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

century, has been especially prominent in this context. This disorder involves a selective difficulty in naming visually presented objects, with no corresponding difficulty in naming by touch or in response to verbal definitions. The modality-specific nature of the difficulty cannot be attributed to a deficit in low-level visual processing because the patients can copy the objects they are unable to name, and can even provide accurate mimes for their use.

One interpretation of optic aphasia is that it reflects a disconnection between two semantic systems: one representing visual information and accessed directly only by objects and pictures, the other representing verbal information and accessed only by words[4,5]. In this framework, the visual semantic system represents the visual properties of objects, for example the fact that tables have legs and a flat surface, and the verbal semantic system represents functional/associative properties of objects, for example the fact that tables are furniture and are used for eating and writing (a in the figure). A related claim, also based on the performance of optic aphasics, is that verbal semantics is represented only in the left hemisphere, but visual semantics is represented in both the right and the left hemisphere[6]. However, the neuropsychological evidence is also consistent with the view that semantic knowledge is organized as a functionally (though not necessarily neuroanatomically) unitary system in the left hemisphere, and that it can be accessed directly and independently by both words and visual objects (b in the figure)[7,8]. The significance of the new study reported by Vandenberghe et al.[1] is that it provides the evidence needed to choose between the two theories.

The authors measured neural activation, by means of positron-emission tomography, in subjects engaged in semantic processing of pictures and words. One task involved making semantic judgements about visual and the other about functional/associative attributes of concepts. There were three main results: first, there is considerable overlap in the areas activated during semantic processing of pictures and words; second, these areas are distributed widely in the left hemisphere, including regions of the frontal, temporal, parietal and occipital cortices; and third, there are some areas that show activation only in response to pictures or words, but these are not likely to be modality-specific semantic systems because the activation is not specific to a type of semantic content.

