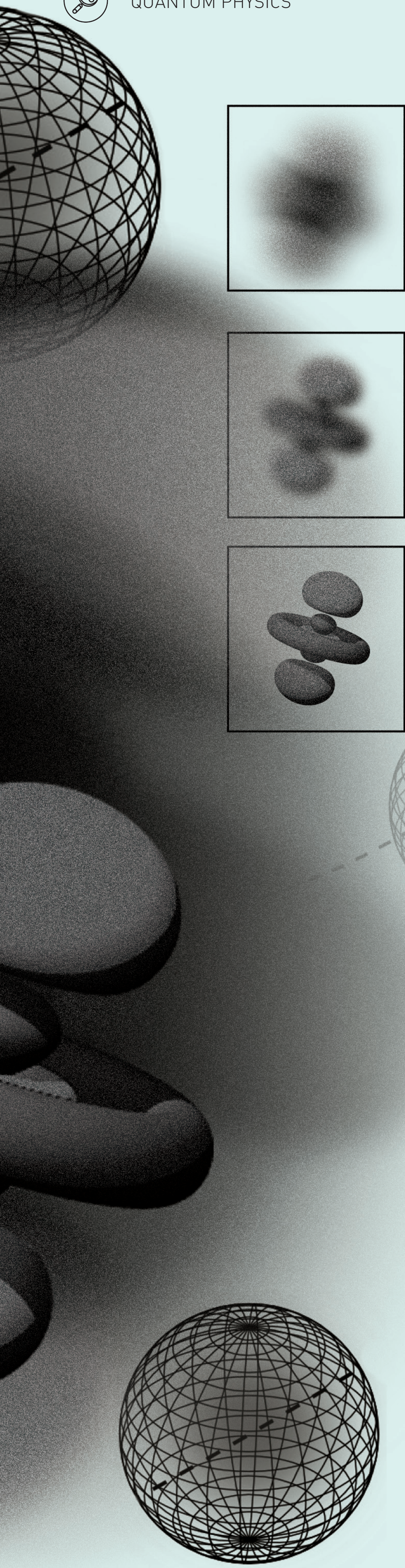


Partners on the quantum level

Mathematician **Professor Stéphane Attal** and theoretical physicist **Professor Denis Bernard** have assembled a cross-disciplinary team to tackle some of the questions quantum dynamics presents

What are your respective academic backgrounds and what inspired you to focus your research on the interface between modern probability and modern physics?

SA: I am a mathematician and initially studied stochastic processes and stochastic calculus. My PhD thesis was on the subject of quantum probability and quantum stochastic calculus. Although these fields of research are motivated by quantum mechanics and quantum statistical physics, I originally studied them solely as a mathematical tool. Some years later, I decided I wanted to understand the physical meaning and the possible physical applications of my work. I began to familiarise myself with quantum mechanics and quantum open systems. The results of my interactions with theoretical physicists were very fruitful, and have informed my research over the last 15 years I have devoted my research to them.

DB: I am a theoretical physicist whose work has always been positioned at the interface between physics and mathematics. I am either using mathematical tools to deal with physical problems or attempting to extract mathematical structure for studying physical models. In the past, physics and mathematics have moved together via interactions centred on mechanics and analytic analysis, dynamics and geometries, symmetries and algebras, etc. Recently there has been an increase of probability theory in this interaction. This led me to further explore the interaction between probability and quantum physics.

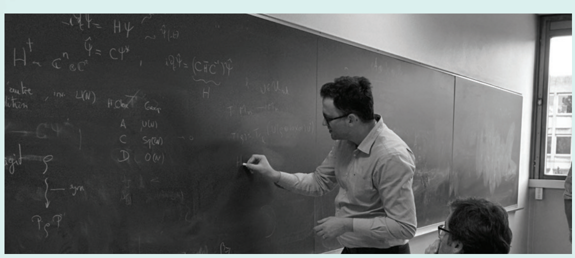
My recent work on the interface is 'curiosity orientated' research. Four or five years ago I was listening to a seminar by Serge Haroche presenting a fundamental experiment on manipulation of small quantum systems. That motivated me to work on this topic because: a) it was clear to me that I did not properly understand what it was about and b) there was something that could be done theoretically to better formulate or extract the relevant theory.

As an interdisciplinary project, Stochastic Methods in Quantum Mechanics (StoQ) brings together mathematicians and physicists. What are the advantages of this?

