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.

the number of states). For a typical astrophysical black hole, the Bekenstein–Hawking temperature is unobservably small, whereas the Bekenstein–Hawking entropy is huge — much bigger than the entropy of an ordinary star, for instance — and difficult to interpret.

While Hawking's result perhaps eliminated the most naive paradox posed by quantum-mechanical black holes, many apparent contradictions remain. Speculations about how the puzzles will ultimately be resolved have ranged all over the map. At the risk of some oversimplification, two main competing points of view are as follows:

(1) Quantum mechanics as we know it does not work for black holes. Some modification of quantum mechanics will be necessary to understand them.

(2) Black holes will ultimately turn out to obey the standard laws of quantum mechanics. The Bekenstein–Hawking entropy of a black hole — like the entropy of any other quantum-mechanical system — will turn out to equal the logarithm of the number of quantum states of the black hole.

To make progress on these questions, one needs a theory that consistently combines quantum mechanics and general relativity, because the whole issue concerns the application of quantum mechanics to a general-relativistic object, the black hole. The only real candidate for reconciling quantum mechanics and general relativity is string theory, which has been intensively developed in recent decades with the hope of obtaining a more unified understanding of natural law. In this framework, the fundamental objects are tiny strings, which do not produce the awkward infinities thrown up by the point-like particles of conventional physics. Surprisingly, when particles are replaced by strings, gravity is an inevitable consequence.

In practice, though, the development of string theory has shed very little light on black holes until the past few months. String theory is very imperfectly understood, and until recently it has only been possible to calculate quantum gravity effects when those effects are small, which is not the case in the context of black holes.

But since the spring of last year, in an upheaval sometimes called 'the second superstring revolution', physicists have begun to learn what happens in string theory when the quantum gravity effects are big. It turns out that 'dualities' — mysterious symmetries that generalize the relationship between electricity and magnetism to other forces — play an important role here. Perhaps the biggest resulting surprise has been that, as we now understand it, there is only one string theory. The five or six different theories that have been developed and studied independently are — it is now clear — all equivalent. They are different formulations of the same, still rather mysterious theory, each formulation being most useful in its own regime.

Lately, the new techniques have been applied to black holes, shedding at least a bit of light on the old mysteries. In a paper published in June, Andrew Strominger and Cumrun Vafa[3] succeeded in counting the number of quantum states of certain black holes (carrying appropriate electric and magnetic charges) using string theory. String theory is crucial because without a microscopic theory of quantum gravity, one would have no idea where to begin in order to count the quantum states of a black hole. Technically, the Strominger–Vafa computation depended on the fact that, without changing the number of quantum states, a black hole can be deformed into a collection of 'D-branes', exotic objects that we now understand have an important role in string-theory dualities[4]. Counting of D-brane states is a well-honed art, and the relation of black holes to D-branes made the counting of black-hole states possible.

The main result of the Strominger–Vafa computation was that the logarithm of the number of quantum states did coincide with the Bekenstein–Hawking entropy — as it should, if conventional quantum mechanics applies to black holes. The Strominger–Vafa computation was soon followed by a variety of others (refs 5–8, for example) in which the Bekenstein–Hawking entropy was compared with the number of quantum states for black holes with different angular momentum or charge, or in different dimensions of space-time. In many of these instances the classical black-hole solution was not known before the string theory computation was performed, but ultimately one finds agreement between the Bekenstein–Hawking entropy and the counting of quantum states.

These computations have given striking support to the view that black holes obey the standard general principles of quantum mechanics. But quantum black holes remain extraordinary and mysterious in many ways. Ambitious proposals concerning a new kind of black-hole 'complementarity'[9] (echoing the more familiar complementarity of quantum and classical physics) and a holographic interpretation of the Universe[10,11] give hints of how little we understand, even now. ☐

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NEUROPSYCHOLOGY

Pictures, words and the brain

Alfonso Caramazza

OVER the past few years cognitive neuroscientists have made great strides in charting the functional organization of the human brain. These developments have been made possible by increasingly sophisticated functional neuroimaging techniques, such as positron-emission tomography and functional magnetic-resonance imaging, which provide an index of neural activity in different areas of the brain during the performance of a cognitive task. Several notable contributions have been made by scientists at the National Institute of Neurology, London, who have concentrated largely on the neural representation of language processes. On page 254 of this issue[1] they describe their latest result, and it is an important one — a map of the areas of the brain that are involved in processing the meaning of words.

Until recently, virtually all that was known about the neural basis of language came from the study of neurologically impaired patients. By investigating the disorders in language and cognition that are associated with specific forms of brain damage, neurologists and neuropsychologists have been able to chart the functional organization of the human brain. For example, it has been shown that damage to specific regions of the left frontal lobe frequently results in a deficit restricted to processing the syntactic structure of sentences[2]; and that damage to the medial and inferior parts of the left temporal lobe is often associated with a deficit in retrieving words but not in processing syntactic structure[3]. These and other such aphasic disorders have been used to chart the functional organization of syntactic and lexical processes in the brain.

The performance of neurologically impaired patients has also been used to inform theories of the representation of word meaning in the brain. Study of a disorder known as optic aphasia, which was first described near the end of the last