In this issue

Why string theory?

Elementary particle physics and cosmology are among the most basic pursuits of modern science. The former pertains to questions about the fundamental structure of matter and its interactions. The latter deals with issues pertaining to the origin, evolution and the fate of the universe.

The standard model of elementary particles is the unified gauge theory of electromagnetic, weak and strong interactions. The basic building blocks of this model consist of three families of quarks and leptons, and the force carriers of the electromagnetic, weak and strong interactions. It successfully calculates with great precision all elementary particle processes up to energies of about 2×10^{11} electron volts. The distance being probed at these energies is 10^{-16} cm. The success of the standard model is a great achievement of modern science[1].

However, it is at best a phenomenological model with 20 parameters, which cannot be calculated from within the standard model and are to be fixed experimentally or calculated from a more fundamental theory. These parameters include the masses of the quarks and the leptons, the scale of electro-weak symmetry breaking, the small CP violating phase that is responsible, in part, for the fact that we see a dominance of matter over anti-matter in the universe. Incorporation of massive neutrinos remains an issue in the standard model. A more elementary question on the list of mysteries of the standard model is: why are there three families of quarks and leptons? Why not four?

Besides these numbers that await explanation, there are outstanding theoretical problems: (i) a quantitative explanation of the phenomenon of quark confinement; (ii) the ratio of the electroweak scale 10^{-16} cm to the Planck scale 10^{-33} cm (where quantum gravity becomes relevant) is a number which is very, very tiny: 10^{-17}. This hierarchy of scales needs to be explained. (It is not clear whether this is a real problem or whether it parametrizes our ignorance of new physics beyond the standard model.)

For all these reasons, the standard model is not a fundamental theory. Its outstanding quantitative and qualitative problems cry out for a more basic theory. The minimal supersymmetric extension of the standard model (with soft supersymmetry breaking at a scale of 10^{-17} cm) addresses the hierarchy problem. It also has the attractive feature to unify all the three interactions at 10^{-30} cm. However, it is also a phenomenological theory with many more parameters that cannot be calculated within its framework.

The experimental future of high-energy particle physics rests on the Tevatron at Fermilab and experiments at the proposed Large Hadron Collider (LHC) at CERN (Geneva). LHC will probe nature up to 10^{-21} cm. Here one hopes to find the elusive Higgs particle of the standard model and supersymmetry. Of course, surprises will be welcome! Various neutrino laboratories are very likely to provide important input into theory. Experiments that probe millimeter-scale gravity in search for higher dimensions, may also throw valuable light on whether the Planck scale is really so far removed from the electro-weak scale. If so, then we may see the opening up of new space dimensions[2].

Let us now turn to the standard model of cosmology which is based on the general theory of relativity. It incorporates the fact that the universe began with a big bang, and then approximately after 10^{-36} s, it inflated by 30 orders of magnitude to an enormous size. Several ingredients of the standard model of cosmology are not on as firm a footing as in the standard model of matter. Even so, it successfully explains various features about the evolution of the universe from very early epochs. Besides being a successful basis of cosmology, general relativity has been verified to a great accuracy. Its predictions match experiment to within one part in ten-thousand. The validity of the general theory is from centimetre scale to almost the edge of the visible universe which is 10 billion light years[3].

However, general relativity is not consistent with quantum mechanics. Perturbation theory about flat space (our world!) is divergent due to virtual high-energy effects. The problem cannot be redressed in the way the divergences of gauge theories are cured by the renormalization procedures originally invented for quantum electrodynamics by Feynman, Schwinger and Tomonaga and extended to non-abelian gauge theories by 't Hooft, Veltman, Gross, Wilczek and Politzer[4].

This means that general relativity does not provide a framework to discuss phenomena at very high energies and at very high curvatures. The scale of energy and curvature is set by the Planck length (10^{-33} cm). These phenomena include the beginning of the universe and the black-hole singularity. The surprise is that general relativity is inconsistent with quantum mechanics not only at high energies, but also at low energies in the presence of black holes! This is called the information paradox.

Another well-known problem is that of the cosmological constant. The models of elementary particle physics have phase transitions. An example is the phase transition to a phase where electromagnetism and the weak force are not unified, but are distinguished by the weak force becoming short range, while the electromagnetic force continues to have infinite range. This electro-weak phase transition is expected to happen when the universe is approximately 10^{-12} s old and, according to current thinking, it would have released a vacuum energy with density 10^{47} ergs/cm^3. Cosmological observations however imply a bound $< 10^{-10}$ ergs/cm^3. How does one reconcile this[5]? More recent observations seem to indicate that the universe is accelerating rather than slowing down. This requires a positive cosmological constant and the universe is described by a de Sitter space–time. It seems that such a space–time is not consistent with quantization[6]!

Our discussion so far was intended to make the case that even though our present theories of matter and the universe are impressive edifices, there are deep and important consistency issues that arise within the existing framework of quantum field theory and general relativity. In fact, such a circumstance motivates a genuine need for a new theoretical framework that unifies a consistent quantum theory of gravity with a theory of elementary particles, while retaining the established features of both.

It is becoming increasingly clear that string theory is such a candidate theory. Gravity is a prediction of string theory. String theory provides a consistent theory of quantum gravity and also a model for the theory of matter, which has most of the qualitative features of the standard model. String theory is far from complete and it is a theory in the making. We only know bits and pieces of the theory, like the peaks of mountains that appear above a thick canopy of clouds[7]. Very little is known about the massive beneath, except that it exists! This massive is called *M*-theory. *M* stands for meta, magic, mystery, matrix, etc.

