Quantum field theories have had great success in describing elementary particles and their interactions, and a continual objective has been to apply these successful methods to gravity as well.

The natural length scale for quantum gravity to be important is the Planck length, $l_p = 1.6 \times 10^{-33}$ cm. The corresponding energy scale is the Planck mass, $M_p = 1.2 \times 10^{19}$ GeV. At this scale the effect of gravity is comparable to that of other forces and is the natural energy for the unification of gravity with other interactions. Evidently this energy is far beyond the reach of present accelerators. Thus, at least in the near future, experimental tests of a unified theory of gravity with the other interactions are bound to be indirect.

When we try to quantize the classical theory of gravity, we encounter short-distance (high-energy) divergences (infinities) that cannot be controlled by the standard renormalization schemes of quantum field theory. These have a physical meaning: they signal that the theory is only valid up to a certain energy scale. Beyond that there is new physics that requires a different description.

**Quantum gravity**

Such a phenomenon is not unfamiliar. The short-distance divergences of Fermi’s original theory of the weak interactions (with four particles meeting at one space-time point) signal that the description is only valid for energies less than the masses of the W and Z carrier particles. The divergences are resolved by introducing these particles in the Glashow–Salam–Weinberg theory.

We expect that the divergences of quantum gravity would similarly be resolved by introducing the correct short-distance description that captures the new physics. Although years of effort have been devoted to finding such a description, only one candidate has emerged to describe the new short-distance physics: superstrings.

This theory requires radically new thinking. In superstring theory, the graviton (the carrier of the force of gravity) and all other elementary particles are vibrational modes of a string (figure 1). The typical string size is the Planck length, which means that, at the length
Two important features of string theory are implied by the consistency requirement. First, superstring theory is consistent only in 9+1 space-time dimensions. This seems to contradict the fact that the world that we see has 3+1 space-time dimensions. Second, there are five consistent superstring theories: Type IIA, Type IIB, Type I, $E_8 \times E_8$ Heterotic and SO(32) Heterotic. Type I is a theory of unoriented open and closed strings; the others are theories of oriented closed strings. Which should be preferred?

All five possess supersymmetry, hence the name superstrings. According to supersymmetry theory, any boson (integer spin particle) has a fermionic (half-integer) superpartner and vice versa. One way to view supersymmetric field theories is as field theories in superspace – a space with extra fermionic quantum dimensions. Many physicists expect that supersymmetry exists at the tera electron volt scale, so that the new ‘superpartner’ particles could be seen by CERN’s LHC proton collider.

**Compactification and stringy geometry**

The time and the three spatial dimensions that we see are approximately flat and infinite. They are also expanding. Just after the Big Bang they were highly curved and small. It is possible that while these four dimensions expanded, other dimensions did not expand, remaining small and highly curved.

Superstring theory says that we live in 9+1 space-time dimensions, six of which are small and compact, while the time and three spatial dimensions have expanded and are infinite.

How can we see these extra six dimensions? As long as our experiments cannot reach the energies needed to probe such small distances, the world will look to us 3+1-dimensional and the extra dimensions can be probed only indirectly via their effect on 3+1-dimensional physics. It is not known at what energies the hidden compact dimensions will open up. The possibility that new dimensions or strings will be seen by the LHC is not ruled out by the current experimental data.

Superstring theory employs the Kaluza-Klein mechanism to unify gravitation and gauge interactions using higher dimensions. In such theories the higher dimensional graviton field appears as a graviton, photon or scalar in the 3+1-dimensional world, depending on whether its spin is aligned along the infinite or compact dimensions.

The number of consistent compactifications of the extra six coordinates is large. Which compactification to choose is the prize question. The answer is hidden in the dynamics of superstring theory. Using a limited (perturbative) framework, one can attempt a qualitative study of the 3+1-dimensional phenomenology obtained from different compactifications. It is encouraging that some of these compactifications result in 3+1-dimensional models that have qualitative features such as gauge groups and matter representations of plausible grand unification models. Interestingly the low-mass fermions appear in families, the number of which is determined by the topology of the compact space.

**T-duality**

Not all of the compactifications are distinguishable. To illustrate this, take one spatial co-ordinate to be a circle of radius $R$. There are two types of excitations. The first, which is familiar from theories of point-like objects, results from the quantization of momentum along the circle. These are called Kaluza-Klein excitations. The second type arises from the closed string winding around the circle. These are called winding mode excitations. This is a new feature that does not exist in point-like theories. When we map the size of the radius, $R$, of the circle to its inverse, $1/R$, with the string scale set to one, the two types of excitations are exchanged and the theory remains invariant. There is no way to distinguish the compactification on a circle of radius $R$ from a compactification on a circle of radius $1/R$. This means that the classical geometrical concepts break down at short
distances and the classical geometry is replaced by stringy geometry.

In physical terms, this implies a modification of the well known uncertainty principle. The spatial resolution, $\Delta x$, has a lower bound dictated not just by the inverse of the momentum spread, $\Delta p$, but also by the string size. The mapping of the radius of the compactification to its inverse, exchanging Kaluza-Klein excitations with winding modes, is called T-duality.

Another example of stringy geometry is "mirror symmetry". In the previous example, both circles had the same topology and different sizes. In contrast, mirror symmetry is an example of stringy geometry where two six-dimensional spaces, called Calabi-Yau manifolds, with different topology are not distinguishable by the string probe.

String duality and M theory
To select the "best" theory, we have to introduce the idea of S-duality. Consider a strongly coupled physical system. There may be another set of variables in which the system is weakly coupled. The transformation from one set of variables to the other is called S-duality. In practice it is usually impossible to find the exact change of variables from the strongly coupled degrees of freedom to the weakly coupled ones. Unlike T-duality, S-duality is non-perturbative. This prevents us from proving it, but we can accumulate enough evidence to convince ourselves of its existence.