This last point is important. The multiple semantics theory predicts that the activation of modality-specific semantic systems depends on the type of information being queried: perceptual for visual semantics, and functional/associative for verbal semantics. But the areas that
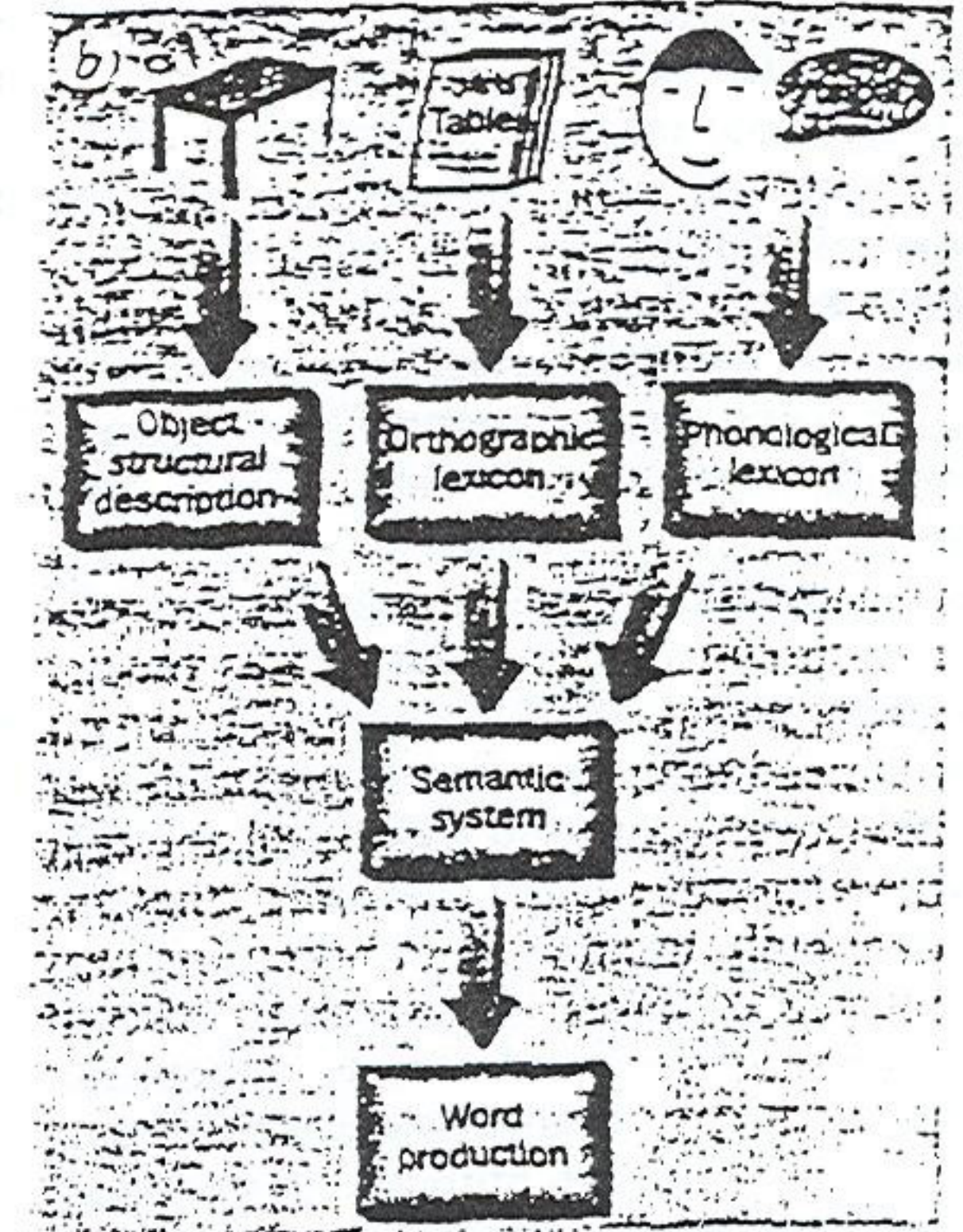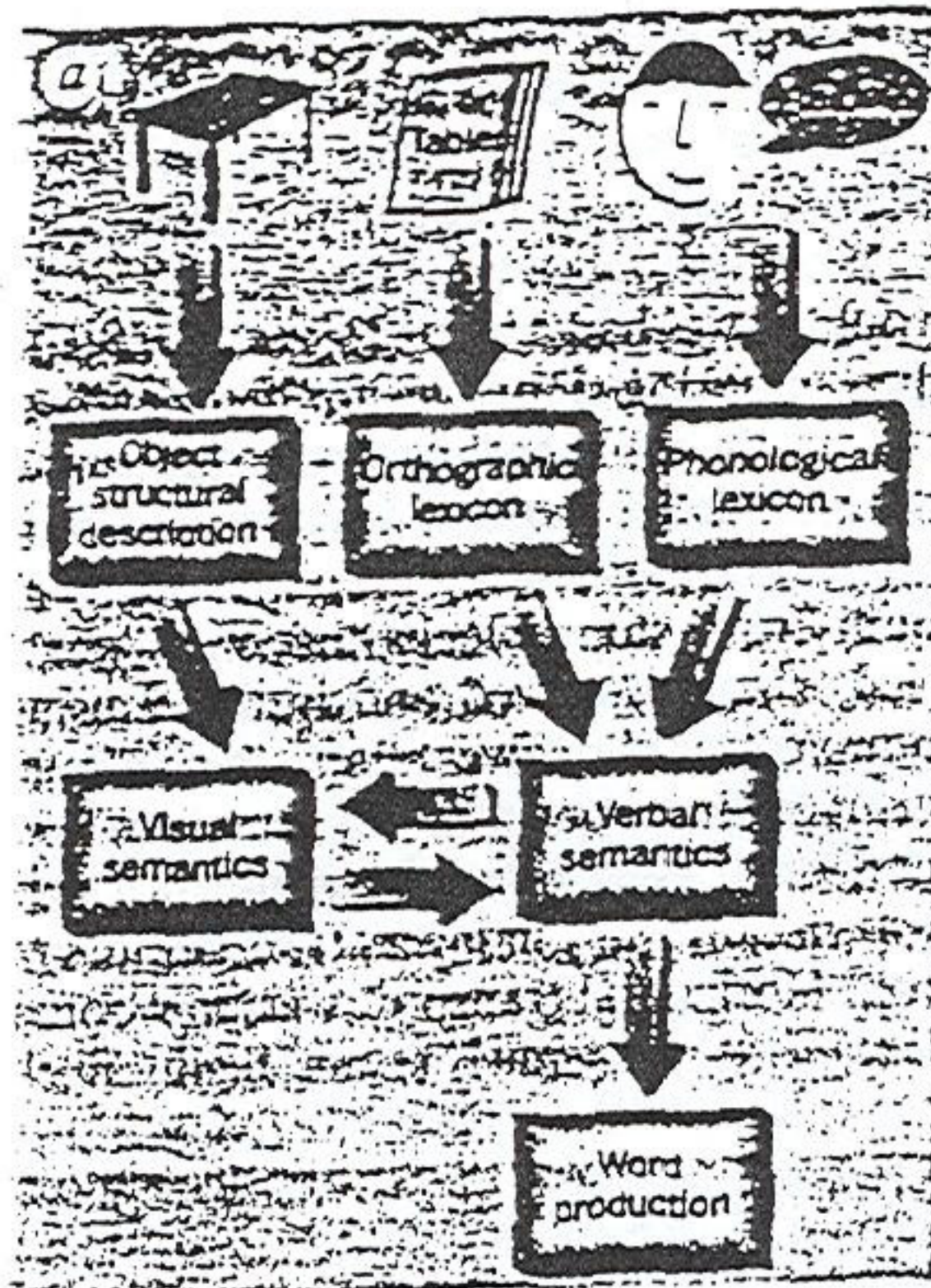
Two theories of the relationship between components of the lexical processing system. a, The multiple semantics theory, which assumes that the representation of meaning is organized into two modality-specific systems — a visual and a verbal semantic system, each of which is accessed directly only by visual objects and words, respectively. Similarly, language production necessarily goes through the verbal semantic system. The visual semantic system represents only those properties of objects that are acquired through the visual modality; the verbal semantic system represents those properties of objects that are acquired through spoken and written language. In this framework, the neurological disorder optic aphasia is thought to reflect a disconnection between intact visual and verbal semantic systems. b, The unitary semantics theory, which assumes that meaning is represented in a functionally unitary system, accessed directly by both visual objects and words. In this framework, optic aphasia is thought to reflect a disconnection between intact neural mechanisms for the recognition of objects and the semantic system.

