lasting legacy is the many outstanding PhD students and postdoctoral researchers that they formed over decades, and who continue to dynamize the field. The impact of the findings of these three physicists over our vision of the world is tremendous and it goes actually far beyond the Physics community. Philosophers and epistemologists have now incorporated all these results in their own works and concepts. The hope of Einstein for a local and realistic description of the physical world has failed, and quantum mechanics is in perfect agreement with experimental results on

Figure 2: At a conference honoring the memory of Alfred Kastler in 1985, photo of A. Messiah, A. Aspect and J. Bell, discussing. ©Laboratoire Kastler-Brossel.

this matter. The results of Aspect, Clauser and Zeilinger are now at the core of several modern textbooks in quantum mechanics.

These seminal works crowned by the Nobel prize did not remain limited to closing a philosophical debate or to textbooks, but were rapidly followed by a stream of applications of entanglement, and to the birth of a blooming field, **quantum information processing**, that spans from teleportation, to quantum cryptography, to quantum computing. All these feats rely heavily, at their core, on the phenomenon of quantum entanglement and on non-locality. Quantum information processing is now a very active field worldwide, involving thousands of groups, and poised to revolutionize the way we communicate and compute. Quantum communications, be it on deployed fibered networks spanning across countries (and enabled by meshes of "quantum repeaters"), or along free-space link through satellites, are already a reality for unconditionally-secure cryptography. Quantum computing has recently demonstrated over different platforms the so-called "quantum advantage": its capacity to perform some specific calculations with an exponential speedup over conventional computers. While a large-scale universal quantum computer remains years away, the world is already getting prepared for the "post-quantum" era, where quantum technologies may render several of our current approaches to information processing obsolete.For example, it is reasonable to expect that quantum simulators could soon be used to solve currently intractable problems in chemistry and physics, with crucial applications such as the design of new drug molecules.

It remains a humbling lesson to witness how such a profound technological and societal change may stems from sheer curiosity-driven research : from the deep philosophical considerations of the founders of quantum mechanics, later formalized by John Bell into measurable quantities, and ultimately to the experiments imagined by Alain Aspect, John Clauser and Anton Zeilinger.

REFERENCES

[1] Demonstrations of quantum entanglement earn the 2022 Nobel Prize in Physics, Physics Today (2022)

[2] A. Zeilinger *et al.*, Nature **433**, 230 (2005)

[3] S.J. Freedman and J.F. Clauser, Phys. Rev. Lett. **28**, 938 (1972). https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.28.938

[4] A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982). A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. 49, **91** (1982)

[5] G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, A. Zeilinger, Phys. Rev. Lett. 81, 5039 (1998). D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, Nature **390**, 575 (1997)

[6] A. Aspect, Physics **8**, 123. (2015)

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