

**Opening Address by David Gross,
Chair of the 25th Solvay Conference on Physics
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A Century of Quantum Mechanics

One hundred years ago, twenty-four physicists met at the Hotel Métropole in Brussels; they were invited by Ernest Solvay to participate in a new kind of scientific congress. One of the first international scientific meetings, the Solvay conferences were characterized by a highly restricted invitation list and an unusual mixture of short talks and long discussions. Solvay played a unique and important role in the development of twentieth century physics — most notably in the quantum revolution whose birth overlapped the initiation of these meetings. The Solvay tradition has continued with a physics conference every three years, except for unfortunate lapses due to war. Solvay, one of the few traditions that remains in the rapidly changing scientific landscape, represents excellence, internationalism, free discussion and lively debate — a tradition worth preserving, but a tradition that is hard to maintain as the number of physicists has increased in the last century by two orders of magnitude, whereas the number of invitees can only increase by a factor of two or three! I thank the members of the Solvay Physics Committee for their help in the difficult task of compiling the invitation list to this conference. Many of our colleagues that should be here are absent. We will miss them. We must regard ourselves as representatives of a much larger community. I also thank the chairs of the individual sessions, the members of the Solvay physics committee (R. Blandford, S. Chu, R. Dijkgraaf, B. Halperin, G. 't Hooft, G. Parisi, P. Ramond, K. Von Klitzing, P. Zoller) and the scientific leaders of the Solvay Institutes, Marc Henneaux (Director) and Alexander Sevrin (Scientific Secretary) for their invaluable contributions to making this conference possible.

For this centenary year and for the 25th Solvay Conference in Physics, we decided to cover physics broadly, but to focus on quantum mechanics, whose early birth pangs and later applications were most often the subjects of the Solvay meetings. Quantum mechanics emerged in the period between 1900, when Planck first quantized the energy of radiating oscillators, and 1925-26 with Heisenberg, Schrodinger, Born and Dirac's formulation of the principles of quantum mechanics, and thus is approximately one century old. The development of quantum mechanics and its application to atomic theory and the structure of matter dominated the first five Solvay conferences, culminating in the most famous 1927 Solvay meeting, where the meaning of quantum reality was heatedly debated between the pioneers and the revolutionaries of quantum mechanics.

The first Solvay conference, one hundred years ago to the month, addressed the central problem of physics at that time: *Was the quantum structure of nature truly unavoidable?* Lorentz's opening address at the first Solvay conference reverberates with the anguish that this master of classical physics felt at the first glimpses of the

quantum world:

Modern research has encountered more and more serious difficulties when attempting to represent the movement of smaller particles of matter and the connection between these particles and phenomena that occur in the ether. At the moment, we are far from being completely satisfied that, with the kinetic theory of gases gradually extended to fluids and electron systems, physicists could give an answer in ten or twenty years. Instead, we now feel that we reached an impasse; the old theories have been shown to be powerless to pierce the darkness surrounding us on all sides.

We face no such crisis today.

Quantum mechanics is the most successful of all the frameworks that we have discovered to describe physical reality. It works, it makes sense, and it is hard to modify. The order of this list of successes is in the order of importance that most physicists demand of a physical theory: It works, it makes sense, and it is hard to modify. I shall start with the second point.

Quantum mechanics does make sense, although the transition, a hundred years ago, from classical to quantum reality was not easy. It took time to learn how to get out of phase space and to live in Hilbert space. Some of the boldest pioneers of quantum theory (notably Einstein) resisted the replacement of classical determinism with a theory that often can only make probabilistic predictions. Even harder to get used to was the idea that in quantum mechanics one can describe a system in many different and incompatible ways, and that there is no unique exhaustive description. The freedom one has to choose among different, incompatible, frameworks does not influence reality — one gets the same answers for the same questions, no matter which framework one uses. That is why one can simply “shut up and calculate”. Most of us do that most of the time. Different, incompatible aspects cannot both enter a single description. If one errs by mixing incompatible descriptions or histories, we produce paradoxes.

By now, especially with the consistent (or decoherent) histories approach, initiated by R. Griffiths, and further developed by Gell-Mann, Hartle, Omnes, Zurek and others, we have a completely coherent and consistent formulation of quantum mechanics that corresponds to what we actually do in predicting and describing experiments and observations in the real world. For most of us there are no problems.

Nonetheless, there are dissenting views. Experimentalists continue to test the predictions of quantum theory, and some theorists continue to question the foundations. We will hear from them, and we will debate them in our second session. Most interesting to me is the growing understanding as to how the classical framework emerges from quantum mechanics, especially interesting as our experimental friends continue to astonish us with their ability to control and manipulate quantum systems while preserving their quantum coherence. How can we explain measurements without invoking the absurd collapse of the wave function? How does classical physics emerge from quantum reality? The mathematics of the classical limit and the growing understanding of decoherence will also be discussed in our second session.