A major discovery is that all five consistent string theories are related by dualities such as T- and S-dualities. This puts the five string theories in a unified framework - they are equivalent descriptions of the same physical system with different variables.

Figure 2 describes the parameter space of string theories - the edges are points where the corresponding string is weakly coupled. In the interior the coupling is generically of order 1. One additional item in figure 2 is 11-dimensional M theory, which at low energies is described by 11-dimensional supergravity, a supersymmetric theory including gravity.

Unlike string theory, M theory does not have a coupling constant. It is reduced under various compactifications to the five string theories. As an example, consider M theory compactified on a circle of radius $R$. This is dual to Type IIA string theory with the string coupling proportional to $R$. The strong coupling limit of 10-dimensional Type IIA string theory corresponds to a large $R$ and, amazingly, another dimension opens up, so that it is described by 11-dimensional theory.

Not much is known about M theory. With no coupling constant there is no systematic perturbative expansion. One attempt to provide a non-perturbative definition is Matrix Theory, based on supersymmetric quantum mechanics of infinite matrices.

Strings and quantum black holes
Classical black holes are completely black, swallowing whatever crosses their event horizon and emitting nothing. Hawking argued that quantum black holes emit radiation. This raises a long-standing puzzle. We can start with a pure quantum state to form a black hole and end with a mixed state of thermal radiation. This contravenes the basic rules of quantum mechanics. Black holes also carry entropy proportional to their event horizon. To understand these features of black holes requires a quantum theory of gravity, and string theory provides such a framework. The entropy of the black hole is a measure of how many quantum states it has. For certain black holes these can be identified as D-branes - non-perturbative excitations of string theory on which open strings can end. (D-branes provide Dirichlet boundary conditions for the strings; figure 3.)

Open strings have gauge fields, so the D-branes define a gauge theory. There is a class of black holes made of D-branes, and these have a gauge theory description. The closed strings define a field theory of gravity.

Strings and gauge theories
For an ordinary quantum field theory of a physical system in a volume $V$, the number of degrees of freedom is proportional to the volume.

A quantum theory of gravity is believed to possess a remarkable property called holography, which was introduced by Gerard 't Hooft and Leonard Susskind. Here the number of degrees of freedom of a quantum gravitational system in volume $V$ is expected to be proportional to the area of the boundary of the volume. This means that the physics of a quantum gravitational system in $d+1$ dimensions is coded in a holographic way in $d$ dimensions. As in an optical hologram, the information is coded in a complicated way.

Because string theory is our candidate for a theory of quantum gravity, it should exhibit such holography. This has been realized recently in Matrix Theory, and for strings on certain spaces with negative cosmological constant, known as Anti de Sitter spaces. "Holograms" are located on the boundaries of these spaces. In both cases the hologram that encodes the quantum gravity properties is a gauge theory. Remarkably, the secrets of the evaporation of quantum black holes are hidden in such a hologram – the strong
Quantum gravity

On one hand the theory of D-branes is a gauge theory. On the other, D-branes are massive objects that curve the space-time in which they are embedded. The consideration of the D-branes from these two viewpoints led to a conjecture by Juan Maldacena (Harvard) on the duality between gauge theories and string theory on Anti de Sitter spaces.

Of particular interest is the equivalence between gravity in five dimensions and gauge theory in four. The additional fifth dimension corresponds to the energy scale of the four-dimensional quantum field theory. Just as theories of three spatial dimensions and one of time became four-dimensional space-time theories, we may be led to add the energy scale and have five natural co-ordinates.

The duality conjecture has been extended by Ed Witten to non-supersymmetric gauge theories, such as pure quantum chromodynamics (QCD) - the field theory of gluons. The Anti de Sitter spaces are now replaced by Anti de Sitter black holes. When the gravitational background is regular, the supergravity approximation of string theory can be used and exhibits the required properties of QCD, such as the colour confinement of quarks. To study QCD quantitatively requires singular gravitational backgrounds, and it seems that the key to long-standing questions, such as computation of the hadron spectrum, is hidden in the geometry of string theory.

**Unification**

In the supersymmetric extension of the Standard Model, the strong and electroweak gauge couplings seem to unify at an energy of \(10^{16}\) GeV. The gravitational coupling does not unify with the others at this energy. Traditionally it is expected to unify at the Planck scale.

There is, however, another interesting possibility. The energy dependence of the gravitational coupling can be changed by using the extra dimensions. The unification energy of the gravitational coupling can be lowered if, as in the D-brane physics of figure 3, the gauge fields live in 3+1 space-time dimensions while the gravity also propagates in the other dimensions.

This can dramatically change the scales of string physics. The string scale cannot be less than 1 tera electron volt because string excitations have not been observed by accelerators. It is possible, however, that the string scale is at the tera electron volt scale, and that string excitations will be seen by the LHC. The compactification scale - the size of the largest compact dimension - can be even lower. Amazingly, it can be millimetre-sized.

Although this seems to be in contradiction with laboratory experience, in fact this is not the case. The gauge fields do not propagate in the compact dimensions, so they do not have Kaluza–Klein excitations. There are Kaluza–Klein excitations from the closed strings in figure 3, but they are weakly coupled and could not be observed. Larger dimensions are ruled out by experiments measuring gravitational effects at short distances.

The extra dimensions can be used to lower the unification energy so that a complete unification of all forces can occur already at tera electron volt energies.

Yaron Oz, CERN.

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