showed selective activation for type of stimulus (picture or word) did so for both visual and functional/associative judgements. This result shows that the areas selectively activated for pictures and for words are not modality-specific semantic systems but neural mechanisms involved in the recognition of pictures and words, respectively.

Vandenberghe et al. show that a functionally unitary semantic system — that is, one that is accessed directly by both words and pictures — is represented in a distributed form in the left hemisphere. But an important question remains unanswered: are the different regions functionally homogeneous, or do they represent different aspects of meaning? This question is especially relevant in the light of neuropsychological evidence showing that brain damage can selectively affect different semantic categories[9] (for example, difficulty in naming and understanding animal words but not tools or vehicles), as well as functional neuroimaging results showing that different regions of the left hemisphere are activated by different semantic categories[3,10]. These results indicate that the semantic system is not functionally homogeneous, but its organizing principle remains unclear.

Another issue concerns the relation between semantic knowledge and other aspects of lexical processing. How is the spatially distributed semantic system related to information about word forms

(that is, the sound and spelling of words) and their grammatical properties (for example, the fact that a word is a noun)? Are different parts of the semantic system differentially related to different aspects of lexical knowledge? Here, too, the answers have yet to emerge. Nonetheless, it is clear that we are entering an exciting new phase in the study of the human brain: functional neuroimaging studies are already providing answers to century-old questions and promise to answer increasingly finer-grained questions about the organization of language processes in the brain. □

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