

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<sup>3</sup> 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<sup>4</sup>. 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'<sup>9</sup> (echoing the more familiar complementarity of quantum and classical physics) and a holographic interpretation of the Universe<sup>10,11</sup> give hints of how little we understand, even now. □

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## NEUROPSYCHOLOGY

# Pictures, words and the brain

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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<sup>1</sup> 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<sup>2</sup>; 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<sup>3</sup>. 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

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