Abstract for the General Public

Quantum mechanics is a notoriously counter-intuitive physical theory. Notably, even Einstein –- despite his instrumental role in the development of the theory –- had trouble coming to terms with its bizarre predictions. In spite of this, quantum mechanics continues to pass every experimental test which comes its way. More remarkable, still, is the fact that we have now discovered how these bizarre properties of quantum theory can actually be used to develop new technologies, which would be physically impossible if the world was governed solely by classical laws. These technologies include cryptographic protocols whose security is guaranteed by the laws of quantum physics, and computers that can produce results which, if we were to use our fastest current classical supercomputers to compute them, we would need to wait for a time longer than the age of the universe before finding the results.

As of yet we do not have a complete theoretical understanding of how the quantum and classical theories of physics diverge from one another – that is, there are ***fundamental non-classical phenomena*** out there in the quantum world that we are yet to identify. This represents a gaping hole in our foundational view of nature. In certain simple, idealised, situations the picture is relatively clear, but, in more complex, realistic, situations quantum theory remains a mystery. However, it is in precisely these more complex realistic scenarios in which future quantum technologies will be developed. A lack of understanding of these fundamental non-classical phenomena therefore translates into a lack of understanding of the ***crucial quantum resources*** that will underpin these technologies. The overarching goal of this research is therefore to:

Deepen our understanding of
the non-classicality of nature and
the resources that it enables.

The key tool that we will use to tackle these theoretical issues is a rapidly developing branch of mathematics known as ***applied category theory***. Category theory has traditionally been viewed as a famously abstract branch of mathematics, subsuming many other disciplines under its umbrella. Category theory allows us to compare and contrast these disciplines, and to transfer tools and knowledge from one to another. More recently, moreover, it has been identified as the mathematics of ***composition***, that is, a study of the fundamental mathematical ways in which large complicated things can be built out of smaller simpler things. Nowadays, category theory has become useful even for applied problems in mathematics, physics, and computer science, beyond its initial abstract scope. Indeed, Quantum theory itself has been recast in this language, a branch of research known as ***categorical quantum mechanics***. All of these aspects of category theory will be critical to our research. On the one hand, the categorical tools that allow for theories to be compared and contrasted, are what will allow us to compare and contrast quantum and classical theory. On the other hand, the compositional tools provided will allow us to take our knowledge of non-classicality of simple scenarios and extend it to more complex situations.

Utilising these novel tools should allow us to: (i) make substantial progress on our overarching goal, (ii) substantially push forwards the state-of-the-art in the field of quantum foundations, and (iii) develop tools which will become part of the standard toolkit for researchers studying the non-classicality of nature and its technological applications.

The particular perspective provided by our approach will deepen our understanding of the previously studied non-classical phenomena based on ***speakable information***, such as ***Bell non-locality***. But more crucially, it will allow us to study the non-classicality of ***unspeakable information*** within quantum theory. This opens the door to discovering an entirely new non-classical phenomena, likely to power quantum advantage in precision measurements of fundamental physical quantities.