SA: This collaborative element supplies the force and the originality of our project and is a major success of our group. Although many mathematicians are working on subjects inspired by physics, and many physicists are using developed mathematical tools, it is rather rare to see a true, long-term and efficient collaboration between physicists and mathematicians. From the mathematical side, this collaboration offers a framework, true applications and a source of relevant problems. From the physical side, the collaboration offers the possibility to access the efficiency of new tools and ensures maximum rigour.

Why did you choose to analyse out of equilibrium quantum behaviours?

SA: Out of equilibrium systems are one of the most important open problems of statistical physics today. Understanding the flow of energy, changes of entropy and distribution of temperature for a system in contact with several reservoirs is still very difficult to handle at a rigorous level. In classical statistical mechanics some important results have been already obtained using the noise approach, but in the case of quantum systems there are almost no rigorous results in this direction. We hope that the quantum noise approach will bring interesting new results.



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DB: There is no existing effective synthetic way to deal with out of equilibrium phenomena and a large community of physicists does case studies to try to decipher equations for out of equilibrium physics. This research has recently been boosted by new experimental progress that allows us to test quantum phenomena out of equilibrium. Additionally, the theoretical and experimental development of quantum information demands to deal with an open quantum system, that is, with a quantum system in contact with an exterior environment, say to manipulate the system. And such systems are necessarily out of equilibrium.

What makes StoQ unique and how do you intend to develop further applications of the Probability Theory in Quantum Physics?

SA: StoQ does not only concern quantum noises and quantum open systems; a large part of our activity also centres on quantum information theory and, in particular, the probabilistic aspects of this. It is a very rapidly growing theory, with many practical applications. What makes StoQ unique is largely the systematic focus on the interaction between probability theory and quantum physics (in many of its aspects), but also the true and fruitful dialogue between physicists and mathematicians.

The study of quantum trajectories has the potential to heavily influence several branches as well as provide invaluable results for the progress of quantum information theory

Achieving the perfect equilibrium

Researchers at the **University of Lyon** and **École Normale Supérieure de Paris**, France, are joining together to unite mathematics and quantum physics. They hope the two disciplines can help one another advance, particularly in the fields of quantum open systems and quantum information theory

PHYSICS AND MATHEMATICS have a long history of interaction. Physicists have always sought to describe their work in mathematical terms and, in turn, mathematicians have long been influenced by the discoveries of physicists. Key examples of this mutual discovery and development can be found in classical physics, with fundamental mathematical tools such as calculus having been developed to determine the laws of motion. Similarly, geometry has been immensely influential both in describing the world and in engineering.

Despite this inherent overlap between the two disciplines, there have been few large-scale, long-term collaborations between physicists and mathematicians. These interactions are particularly lacking in quantum mechanics, the most recent, novel field of physics. quantum mechanics deals with extremely small-scale physics that cannot be described through classical models. Naturally, mathematical tools continue to be used in in this field. However, unlike in classical physics, which prompted development of new branches of mathematics, new fields of study are yet to evolve from research into quantum mechanics.

THE POWER OF TWO

Professors Stephane Attal and Denis Bernard are addressing these issues through an international collaboration between mathematicians and physicists entitled Stochastic Methods in Quantum Mechanics (StoQ). Attal, a mathematician who has worked extensively in stochastic (random) processes in quantum mechanics, has long been convinced of the effectiveness of close collaboration between quantum physicists and mathematicians. He believes the overlap between mathematical probability theory and the random aspects of quantum physics in particular will yield the best results.

Bernard, the pair's quantum physicist, agrees that the input of mathematicians will be invaluable in advancing both fields: "Collaborating with a mathematician (and more generally with someone with a different background) enables us to share our different knowledges and interests. This is positive because it adds information, increases

STOCHASTIC METHODS IN QUANTUM MECHANICS

OBJECTIVE

To obtain important new and rigorous breakthrough results in the areas of quantum open systems and quantum information theory, by means of advanced tools in probability theory

KEY COLLABORATORS

Guillaume Aubrun; **Ivan Bardet**, Institut Camille Jordan, University Lyon 1, France

