Journal of Theoretical Physics

Founded and Edited by M. Apostol **153** (2007)

ISSN 1453-4428

A short overview of Physics
(Lecture eleven of the Course of Theoretical Physics)

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Introduction. Observations on the Natural World have been made by ancient populations like the Babylonians and the Greeks. However, modern science started with experiments, made by people like Galileo around 1600, and by a positive, *i.e.* a reasonable and relatively controlable, thinking, as advocated by Descartes about the same time.

Newton. The great step forward in Science has been taken by Newton, around 1680, with his law of motion $d\mathbf{v}/dt = f$, where $\mathbf{v} = d\mathbf{r}/dt$ is the velocity and f is the force. Free bodies ($f = 0$) move inertially; this is the celebrated principle of inertia. The Planets move around the Sun under the action of a gravitational force $f \sim 1/r^2$, where r is their distance to the Sun.

Newton's theory is great because it introduced new concepts like the continuum of numbers, the differential and the derivative, and because it explained satisfactorily the motion of the Planets around the Sun. All of the subsequent Mathematical Physics originated in the concept of differential equations, and astronomical observations got a new impetus under the influence of the Newtonian theory of motion.

Elasticity and Fluids. The next two centuries witnessed a powerful refinement of the Newtonian theory of motion made by people like Euler, Lagrange, Jacobi, who described the motion by the least (or extremal) values of a function called the action. This theory of motion culminated in the famous Lagrangian and Hamiltonian doctrines, and in the Hamilton-Jacobi equation for the motion of the action.

Such refinements allowed the development of the theory of the elastic bodies and the theory of the motion of the fluids. Distribution of forces in continuous bodies, propagation of sound and, in particular, the fluid vortices were among the great achievements of these theories. Newton's Mechanics, Elasticity and the Theory of Fluids are the classical body of Physics, constituted more as mathematical theories than physical ones.

Poincare. It seemed that things were quite satisfactory with Newton's Mechanics, untill Poincare pointed out a very uncomfortable situation in Celestial Mechanics, around 1900. Ensembles of interacting many bodies, like, for instance, the Earth, the Moon and the Sun, move as a whole; it is impossible to separate the one-particle motion in such ensembles. The motion of interacting many-particle ensembles is not integrable in terms of one-particle motion. This disturbing issue appears also in the attempt of seting up the kinetic theory of gases on a mechanical basis. Moreover, such ensembles may be very sensitive to the initial conditions, such that their motion may become chaotical. The theory of the chaos may be a modern, though minor, direction of research.

Maxwell. Building upon the experimental work of Faraday, Maxwel set up the equations of the electromagnetism around 1860. This is a quite different physical theory, in comparison with

Mechanics. It deals with fields. Since the begining, it incorporates a very uneasy feature. The fields are extended objects, but they are produced by, and interact with, electrical particles, which are point-like objects. The electromagnetism holds a contrasting view. It poses two distinct objects, fields and particles, and, at the same time, it identifies them through its equations. This leads to a very uncomfortable situation, regarding the difficulty of accommodating point-like particles in such a theory. The infinities related to the electromagnetic mass of the electron for instance, or those appearred later in the renormalization of the quantum fields interactions are rooted in this difficulty.

Boltzmann. The 19th century imposes gradually the ancient Greeks' notion of atoms, especially by extensive works in chemistry. Gases were made of interacting atoms or molecules in motion. All the matter is made up of such atoms. The atomism is a core conception of our view of the Natural World. It was found that such ensembles are described by overall notions as pressure, volume, number of particles. These characteristics are correlated to the atomic motion, which is of a very special kind, characterized by temperature. The fundamental concept in this motion is the probability, as first pointed out by Maxwell for the kinetic theory of gases. The theory has been extended to general atomic ensembles by Boltzmann, Gibbs, Einstein, and was completely developed up to the beginning of the 20th century in the Theory of the Statistical Physics. It is one of the cleanest and most powerful physical theory. It was further developed to include the transport phenomena, the quantum physics, the phase transitions, and it is the basis of the modern Theory of Condensed Matter. Its only shortcoming consists in the unfounded attempts, which never cease to recur, to put its basis on mechanical motion. It is not a Mechanical Statistics, it is a Statistical Physics.