Quantum mechanics is more powerful and richer than classical mechanics, for, after all, classical physics is just a limiting, special case of quantum physics. In recent years we have also become aware of the increased computational power of quantum mechanical states. Entanglement, the strange new feature of quantum states, can be efficiently used to amplify computation, and has motivated an intensive effort to develop a quantum computer. This goal might take many decades to realize, but meanwhile the effort has provided enormous stimulation to atomic and condensed matter physics. Quantum information theory will be discussed in our second session.

The dream of a quantum computer is only conceivable because of the enormous advances made in recent years towards greater control and understanding of matter, down to the scale of individual atoms: mesoscopics, atomic traps, quantum optics, and spintronics. A new field is developing that might be called quantum engineering, with enormous potential for both technological innovation and for use as a marvelous tool for the experimental exploration, and the simulation, of fascinating states of quantum matter. These tools enable not only the study of the static phases of complicated many body systems, but also of their dynamics and non-equilibrium behavior. This development is the subject of our third session.

Quantum mechanics works.

It works not just for simple systems such as single atoms and molecules, but also for collections of 10^{23} atoms, sometimes strongly interacting, over an enormous range of energies. It explains not just the anomalies in the classical description of blackbody radiation and the specific heat of solids at low temperatures (that stimulated early developments), but also the detailed properties of ordinary matter, such as conductors, insulators, semiconductors as well as more exotic materials.

The quantum theory of matter (many-body theory) and the quantum theory of fields share many common features; indeed they are essentially the same thing. Thus, critical developments in condensed matter physics and in elementary particle physics towards the end of the twentieth century often occurred in parallel. In these developments, symmetry principles played a fundamental role. But if the secret of nature is symmetry, much of the texture of the world is due to mechanisms of symmetry breaking. Magnetism and chiral symmetry breaking are two important examples of the spontaneous breaking of a global symmetry.

One of the most important quantum phenomenon — that of superconductivity — was discovered by Onnes 100 years ago and discussed at the first Solvay conference. Parenthetically, Rutherford's discovery of the nucleus of atoms, made also in 1911, was not discussed, although Rutherford attended! It took almost half a century (until 1957) for Bardeen, Cooper and Schrieffer to come up with a full understanding of this first example of the spontaneous breaking of a local symmetry, which later played a fundamental role in the understanding of the weak nuclear force — the so-called Higgs mechanism — with the final confirmation coming from the LHC. Even today, unconventional superconductors are still a great mystery at the frontiers of the understanding of quantum states of matter. It now appears that that there are new forms of matter — labeled not by symmetry but by topology. The

important question, “What are the possible quantum phases of matter?” remains wide open, and will be discussed in our fourth session.

Quantum mechanics works.

It works at distances that are a billion times smaller than the size of the atom, well within the nucleus and its constituent quarks. It works for energies that are a trillion times larger than atomic energies. From the beginning it was clear that quantum mechanics fit together seamlessly with special relativity and with Maxwells theory of the electromagnetic field, despite a few technical difficulties that took some time to resolve. The resulting edifice, the quantum theory of fields, resolved the perplexing duality of particles and waves, and, in what I regard as one of the most amazing successes of theoretical physics, predicted anti-matter, the first examples of which were soon discovered.

Quantum field theory has been tested with extraordinary precision. Much of the incredible precision that physics is able occasionally to achieve rests on quantum features of nature, such as the identity of indistinguishable particles and the existence of discrete sharp states. I cannot refrain from noting one of the most amazing of these precision tests, that of the measurement of the anomalous magnetic moment of the electron:

$$a_e = \frac{g_e - 2}{2} = 0.00115965218085 \pm .000000000000076,$$

a test of Quantum Electrodynamics (QED) to almost one part in 10^{12} , sensitive to all the components of the standard model, but especially QED (the comparison involves 5 loop quantum effects). Quantum field theory works and has been tested over an incredible range of physical phenomena from the edge of the galaxy (10^{27} cm.) to the nano-nano centimeter scale, over forty-five orders of magnitude. In fact, we know of no reason why the framework of quantum field theory could not continue to be adequate until we reach the Planck scale (10^{-33} cm), where quantum effects of gravity become important.

Quantum Mechanics works.

It provides the explanation, not only of the structure of atoms and molecules, but also of the structure of the nucleus, and the nature of the strong and weak nuclear forces. In a reductionist sense, the standard model of elementary particles (with 3 families of quarks and leptons, charged under 3 gauge groups that generate three forces) is an amazing theory, powerful enough to encompass almost all of the known forces that act on the known particles of nature (with the exception of dark matter and the right-handed partner of the neutrino). The standard model is so extraordinarily successful that we currently strain, so far unsuccessfully, to find deviations. The successes and failures of the standard model will be discussed in the fifth session.

Finally, Quantum Mechanics is hard to modify.