Michel Bauer, CEA Saclay, France

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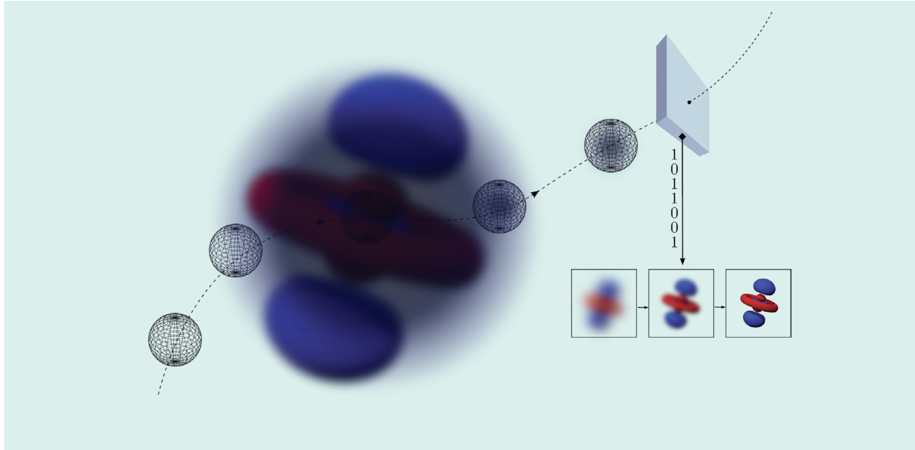
PROFESSOR STEPHANE ATTAL is a mathematician and Professor at Institut Camille Jordan, University of Lyon with research interests in quantum noises, quantum statistical mechanics and quantum random walks.

PROFESSOR DENIS BERNARD is Research Director at the French National Research Centre (CNRS) and a professor at the Ecole Polytechnique. Having worked on different topics of theoretical physics such as turbulence, conformal field theory and random geometry, his current research focus now lies with quantum noises and open quantum systems.



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our technical abilities and enlarges our perspectives and the domain of application of what we are trying to develop".

STOCHASTIC METHODS

The beginning of the 20th Century brought with it a revolution in Physics. By this point it had become clear that classical physics could not be readily applied to all situations. Particularly, it was emerging that established physics broke down at the atomic level (and smaller). Physicists such as Max Plank and Albert Einstein published papers that insisted on a new set of rules with which to interpret this scale. Since these early publications, quantum mechanics has become an established force in physics and has moved, in the intervening years, from theoretical to practical applications such as the microprocessor and lasers.
The current paradigm in the field describes quantum mechanics as the calculation of the probabilities that experimental work will yield a certain outcome. This interpretation explicitly requires that the field be treated as a series of probabilities rather than hard numbers. In essence, quantum mechanics is random by its very nature.

CONNECTING THE DOTS

Given the obvious connection between quantum mechanics and probabilistic mathematics, it is a little surprising that the two fields have not interacted more extensively. This is becoming ever more important as experimental work progresses and offers new opportunities to study mathematics that deals with quantum systems. Attal and Bernard realised that close collaboration between the mathematicians, who can create the tools with which to interpret such systems, and the quantum physicists, who can test these tools in the real world, was essential.

Together, Attal and Bernard have decided to centre their studies on four key areas: open quantum systems, quantum trajectories, randomness in quantum information theory and open quantum walks. These areas of research are currently at different points in their development. Open quantum systems have been well-studied; however Attal is hoping to provide rigorous data that will help shape current theories. The study of quantum trajectories has the potential to heavily influence several branches as well as provide invaluable results for the progress of quantum information theory. Finally, they plan to study the quantum random walks. Doing so should allow the development of powerful tools with which to interpret out of equilibrium quantum systems.

MORE THAN A RANDOM ENCOUNTER

The project will initially involve 12 researchers from three countries. The majority of participants will be spread between several institutions across France. There is, therefore, a rigorous plan for regular meetings and personal collaborations between the researchers involved in the project. Given the international nature of the project, the plan is to have monthly regional seminars and then to meet with groups outside of the region a minimum of once a year. Additionally, there are to be three meetings attended by everyone involved in the project over the course of the project's five-year duration.

It is hoped that, by fostering regular contact and close relations, the researchers will explore new options for their work. The collaborative nature of the project will allow for efficient exchange of ideas. Particularly, it will lead to an exchange that will allow for the researchers to open new perspectives on their work through novel insights from their colleagues in the opposite discipline. It is clear that the project offers immense potential for advancing both probability mathematics and stochastic quantum mechanics. Given the fundamental nature of both of these subjects, it is likely that the results of the project will provide the foundation for many future technologies.