A Panorama of Scientific Challenges for 21st Century Physics

The progress we have made over the last hundred years in our understanding of the physical world is truly remarkable. However, even if we are well aware of the breakthroughs of quantum theory and relativity of the early 20th century, we rarely stop to reflect on just how much our everyday life is shaped by the advances in knowledge and technology they have brought about. When using a handheld device to navigate our way around town, we crucially rely on the physical laws of general relativity and quantum mechanics. These spectacular, early discoveries laid the basis for a golden age of uncovering new physical phenomena, from the microscopic quantum world of elementary particles to the vast expanse of our universe.

Do these successes imply that the role of physics research in the future is merely to “fill the gaps”? Far from it. We enjoy ever-increasing computational power, capabilities to handle and infer knowledge from big data, and advances in instrumentation enabling access to experimental and observational data of unprecedented precision. On the one hand, this allows us to explore extreme regimes previously out of reach, which has already produced spectacular new insights, with gravitational waves and exotic quantum matter as prominent examples. On the other hand, it brings into focus the limitations of our current physical theories and the challenges we still face in pushing their boundaries. While detailed research strategies for tackling them are formulated elsewhere , this document takes a complementary approach. By presenting a selection of such challenges, seen through the eyes of individual researchers, it aims to bring alive the beauty and richness of the subject, fueled by the drive, passion, and diversity of its practitioners. All these ingredients are essential for the Dutch physics community to continue to progress, flourish, and contribute.

Ronald Hanson seeks a new window onto the quantum world:

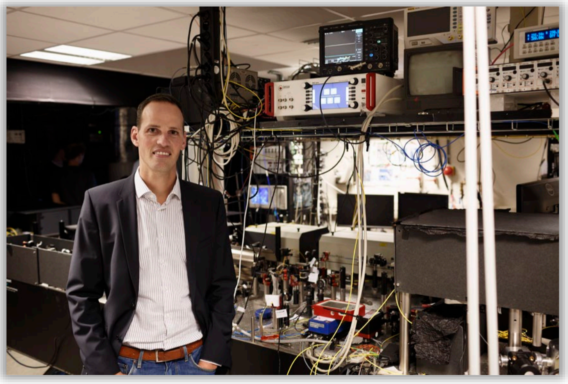


Photo: Bob Bronshoff Fotografie

Quantum theory is the most fundamental theory of Nature. It tells us that at the fundamental level our world is a strange place. Particles like electrons can be in two places at the same time, and particles can be entangled with each other, which means that they are more strongly correlated than classically possible. In the 20th century we could only observe these phenomena as passive bystanders. However, a string of break-throughs in the last two decades has enabled us to take control of the quantum world, thereby opening up exciting new opportunities for fundamental science. Remarkably, this new frontier is also expected to form the basis for radically new technologies such as quantum computing, quantum communication, and quantum sensing.

Marjolein Dijkstra studies the world on the nanoscale and aims to take nanofabrication from two to three dimensions:

> Traditional nanofabrication techniques like etching, lithography, deposition, and layer-by-layer growth are limited to two-dimensional structures. My challenge is to find a way to grow three-dimensional, complex and ordered structures spontaneously: that is, without human intervention. This is called self-assembly or self-organisation. Nature knows how to do this, for example, lipid molecules spontaneously assemble into flexible membranes that surround living cells. Cells then self-assemble into tissues, and tissues into organisms. My aim is to apply self-assembly to the fabrication of multifunctional bio-inspired materials, such as materials that self-heal, are bio-compatible, and posses novel combinations of properties that do not exist yet in nature.

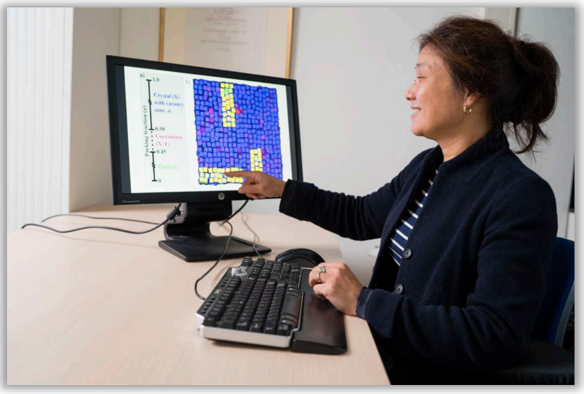


Photo: Ivar Pel

Heino Falcke has seen into a black hole:

Our understanding of the world at the smallest scale, where quantum physics rules, and at the largest scale, governed by relativity, breaks down when we approach a black hole. The distortion of space and time becomes so extreme that a unified theory is needed. The first image of a black hole which we received in 2019 has opened up a new window in our Universe. I hope to discover what is happening at the edge of black holes and find some clues how these two most fundamental theories of our Universe, relativity and quantum physics, can finally be unified.

Photo: Boris Breuer

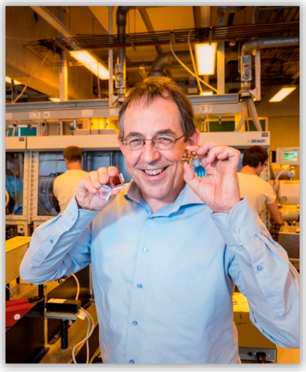
Photo: Rafael Philippen

Marileen Dogterom hopes to build a synthetic cell:

While we have extensive knowledge about the molecular building blocks that form the basis of life, we currently do not understand how these building blocks collectively operate to become living matter, a cell. Truly understanding cellular life based on physical and chemical principles will bring huge intellectual, scientific, and technological rewards. At the same time, it will raise fascinating philosophical and ethical questions about how society may cope with new opportunities that result from these new fundamental insights.

René Janssen seeks to harness solar energy:

The efficiency of photovoltaic panels is now reaching the fundamental limits associated with the current technology. Fortunately, the conversion of sunlight into electricity can exceed the present limits in advanced solar cell architectures employing novel semiconductors in combination with nanostructures and spectral converters aimed to utilise near to all available photon energy in sunlight. Pushing the efficiency to the ultimate limits poses formidable challenges to physics and materials science, also because new technologies must be affordable and environmentally benign.



Source: Wikipedia

Nynke Dekker aims to unravel the dynamics of genetic replication:

The copying, or replication, of DNA and RNA is one of the central processes that take place in all living organisms. Human beings copy a lightyear of DNA over the course of their lifespans, and the optimal accuracy per copying cycle is very high. viruses such as SARS-CoV-2 on the other hand, have a much lower optimal accuracy that facilitates mutation. In both cases, there is much we still do not understand about the mechanisms involved. My goal is to visualise how individual component molecules of these replication machineries interact in space and time. How do such molecules cooperate to replicate our genes in an extremely efficient and optimally accurate way?

NWO, Photo: Studio Oostrum/Hollandse Hoogte