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Jean-Daniel Bancal

On the Device-Independent Approach to Quantum Physics

Advances in Quantum Nonlocality and Multipartite Entanglement Detection

Doctoral Thesis Submitted by
the University of Geneva, Switzerland

Springer

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Supervisor's Foreword

One of the most fascinating intellectual adventures of humankind started in the 1920s with quantum theory, the theory of atoms and photons (particles of light). Quantum theory has been extremely successful, both in the vast scopes it covers, from very low energies up to nuclear power, from inside atoms and molecules up to the entire cosmos, and in terms of applications like the lasers used in today's DVDs and the semi-conductors used in all modern electronics. Yet, despite 90 years of successes, quantum theory is still poorly understood.

In quantum physics, we describe the measurements we perform and the results we obtain as classical, i.e., not quantum. But then, where is the quantum/classical boundary? Most physicists merely ignore this "measurement" problem. Furthermore, we describe physical systems separated by arbitrary distances as independent, yet quantum theory predicts that they can be correlated even more strongly than is classically possible, allowing for the violation of "Bell inequalities." But, how does Nature do it? Most physicists merely ignore this form of "nonlocality."

Admittedly, some do not ignore these questions, but instead, quite the opposite, they enter into endless and animated debates, as heated as they are vague.

Only recently a community of physicists and computer scientists realized that the classical inputs (measurement settings) and outputs (measurement results) on distant systems with correlations violating some Bell's inequality open entirely new ways to do physics, i.e., to analyze the power of quantum correlations. The only necessary assumption is that distant systems cannot communicate without exchanging some physical messengers carrying the information, quite an obvious assumption, named the no-signaling principle.

Device-Independent Quantum Information Processing (DIQIP), as this new approach to physics is called, is the subject of this Ph.D. thesis. This name reminds one that, in addition to the no-signaling principle, only the input–output relations between classical variables are needed. In particular, neither description nor understanding of the internal functioning of the measurement devices is needed. Think about it. It is truly astonishing that anything nontrivial can be deduced from such minimal assumptions.

This thesis first introduces the mathematical tools needed to study DIQIP. Next, Jean-Daniel Bancal illustrates the power of these tools by analyzing the 2-partite case and—mostly—some multi-partite scenarios. I consider the possibility to detect genuine multi-partite entanglement in this framework as especially remarkable. All these theoretical analyses are accompanied by presentations of experimental results. Finally, the last chapter deals with the profound question "How does Nature produce nonlocal and yet no-signaling correlations?", a question to which Jean-Daniel contributes here with a negative but amazing result … for the reader to discover.

Geneva, April 2013 Prof. Nicolas Gisin

Abstract

During the last century, quantum physics participated in the development of numerous fields: be it computer science which relies on transistors to manipulate information electronically, communications, made possible on large scales thanks to laser light guided by fiber optics, or medicine with the recent development of noninvasive imaging techniques. Who could have forseen that the quantum hypothesis formulated by Max Planck at the dawn of the twentieth century would have such a repercussion?

Nevertheless, quantum physics still remains fairly mysterious. One of its most intriguing aspects being probably its nonlocal character, i.e., the possibility it offers to violate a Bell inequality with systems isolated from each other. Such a violation indeed suggests the existence of a causal connection between admittedly separated systems.

The way in which nonlocality appears in experimental results makes it testable under a minimum set of hypotheses. In particular, no calibration error of individual measurement devices can question the result of such an experiment. This robustness toward implementation errors which are inherent to every experimental realization, opens the way for new experimental approaches. It shows that whenever measured systems are sufficiently separated from each other some questions can be answered by calling upon virtually no additional hypothesis.

Which question can be answered in this way? What can a Bell inequality violation be used for? But also, how does nature manages to violate a Bell inequality? What are the limits of quantum nonlocality? Here are some of the questions considered in this thesis.

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