Our present fundamental framework, quantum field theory, appears under no threat from observation or experiment, and seems to be completely adequate for

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the understanding of macroscopic and microscopic physics, from the edge of the universe to the nano-nano meter scale. It is very difficult to construct consistent alternatives to this framework that agree with observation. But no framework, no theory, is likely to survive untouched forever. Where might our present quantum mechanical framework breakdown and how?

Hints from observation and from experiment point to physics beyond the standard model. The existence of dark matter, the non-vanishing neutrino masses and the many unanswered questions regarding quark and lepton masses and their mixing require non-standard-model physics; but the necessary modifications do not necessarily force us to abandon the framework of quantum field theory. More hints come from trying to extend our standard theory to new regimes of energy and distance and from challenging our concepts with thought experiments.

The extrapolation of the standard model to high energy, or equivalently short distance, suggests that the atomic and nuclear forces are unified at very high energy. Such unification does not necessarily suggest a breakdown of the framework of quantum field theory; we can construct grand unified gauge theories. However, the fact that the implied unification scale is so close to the Planck scale, where the quantum nature of gravity becomes essential, is an important hint that the grand synthesis must include quantum gravity. Traditional quantum field theory appears to be at a loss to consistently describe gravity, due to the uncontrollable quantum fluctuations of the metric at the Planck scale. In the search for a unified theory of standard model forces, we have been led to string theory, which also automatically includes gravity and yields a consistent extension and quantization of classical Einstein gravity.

String theory was originally thought to break with traditional quantum field theory in important ways, but recently we have realized that string theory and quantum field theory are not mutually exclusive. Quantum field theory, in the old fashioned sense, is not sufficient to contain gravity. But it is part of a bigger framework that includes extended objects, strings, membranes, and higher dimensional “branes”. The formulation in terms of strings is often best understood — thus “string theory”. String theory always describes dynamical space-time — gravity. On the other hand, some string theory quantum states can be usefully described in terms of quantum field theory. This insight has been inspired by the remarkable duality between supersymmetric gauge theory in four dimensions (or more generally conformal field theory) and string theory in an AdS background. Even the theoretical framework we use for the standard model, consisting of quantum gauge theory with fundamental fermions and a few scalars has (many of us believe) a dual description in terms of a string theory with highly curved extra dimensions. A close cousin of Quantum Chromodynamics, endowed with extra (super) symmetry, is undoubtedly identical to string theory in AdS space. So string theory and quantum field theory are part of a larger quantum mechanical framework, whose structure and extent are still being explored.

Finally, there are indications that once again we might be forced to modify our

most fundamental of physical concepts, that of space and time. Many of us are more and more convinced that space is an emergent, not fundamental, concept. We have many examples of interesting quantum mechanical states, for which we can think of some (or all) of the spatial dimensions as emergent. Together with emergent space, we have the emergent dynamics of space and thus emergent gravity. But it is hard to imagine how time could be emergent? How would we formulate quantum mechanics without time as a primary concept? Were time to be emergent, our understanding of quantum mechanics would have to change.

To describe nature and to make predictions, we need more than just the framework of quantum mechanics, or of quantum field theory, or of quantum string theory. We need a particular dynamical principle, a Hamiltonian that determines the time development, and we also need an initial state. So what picks the dynamics? Quantum field theory offers little guide, except symmetry. String theory, in which all parameters are dynamical, appeared at first to offer the hope of providing a unique answer. But this hope appears to be a mirage. String “theory” does not provide such a principle; rather it consists of a set of tricks to find consistent quantum states, often constructed in a perturbative semiclassical expansion. And there are many such quantum states, an infinite number in fact, perhaps 10^{500} that resemble our universe. Some believe that this is the complete story, and that all of these universes might exist somewhere in a multiverse, and that to make predictions we must resort to arguing that our patch of the multiverse is particularly suited for our existence.

Since a theory of quantum gravity is a dynamical theory of space-time, we must finally come to grips with quantum cosmology. Here it makes no sense to separate the observer and the observed, and we are faced with many puzzling conceptual issues. What picks the initial condition? the final condition? In addition, we are challenged by astrophysics. In the last hundred years, we have learned much about the universe, including a detailed description of most of its history. The outstanding mysteries that remain — the dynamics of inflation, the mystery of the big bang and the accelerated expansion — represent serious challenges to our theoretical framework.

String theory and quantum cosmology will be discussed in the sixth session.

So what is the whole picture? We are faced today not with a crisis but with confusion at the frontiers of knowledge. Fundamental physics today is in a state more analogous to the one that prevailed in 1891, rather than in 1911. In 1891, with all the successes of classical physics — mechanics, electrodynamics, kinetic theory and statistical mechanics — physics appeared in fine shape. Who could have dreamed of the conceptual revolutions that lay in store?

Many of the issues I have alluded to will be discussed towards the end of our meeting, in the final session. We are unlikely to come to a resolution during this meeting. The most we can hope for is that our discussions will clarify the issues and most importantly stimulate the advances that are necessary. In any case it should be lots of fun.