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Topics from 20^{th} century physics.
An introductory course for students in mathematics

I. INTRODUCTION

1. Historical introduction
   - 1.1. Classical physics: physics up to the end of the 19^{th} century
   - 1.2. Problems of classical physics

2. Physics in the 20^{th} century
   - 2.1. Two revolutions in physics
   - 2.2. Quantum mechanics
   - 2.3. The theory of relativity
   - 2.4. Outlook for the 21^{th} century

1. HISTORICAL INTRODUCTION

1.1. *Classical physics: physics up to the end of the 19th century*

Ancient and medieval civilizations, those of China, India, Greece and the Arab world for instance, were already in the possession of a considerable body of knowledge: insights in certain areas of pure and applied mathematics on one hand and empirical knowledge of physical phenomena on the other hand.

On the basis of this, physics as we know it, a successful *combination* of mathematical and experimental science, began in 16th and 17th century Europe. Mechanics, describing the action of forces, in particular forces on moving bodies, was built on the principles laid down by Newton and was developed further into a beautiful mathematical theory by – among others – Lagrange, Laplace, Hamilton and finally Poincaré. Electricity and magnetism, studied experimentally from the 15th century onward, and later more theoretically, as separate phenomena, were brought together into a single theoretical framework in the second half of the 19th century by Maxwell. The basic notions in his *general theory of electromagnetism* were electric and magnetic *fields*, propagating in space as radiation, with light waves as a special case. In addition to this there was thermodynamics and statistical mechanics, the first a phenomenological framework for describing experimentally observed properties of heat, temperature and energy, the second a way of explaining these 'macroscopic' phenomena by statistical arguments from the 'microscopic' picture of atoms and molecules that gradually became generally accepted.

At the end of the 19th century, the result of all this was *classical physics*, a description of the physical world, believed by many to be essentially complete. It consisted of two main components, Newton's classical mechanics, for the description of *matter*, Maxwell's theory of electromagnetism, for *fields* and *radiation*, together with laws governing the interaction between matter and radiaton.

1.2. *Problems of classical physics*

At the beginning of the 20th century a few small but persistent problems remained, cracks in the walls of the imposing building of classical physics. One of these was the problem posed by the frequency spectra of light emitted by atoms and molecules, measured systematically and with great precision during the last half of the 19th century. These spectra were *discrete*. There was no way in which the classical picture of atoms and radiation could account for this. A second problem was the *ether*, a special medium that was assumed to fill empty space. The existence of this ether was thought to be necessary for the propagation of light waves through vacuum, but was forced to have very contradictory properties. These problems could not be solved within classical physics; fundamentally new physical ideas were needed. These were found in two new theories which emerged in the first half of the 20th century.

2. PHYSICS IN THE 20^{th} CENTURY

2.1. *Two revolutions in physics*

The two new theories that solved the problems of classical physics and broke resolutely with classical notions were *quantum mechanics* and *relativity theory*. They led eventually to a thorough revision of the foundations of physics, with new ideas, in quantum mechanics on causality and determinism on one hand, and in relativity on space and time on the other hand. In this process classical mechanics and classical electromagetism were relegated to the role of practically useful *approximations* to an underlying more general picture.

2.2. *Quantum mechanics*

Quantum mechanics was introduced in 1924 by Heisenberg, Schrödinger, Born and others. It solved the problem of discrete spectra and led to a new and much deeper understanding of physics at the submicroscopic level. It is now seen as a truly fundamental theory, which is assumed to hold for *all* physical phenomena. The technical applications of quantum theory are very important; think of transistors, microprocessors, computers and CD-players. Without quantum theory the world in which we live would look very different.

2.3. *The theory of relativity*

The theory of relativity is the creation of Albert Einstein. In 1905 he wrote a paper of fundamental importance in which he introduced what is now known as the *special theory of relativity*. In this theory space and time are intimately related, forming together a single 4-dimensional affine space. Which part of this should be considered space and which time depends on the motion of the observer. He also showed that the notion of ether could be dropped altogether. Using differential geometry, then a new part of mathematics, he went on to formulate a *general theory of relativity* in which the 4-dimensional affine space becomes a 4-dimensional *Riemannian manifold*, with the Riemannian metric and its curvature describing gravity. His main paper on this appeared in 1916. The experimental consequences of the theory of relativity appear only at very high velocities, at the velocity of light; relativity has therefore less consequences for practical applications than quantum mechanics. This does not of course diminish its importance for our view of the physical world.

2.4. *Outlook for the 21^{th} century*

The situation in physics now is reminiscent of that around 1900. Again we have an imposing theoretical framework, giving valid descriptions of physical phenomena, from the small scale of quarks and gluons in elementary particle physics to the large scale of stellar systems in astronomy. Again there are very persistent remaining problems. This time they are not caused by experimental facts that do not fit our experiments, but by the seeming impossibility to integrate conceptulally the two pillars of 20^{th} century physics, quantum theory and relativity, into a single unified theory. So far quantum theory and the theory of relativity are on a very fundamental level *incompatible* with each other. Solving this problem is the great challenge of physics in the 21^{th} century.