Einstein. The electromagnetic theory of Maxwell predicts that light, which is an electromagnetic field, propagates like waves with a certain finite velocity c. The corresponding wave equation is invariant under certain coordinate transformations, called the Lorentz transformations, which reflect the invariance under uniform translations. Such an invariance is known as the principle of relativity. The trouble is that Newton's equation is not invariant under such transformations; it is invariant under others, known as Galileo's transformations. In 1905 Einstein modified Newton's equation such as to be invariant under Lorentz transformation, and showed that for velocities much smaller than the light velocity, the Lorentz transformations become the Galileo's transformations. So there was given birth to the Theory of Relativity (sometimes called also the Special Theory of Relativity). It modified our notion of time and space, in the sense that it showed that time and distances depend on the observer, and the simultaneous events are only those connected by light. There is no physical velocity greater than the velocity c of light, which is an absolute and universal constant. The theory ascribed an energy $E = mc^2$ to any inertial mass m (and viceversa, a mass $m = E/c^2$ to any energy E).

Up to 1916 Einstein showed that any mechanical motion, either of particles or of fields, can be viewed as a free motion in a curved space-time. The curvature is universal for universal forces, like the gravitation or inertial forces. All the equations of motion are modified such as to have a tensorial character, being thus invariant under any local coordinate transformation. The laws of mechanical motion, gravitational field included, obey now a general Principle of Relativity, not restricted to uniform translations. The price for such a generalization was that time and distances become indefinite, they depend on the observer and on the physical process. The gravitational field bends the light ray and shifts its frequency to the red. Corrections are brought to the Newtonian theory of motion. When applied to the entire Universe, the theory has to deal with the Universe expansion (Hubble's law), singularites like black-holes, and perhaps an originary creation like the Big Bang. Cosmogonic and cosmologic doctrines got a new impetus under the influence of the General Theory of Relativity, which is a direction of modern research.

The Theory of Relativity, General or Special, is just another way of describing the mechanical motion, by allowing time and distance to be measured differently, in accordance to the forces and processes. It is convenient for describing motion with high velocities and the gravitational field. It is certainly an extension of Newton's law and Maxwell equations.

Quantum Mechanics. A few investigations of matter forced an entirely new conception of the motion at the begining of the 20th century. Among them, there was the spectra of gases, with their discrete spectral lines, the thermodynamics of the black-body radiation and the photoelectric effect. First, for the black-body radiation, Planck showed the necessity of another universal constant $\hbar$, the smallest quantity of mechanical action. Then, Einstein conceived the smallest quantity of energy, the quanta of energy, associated to the frequency of light in the photoelectric effect; this quanta was called the photon. Then, Bohr admitted the existence of discrete energy levels in the atom, which would explain the discrete spectral lines. A particle like the electron would have also a wavelength, like any other wave, associated to its momentum, according to de Broglie; the material standing waves would explain the Bohr atom.

Soon it became clear that the mechanical quantites have not definite values for the motion at the atomic level; instead, they are operators, representable by matrices. This was done by Heisenberg, Born, Jordan, around 1925-1926. The mechanical action has then been represented as the phase of a wavefunction, and in 1926 Schrodinger established his equation by the Hamilton-Jacobi equation. The Bohr motion for the Hydrogen atom was fully determined. The physical quantites are operators, without definite values. But they have mean values and deviations, so that a statistical meaning must be given to them, and to any act of measurement. Restrictions are imposed upon measurements, according to the operatorial nature of the physical quantities, as shown by Heisenberg's principle of uncertainty. The new motion was called the quantum motion, and the Quantum Theory generated all of our basic understanding of the atomistic Natural World.

Condensed Matter. There are basically three main fields of research today in Physics: Condensed Matter, Nuclear Physics and Fields and Particles.

The Quantum Mechanics gave first a new impetus to the Atomic Physics, dealing with atoms and molecules, their motion, their spectra and their interaction. The electromagnetic theory was soon incorporated in the Quantum Physics, at least for radiation, by Fermi around 1932.

Then, the Quantum Mechanics opened the way of understanding the building of molecules and the cohesion of matter, a direction of research which is active even nowadays with the nanostructures for instance. After the Hartree-Fock equations, the chemical bonding was long championed by people like Pople, starting around 1940, and Kohn and Sham, since 1960, with a great deal of computer calculations.

