PhD THESIS DEFENSE: Bell nonlocality and causal networks

EMANUEL CRISTIAN BOGHIU

July 09, 2024

11:00

ICFO Auditorium and Online (Teams)

Understanding the cause and effect relationships behind observed correlations is central to how we reason and interact with the world. Causal relationships help us make sense of the patterns we observe and predict what interventions in nature might lead to a desired outcome. These patterns can be mathematically framed as the joint probability distribution of a set of classical random variables which capture information gathered from the environment. This information may range from abstract data, like survey response statistics, to physical events, such as the probability of triggering a photon detector. A fundamental question is that of causal compatibility: Are the observed correlations compatible with a given causal explanation? A causal explanation can be expressed in terms of causal models, which can be systematically studied with the tools provided by the field of causal inference. Causal models consist of observable random variables with known probability distributions

ICFO

and latent variables with unknown distributions which, together, explain observed correlations through causal influences, that is, functional relationships between the values of these variables. Quantum theory---one of the most accurate theories at a fundamental level---is inherently probabilistic. Measurement results are, therefore, represented as random variables. This naturally leads to causal analysis: Which cause and effect relationships can explain observed measurement statistics in a quantum experiment? One of the simplest quantum experiments is that of two distant parties performing space-like separated, independently chosen measurements on a shared quantum state. In 1964, John Bell showed that in this experiment quantum theory predicts correlations that defy any classical common-cause explanation through a result known as Bell's Theorem. This phenomenon is known as Bell nonlocality. This thesis aims to operationally characterize the fundamental differences between classical and quantum theories within causal scenarios beyond Bell's common-cause scenario. Such an understanding may eventually help integrate quantum phenomena into a coherent, conceptually clear framework of causality. Towards this goal, we explore how classical and quantum causal models diverge in operational tasks in specific causal scenarios. We focus on simple scenarios that go beyond Bell's, while seeking to discover new forms of quantum advantage that are fundamentally different from traditional Bell nonlocality. Our goal is to link these new forms of quantum advantage to different nonclassical features of quantum theory and study their potential applications. A critical component of this research is testing for the causal compatibility of specific correlations with a given causal model. As such, an important part of this thesis is dedicated to expanding and refining the scope of current methods for testing causal compatibility.

Tuesday July 09, 11:00 h. ICFO Auditorium and Online (Teams)

Thesis Director: Prof. Dr. Antonio Acin

Hosted by: Prof. Dr. Antonio Acin