The holes are defined by the string

Edward Witten

Must general relativity finally bow to quantum mechanics? Calculations that describe black-hole properties using collections of superstrings have gone some way towards resolving one of the most vexing puzzles in physics.

ACCORDING to Einstein's theory of general relativity, if a sufficiently large mass collapses into a sufficiently small space, a black hole is formed. To the extent that quantum-mechanical effects can be neglected, a black hole has the property that nothing, not even a light ray, can escape from it. That explains the name: an isolated black hole looks literally like a black hole in space, from which no light emerges.

Although classical black holes do not emit anything, they absorb anything that comes near enough. When an object falls into a black hole, its entire rest energy — Einstein's $E=mc^2$ — can potentially be released in the form of radiation, which can escape and be seen by a distant observer. Therefore, although an isolated classical black hole is altogether dark, if a black hole is embedded in a suitable astrophysical environment, the region just outside the hole can shine brilliantly. This has made it possible for astrophysicists to identify candidate black holes both in our Galaxy and in distant quasars.

Black holes are also a fascinating test case for trying to combine quantum mechanics and general relativity. Physicists have found it vexingly difficult to unify, or even reconcile, these two theories. The problems are hard to explain in non-technical terms, but they are definitely there: the delicate constructions that are required in quantum field theory (the most fully known expression of quantum mechanics) seem incompatible with the requirements of general relativity. The contradiction between quantum mechanics and general relativity — which together are the basis for what we know of the fundamental laws of nature — is generally seen as a central challenge in physics, to say the least. Physicists have sought to meet this challenge through the new framework of string theory, about which we will say more later.

When one tries to think about black holes quantum mechanically, one runs into many difficulties. At the most basic level, quantum-mechanical unitarity (the requirement that the probabilities of all possible outcomes add up to one) does not permit the existence of an object that can absorb matter but cannot emit matter. This particular question was addressed 20 years ago by Stephen Hawking, who showed that, quantum mechanically, an isolated black hole is not completely black, but emits radiation at a rate which is proportional to Planck's constant h (and so the rate is zero in the absence of quantum mechanics)[1].

Following earlier heuristic work by Jacob Bekenstein[2], Hawking's discovery led to the idea that a black hole has a certain temperature and entropy at the quantum-mechanical level (generally, entropy is a measure of disorder; in standard quantum systems, it is the logarithm of

Circling the inverse square

ONE bit of physics that almost everyone knows is that the force between two electric charges, or two masses, follows an inverse square law. That is, if they are separated by a distance r then the force between them is proportional to r^{-2}.

If one takes the inverse square law seriously, one must face the fact that the force becomes infinite as r goes to zero. Early in this century, physicists realized that a classical electron orbiting an atomic nucleus should emit electromagnetic radiation and spiral into the nucleus in a finite time, driven by the singularity of the r^{-2} force at small r.

From grappling with this contradiction, quantum mechanics was born. By the mid-1920s, the Schrödinger equation gave a sensible description of atoms at the non-relativistic level. The quantum uncertainty principle effectively smeared out the electron and prevented it from seeing the singularity.

Extending this success to take account of special relativity was more difficult. It was necessary to develop quantum field theory, quantum electrodynamics and the renormalization theory (a systematic procedure for subtracting the infinities created by the inverse square law) of Feynman, Schwinger, Tomonaga and Dyson. Finally, by about 1950, a satisfactory account of atoms could be made, including the effects of both quantum mechanics and special relativity.

A natural hope was that having understood how to treat the r^{-2} force between electric charges, one could treat the r^{-2} gravitational force similarly. That hope was frustrated: because of the nonlinear mathematics used in general relativity, the new concepts that enabled physicists to cope with electromagnetism fail dismally for gravity.

And so we face a contradiction between quantum field theory and general relativity similar to the contradictions that led to quantum mechanics. Many physicists believe that this contradiction contains the seeds of an upheaval as profound in its own way as the discovery of quantum mechanics or relativity.

String theory is the one concrete proposal for a new framework in which the r^{-2} force of quantum gravity is tamed. In string theory, elementary particles are re-interpreted as small loops of vibrating string. Their 'stringiness' gives a new kind of uncertainty, which plays a role analogous to that of the quantum uncertainty principle, and avoids the r^{-2} singularity. As a result, gravity becomes compatible with quantum mechanics. In fact, when physicists began, more than 25 years ago, to develop string theory, they unearthed a remarkably rich and subtle structure and learned to their amazement that gravity is *required* for the consistency of string theory. So one may fairly say that pre-string quantum theory makes gravity impossible, whereas string theory makes it necessary.

Even after 25 years, the understanding of string theory is in its infancy, and surprises are the norm. It was believed for many years that there were five possible string theories, prompting the question: if one of these theories describes our Universe, who lives in the other four worlds? But recently it has become clear that those five string theories are limiting cases of one majestic and still-mysterious theory. This theory, which is sometimes called M-theory (according to taste, M stands for magic, mystery, marvel or membrane) is seen by many as a likely candidate for a complete description of nature. E. W.