The Quantum Mechanics was soon incorporated by Statistical Physics, leading to the modern Condensed Matter, which deals with solids, liquids, gases, and all sort of interacting ensembles of many particles. Among the best known output of Condensed Matter is the electronics of today and the modern materials. Traditionally, solid-state physics may start with Bloch in the 30s, who showed the existence of the energy bands in solids.

It was soon discovered that the quantum motion may extend to macroscopic bodies too, in certain conditions, which opened completely new fields of research like the lasers and explained strange phenomena like superconductivity, superfluidity, and, in general, any coherent quantum ensembles. The Condensed Matter Physics was basically constructed by people like Landau, starting around 1930. The great achievements are superfluidity, supraconductivity, magnetism, the Fermi liquid, electronic liquid, phase transitions, kinetic theory, transport theory, etc.

Nuclear Physics. At the end of the 19th century the radioactivity was discovered, and soon, through Rutheford around 1910, people become aware of the atomic nucleus, the siege of this radioactive rays; later on they were identified as alpha particles (helium nulei), beta rays (electrons) and gamma rays (photons). Up to the 30s, it was clear that the nucleus is an ensemble of interacting nucleons, *i.e.* protons and neutrons. Their interaction is poorly known, and information about the nuclear structure is obtained through nuclear reactions, *i.e.* scattering of particles accelerated in nuclear accelerators. The big output of the Nuclear Physics was the release of the fission energy in nuclear reactors and atomic bombs. The theory of the nuclear reactions was constructed mainly by Fermi and Wigner, around 1930, and Fermi was also the one who, in 1934, pointed out a new force in Nature, the weak interaction responsible for the beta disintegration. A new particle was then suspected, and later discovered, called neutrino.

Quantum Electrodynamics. To put the quantum equations in accord with the theory of relativity was not an easy task. The first hint came from Dirac in 1928 who showed that the electron is a more complex object, described by a spinor, a sort of wavefunction with four components, and that it posseses a new, strange property called spin, a sort of inner, intrinsic angular momentum. The spin explained much of the observed facts, and it was very welcome, because it fulfilled much of previous expectations. In addition, negative energy levels were predicted by Dirac equation, as well as a new kind of particle, the positron, which was discovered around that time, seen as an antiparticle to the electron. The quantum relativistic difficulties remained, connected especially with the negative energy levels. The solution was given in the 30s, by people like Heisenberg and Pauli, who showed that we need to think about relativistic quantum particles like quantum fields. This means that motion proceeds by creation or destruction of particles, or quanta, represented by fields, *i.e.* both by functions in space-time which obey field equations, and, at the same time, by operators with respect to the number of particles. The spin was immediately incorporated in the quantum field theory. It was shown that the spin must have either half-integers or integers values, that the former values are associated with anticommutation rules and the latter with commutation rules, such that the wavefunctions are antisymmetric in the former case and symmetric in the latter. The first sort of particles are called fermions, the latter are bosons, and their symmetry properties have important consequences upon their statistiscs, as seen easily from counting their available states. This is the famous spin-statistics theorem of Pauli, given finally about that time.

The negative energies were seen as the absence, or destruction, of a particle, so antiparticles of opposite charge were predicted for any charged particles, related to the charge-conservation symmetry. Other symmetries, like time inversion, or parity symmetry, as welll as internal symmetries, beside the Lorentz symmetries, are basic for the quantum field theory.

The interaction of the electrons (and positrons) with the photons, *i.e.* the quantum electrodynamics, was soon established in those years, and basic interaction processes were calculated, *i.e.* their cross-section, as a first approximation of the perturbation theory. Two experimental discoveries at that time, a fine gap in the energy levels of the Hydrogen atom called the Lamb shift, and a very small anomalous deviation of the magnetic moment of the electron, forced the calculations to be performed to higher orders of the perturbation theory. Around 1950, the general scheme of such calculations has been established by Feynman with his diagrams, by Schwinger and Tomonaga with their equations, and the whole formalism was put on a rationalized basis by Dyson. The calculations showed bad infinite quantities, and divergencies, which finally were settled up by redefining the mass and the charge, as if we would start the calculations with infinite, bare of interaction, mass and charge for the electron, and would cancel such infinities along the calculations. This is the renormalization idea, and it works, with limitations. However, its rigourous and fully conducted implementation turns out to be inconsistent, as shown around 1957 by people like Landau, so our quantum electrodynamics is not the final one. The difficulties reside in the the point-like character of the electron, a plague since the old classical electromagnetism.