When one considers important epochs in the history of physics since the mid-19th century, progress has been made by resolving contradictions between existing theories. Let us state these happenings, briefly. Maxwell unified the distinct and contradictory equations of electricity and magnetism into a consistent set of equations by adding the displacement current term to the Biot–Savart law. These consistent equations for the electromagnetic field predicted the existence of electromagnetic waves that travel at a finite speed ($c = 3 \times 10^{10}$ cm per s). The experimental success of Maxwell's theory raised questions about the consistency of the Newtonian framework of physics, which in hindsight was based on the assumption that the speed of light is infinite. The resolution lay in Einstein's special theory of relativity. Then Einstein grappled with the issue of the consistency of Newton's (instantaneous) law of gravitation and the special theory of relativity. The resolution lay in his serendipitous discovery of the general theory of relativity which explained gravity as a space–time warp caused by matter. In another stream, Maxwell's electrodynamics (where accelerating charges radiate) conflicted with the observed stability of atoms. Resolving this and other difficulties eventually led Heisenberg, Schrodinger and Dirac to the discovery of quantum mechanics, which is the basic framework for nature's processes in the small.

However there is one important difference between the historical instances we have recalled and the present situation. While in the previous instances the resolutions were amenable to experimental verification, within reasonable time, the direct experimental verification of any theory of gravity consistent with quantum mechanics may happen only at the presently inaccessible Planck scale. Indirect tests would therefore be very useful. In fact since *M*-theory is a theory in the making, one is hoping for helpful hints from accelerator and neutrino laboratories and also from the various outer-space probes that are expected to deliver a wealth of astronomical data in the coming decades.

With little direct guidance from experiment, the quest for a unified theory of elementary particles, gravity and cosmology is being guided by mathematical consistency and also more subjective notions like simplicity and beauty of the concepts involved. In this endeavour, one is encouraged by the histories of the discovery of general relativity, non-abelian gauge theories and the very idea of unification of interactions. In a future write-up one is likely to add supersymmetry and *M*-theory to this list of theoretical ideas whose experimental verification came only later on[8]!

The articles in the special section on string theory (**pages 1547–1616**) present a broad cross-section of the various directions of pursuit in search for this fundamental theory.

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1. See Wilczek, F., 'Future Summary', xxx.lanl.gov/form/hep-ph, Number 0101187.
2. See the contribution of Antoniadis, I., in this issue.
3. The Confrontation between General Relativity and Experiment, Will Clifford, in *Living Reviews in Relativity*; www.livingreviews.org/Articles/Volume4/2001-4will/index.html.
4. 't Hooft, G., *Rev. Mod. Phys.*, 2000, **72**, 333–339; Gross, David, *Twenty Five Years of Asymptotic Freedom*, xxx.lanl.gov/form/hep-th, Number 9809060.
5. Witten, E., *The Cosmological Constant from the View Point of String Theory*; xxx.lanl.gov/form/hep-ph, Number 0002297.
6. Witten, E., *Quantum Gravity in de Sitter Space*, xxx.lanl.gov/form/hep-ph, Number 0106109.
7. This metaphor has been used in a different context by Witten, E. in his article, in *Mathematics: Frontiers and Perspectives* (eds Arnold, V. *et al.*), American Mathematical Society, 1999.
8. Autobiographical Notes of Albert Einstein, in *Albert Einstein: Philosopher-Scientist* (ed. Schilp, P.), Tudor, New York, 1949; Dirac, P. A. M., ICTP Lectures *From a Life of Physics*, 1968; Chen Ning Yang, *Selected Papers with Commentary*, W. H. Freeman and Co, 1983; Weinberg, Steven, *Dreams of a Final Theory*, Vintage, 1988; Reminiscences by Bunji Sakita, in *A Quest for Symmetry, Selected Works of Bunji Sakita* (eds Kikkawa, K., Virasoro, M. and Wadia, S. R.), World Scientific, 1993; see also xxx.lanl.gov/form/hep-th, Number 0006083.

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Aerosol spectral optical depths

During the last few decades it has become increasingly clear that human activity – industries, power generation, use of automobiles, etc. – has reached a level where it could be having potentially serious implications to the global climate system. Increase in carbon dioxide concentration in the atmosphere is an example. Another, not as well known, is the increase in man-made microscopic liquid and solid particles, aerosols, in the atmosphere. Their impact on climate is complex and depends on a number of factors, such as the particle size, chemical composition and distribution in the atmosphere. Sources of man-made aerosols include factory emissions, auto exhausts, and agricultural burning. While some aerosols reflect or scatter solar radiation, others absorb it, leading to warming of air around them. Some aerosols also absorb and emit infrared radiation back to the earth's surface leading to warming of the air near the surface at night. However, in most cases the net effect of man-made aerosols is to cool the surface.

What are the characteristics of man-made aerosols over and around India? Recently concluded Indian Ocean Experiment (INDOEX) gathered data on aerosols over the equatorial Indian Ocean and over the Arabian Sea. Programmes sponsored by the Indian Space Research Organization have been gathering data on aerosols over India. In this issue S. K. Satheesh *et al.* (**page 1617**) report the first aerosol-related optical measurements over the Bay of Bengal. The authors identify origin of the aerosols over the bay, and compare their characteristics with those found elsewhere. Their findings are important because the bay is important. Processes over the bay play a major role in sustaining activity of the Indian Summer Monsoon. The data reported by the authors improve the database on this region that is crucial to understand the monsoon.

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