PhD Thesis Defense ALEJANDRO POZAS-KERSTJENS 'Quantum information Outside Quantum Information'

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October 15, 2019

Tuesday, October 15, 15:30. ICFO Auditorium

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Quantum Information Theory

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Quantum theory, as counter-intuitive as a theory can get, has turned out to make predictions of the physical world that match observations so precisely that it has been described as the most accurate physical theory ever devised. Viewing quantum entanglement, superposition and interference not as undesirable necessities but as interesting resources paved the way to the development of quantum information science. This area studies the processing, transmission and storage of information when one accounts that information is physical and subjected to the laws of nature that govern the systems it is encoded in. The development of the consequences of this idea, along with the great advances experienced in the control of individual quantum systems, has led to what is now known as the second quantum revolution, in which quantum information science has emerged as a fully-grown field. As such, ideas and tools developed within the framework of quantum information theory begin to permeate to other fields of research.

This Ph.D. dissertation is devoted to the use of concepts and methods akin to the field of quantum information science in other areas of research. In the same way, it also considers how encoding information in quantum degrees of freedom may allow further development of well-established research fields and industries. This is, this thesis aims to the study of quantum information outside the field of quantum information. Four different areas are visited.

A first question posed is that of the role of quantum information in quantum field theory, with a focus in the quantum vacuum. It is known that the quantum vacuum contains entanglement, but it remains unknown whether it can be accessed and exploited in experiments. We give crucial steps in this direction by studying the extraction of vacuum entanglement in realistic models of light-matter interaction, and by giving strict mathematical conditions of general applicability that must be fulfilled for extraction to be possible at all.

Another field where quantum information methods can offer great insight is in that of quantum thermodynamics, where the idealizations made in macroscopic thermodynamics break down. Making use of a quintessential framework of quantum information and quantum optics, we study the cyclic operation of a microscopic heat engine composed by a single particle reciprocating between two finite-size baths, focusing on the consequences of the removal of the macroscopic idealizations.

One more step down the stairs to applications in society, we analyze the impact that encoding information in quantum systems and processing it in quantum computers may have in the field of machine learning. A great desideratum in this area, largely obstructed by computational power, is that of explainable models which not only make predictions but also provide information about the decision process that triggers them. We develop an algorithm to train neural networks using explainable techniques that exploits entanglement and superposition to execute efficiently in quantum computers, in contrast with classical counterparts. Furthermore, we run it in state-of-the-art quantum computers with the aim of assessing the viability of realistic implementations.

Lastly, and encompassing all the above, we explore the notion of causality in quantum mechanics from an information-theoretic point of view. While it is known since the work of John S. Bell in 1964 that, for a same causal pattern, quantum systems can generate correlations between variables that are impossible to obtain employing only classical systems, there is an important lack of tools to study complex causal effects whenever a quantum behavior is expected. We fill this gap by providing general methods for the characterization of the quantum correlations achievable in complex causal patterns. Closing the circle, we make use of these tools to find phenomena of fundamental and experimental relevance back in quantum information.

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