Current research. In the second half of the 20th century there have been discovered many things in Physics, which have not yet a full explanation. First, it came a lot of new elementary particles, especially by the investigation of the cosmic rays and by using powerful accelerators. A great advance was made in classifying them, by noticing a certain intermal symmetry related to the group SU_3. This was done by Gell-Mann, around 1960, and has no explanation. Then, it became obvious that some particles, like the nucleons, have a strong interacting force, which cannot be reduced to the electromagnetic one. In addition, many other particles, as those associated with the beta decay, interact by much a weaker force, of distinct nature, called the weak interaction. Making use of another internal symmetry, like the SU_2 group, it was possible to admit that the electromagnetism and the weak force can be given a common representation, as the electro-weak force. The strong force can itself be included formally, and we may have the Standard Model of three basic interactions in Nature: electromagnetic, strong and weak. Only gravitation is left aside. Apart from the symmetries, a new concept was instrumental in such theories, that of gauge fields introduced by Yang and Mills in 1954. On this basis there was invented the strong-force part of the theory, called the quantum chromodynamics, which assumes the existence of quarks, gluons and their non-linear interaction. Together with the leptons, like the electron for instance, such particles form the basis of all the World. The calculations are however difficult and strange concepts were admitted, like the asymptotic freedom, which means that the quarks are free in nucleons, or in the hadrons they form, but it is impossible to take them apart. The residual forces bewteen the nucleons in the atomic nucleus, which should be an output of such a theory, are still wanted. In addition, the model has about 19 (or 29) free parameters, which makes it quite impractical. In the search of unifying the World we wanted to reduce the enormous number of elementary particles to a few constituents, suceeded not much, but, in any case, ended with a more numerous number of quantum numbers and with many unknowns. We have succeeded in defining the last constituents of the matter, the quarks and the gluons, but we are not able to detect them individually, as free particles.

Meantime, it was found that basic symmetries are violated in some reactions with elementary particles, like the parity and the combined charge-parity. Many other questions arise, like the origin of the mass. The fusion reactions proposed by Bethe in the 30s as fuelling the stars were extended, and now the astrophysics struggles with various nuclear reactions which possibly may explain the creation and the existence of the Universe. Meantime, it seems that there are troubles with the matter in the Universe, which might be missing. Or it might be hidden, as a dark matter, or energy.

Ten great unsolved problems in physics. There are rumors that the following might be ten great unsolved problems in Physics: quantum gravity, the nucleus, fusion, climate change, turbulence, glassy materials, high T_c superconductivity, solar magnetism, complexity and consciousness.

The gravitational field is a field of space-time, created by matter, and moving in space-time. It reflects the way matter distorts the absolute space-time. As for any other field, the question of quantization may be posed for the gravitational field too. Weak disturbances of the gravitational field may propagate as gravitational waves, which can be quantized, under certain conditions, as gravitons. Large gravitational fields are classic objects. The propagation of any quanta, the gravitons included, in a curved space-time, the gravitational field included, are subjected to scattering, *i.e.* they are wavepackets wich may exhibit transition probabilities to any other state. This restricts considerably the question of the quantization in curved spaces, gravitational field included. The quantization in curved spaces has no meaning, or it has this meaning. Beside, there is no evidence for quanta of space-time, as the Planck length for instance.

The nuclear forces are poorly known. However, the quantum mechanics and statistical physics brought much understanding to nuclear physics, such that the knowledge of the nuclear forces might be of an academic interest only. The reason lies in the fact that the nuclear forces are strong and of very short range. Much more interesting is the saturation character of such forces.

The thermonuclear fusion aims at obtaining a dense plasma for a sufficiently long time, such as to sustain a fusion reaction with a great release of energy. In laboratory conditions this is a highly unstable phenomenon, so there are not many chances for it to exist.

Climate changes are very interesting phenomena. A semi-empirical theory could be formulated for them, such as to include dynamical patterns of an oscillatory type under various actions of external parameters. The only problem could be the large variety of behaviour.

The turbulence is a classic unsolved problem. Basically, it is governed by the viscosity of the fluids in conjunction with discontinuities, even at atomic scale.

Glassy materials are an academic curiosity, in spite of their many useful applications and long history. The amorphous solids and disordered solids exhibit, generally, localization of the electrons, nice optical properties, they are difficult to classify either as solids or liquids (for instance the windowpans flow in time to the bottom), and so on. Their own merit as a research direction is that they provide, as in many other cases, the opportunity of an extensive activity.

The high T_c superconductivity was discovered in 1987 by Bednorz and Muller in copper oxides with rare earths like La, and later on Y or Bi. The critical temperature may reach $\sim$ 160K or more. In spite of the economical advantage of using cheaper liquid nitrogen instead of the costly liquid helium, the discovery turned out not to be very fruitful, since the materials are of poor technological quality. The high critical temperature is not a very big surprise, and it may be explained by the interaction with the lattice; though other interactions, like a magnetic one, is not quite excluded. The interest arises from the unusual behaviour of such materials, in comparison with our usual experience.

Solar magnetism may be important for life on Earth, and its effects are worthier studying in this respect than the phenomenon in itself, which does not seem to reveal something deeper.

The science of complexity is based on the self-organized criticality, which means that complex systems may suffer sudden bursts of activity, all subjected to power-law distributions. It is an empirical science, which found a common name for phenomena as diverse as earthquakes, avalanches, land-slides, traffic jams, etc.

Consciousness could be a very interesting problem, as much as patterns and their recognition may have a chemical and physical background.

Why is Physics worth studying. For two reasons. First, it may give us a deeper understanding of the Natural World. That means that we may see something new, and quite general and unexpected. The mechanical motion, as well as the statistical and quantum motion, the theory of relativity, the fields, gravitation, etc, are new things, quite general, which tell us something unexpected. They may provide endless moments of thinking about the nature of the things, without reaching a definite conclusion. The great physical theories are great hypotheses, which may be continued endlessly. This is in fact the force and the "raison d'etre" of the physical research. Any physical theory may be taken again, rethought, with new sensibility, conditioned by the rest of the other theories, with a rewarding intelectual profit. The development of Physics is not linear, and the gaps between theories might be filled, the associations might be fruitful, and new insights may be gained. A logical reconstruction of any physical theory is the basic motivation of the scientific research in Physics. Leaving aside that the scientific spirit educated by Physics may profitable be used in approaching other realms of the Natural World, not yet incorporated in science (this was the case with the quantum mechanics, which tackled much chemistry; had not been Born with his analogy between atoms and the Celestial Mechanics, the quantum mechanics might have been a chapter of chemistry).

The second motivation arises from useful applications. A new material, process, phenomenon may find a useful application, and this is attractive, since it may make our life more comfortable. However, there is no direct connection between the physical research and the commercial applications of Physics. The link resides in technology, which is a domain of activity of its own, with its own principles, practices and doctrines. The connection between Physics and Technology is a very mediated one.

"In the general battle of existence it is of utmost importance to accommodate our sensations with our ideas in the most economical way", this was approximately Planck's idea of Physics.

Therefore, I would recommend as quite worth of research any problem of Physics, whatever. It is always rewarding if we can link it to other theories, if we can shed a new light upon it in accordance with our basic physical theories. It is never a lost time. The physical theories are never dead texts, they are ever living things. The physical research is to live together with the great minds' ideas about our Natural World. There is only one danger in such an endeavour. Do not accept things which cannot be thought clearly, or are not reasonably established by experiment. Such things are not from this world. This is the old indication of Descartes.

I suggest as most promising things for physical research at this moment the turbulence, the climate and more generally the environment (for instance the seismology), the physics of the living objects; the electronics, spintronics, moletronics; nanostructures; pulse processes, like thermoconductivity, electrolysis, fuell cells, solar cells and matter transport, all in pulse regime; optical waveguides in special photonic materials; field quantization in curved spaces; and "a few" many others.

And, as a permanent matter of research, I recommend the Mechanics, Elasticity and Fluids, Electromagnetism, Statistical Physics, Quantum Mechanics, Kinetic and Transport Theory, Fields and Gravity, Quantum Chromodynamics, the Standard Model, Condensed Matter and Nuclear Physics, Plasmas of all kinds (which is part of Condensed Matter), Compexity and even Consciousness.