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From metaphors to models: the use of analogy in neuropsychology

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Many scientists feel uncomfortable with the explicit use of analogy in their work. Brain scientists are no exception: They want to understand the results of their experiments solely in terms of those results. This may be possible when data concern one level of inquiry, but it becomes infeasible whenever an attempt is made to relate several levels of inquiry, as in neuropsychology. In such instances, some metaphor, analogy, or model often serves as a useful tool for organizing the relationships among data so that they reflect the organization of data at adjacent levels of inquiry.

Brain scientists have, in fact, repeatedly and fruitfully used metaphors, analogies, and models in their attempts to understand their data. The theme of this essay is that *only* by the proper use of analogical reasoning can current limits of understanding be transcended. Furthermore, the major metaphors used in the brain sciences during this century have been provided by inventions that, in turn, were produced by brains. Thus, the proper use of analogical reasoning sets in motion a self-reflective process by which, metaphorically speaking, brains come to understand themselves.

Analogical reasoning in science typically begins with metaphors that are only loosely coupled to the data to be organized and ends ideally by furnishing precise models of the fit of those data to the type of organization suggested by the original metaphor. This essay provides examples of how this process has worked and is working in the field of neuropsychology. Specifically, it reviews the influence of metaphors taken from

telecommunications, control systems engineering, computer science, and holography.

First, however, a qualification is in order. The kind of understanding often achieved by metaphor – what we might call existential understanding – is not the kind that is the goal of science. When I listen to a symphony or feel the intimacies of a relationship or enjoy a good meal, I experience a sense of tacit understanding of the symphony, the interpersonal experience, the food before me. This sort of existential understanding can be enhanced by metaphor and complemented by the study of musical form and of the ear and auditory nervous system; the analysis of the constraints and freedoms in interpersonal relationships and of the emotional and motivational makeup of the persons involved; or the caloric content and constituent composition of foods and their metabolism. Such knowledge does not detract from, and may even enhance, each of the existential processes described. It is clear, however, that existential understanding is essentially private, whereas scientific understanding is essentially and eminently shareable.

Once we distinguish between existential and scientific understanding, we can see that skeptics are indeed correct in doubting our ability to achieve an existential understanding of our own brains. Brain tissue is peculiar because, in contrast to other tissues, it is largely insensitive to probing even by neurosurgeons. We cannot, therefore, sense our brains as such. Only the brain's processes are accessible to experience. As an example, when the somatosensory area of the cortex is electrically stimulated, a sensation of tingling in the toes is produced; when the classical motor region is excited, the toes actually move. In epileptic patients, whole trains of remembered experiences can be elicited when the cortex of the temporal lobes of the brain is probed electrically. The patient never exclaims that he feels his brain. He simply feels, and that feeling is referred to those parts of "him" that make neuronal connections with the brain tissue under the probe (see Libet, 1966).

Yet although the brain appears inaccessible to existential understanding, there seem to be no barriers to a scientific understanding. As in other scientific endeavors, such understanding comes from a propitious blend of the three modes of reasoning that guide research and provide some understanding of its results: the induction of principles from data; the deduction of logical relationships among principles; and reasoning by analogy, which attempts to place the relationships in a wider context. This essay is concerned chiefly with reasoning by analogy, not only because it is most closely related to the theme of this volume, but also because – as pointed out above and by C. S. Peirce (1932) – innovation stems almost exclusively from the proper use of analogy. Induction systematizes the familiar; deduction casts it into formal relationships.

Reasoning by analogy, by contrast, brings to bear on the familiar a new perspective derived from another realm of inquiry.

The use of analogy has been fruitful in neuropsychology from its beginning. Often the analogical thinking is implicit. Sometimes it is explicit, as when the brain is compared to a telephone switchboard or to the central processing unit of a computer. In either case, the analogy provides a step in the understanding of how the human brain functions.

The impact of telecommunications

The contribution of telecommunications to neuropsychology came in the form of techniques for measuring the flow of signals. The contribution of Bell Laboratory's Claude Shannon and his collaborator Warren Weaver is a landmark in the development of modern thinking. Shannon and Weaver (1949) developed a measure of signal patterns in impulses of energy transmitted over a given time in a limited communication channel, using a binary Boolean algebra as a base for that measure. Thus, a bit (*binary digit*) of information was first conceived as a unit indicating the match between the signal patterns produced by a sender and those received at the other end of the communication channel. The measure of information related the number of possible understandings (alternatives) contained in the message to those understood by the receiver. When the number of alternatives or possibilities (uncertainties) had been reduced by half, one bit of information was said to have been transmitted. Shannon and Weaver noted that such a measure was related to the idea of entropy. Entropy measures the disorder of a system. The idea is taken from thermodynamics, where it is used to describe the efficiency (or inefficiency) with which energy is used by a machine. Measures of order in the use of energy and in the flow of information promised to yield interesting results when applied to other fields of inquiry.

But this line of thinking ran into difficulties. Shannon noted that the measure of information depends on the uncertainty (the number of alternatives) in a system. For him, the measures of information and entropy were positively correlated – more information implies greater entropy. However, others, like Brillouin (1962), pointed out that an increase in the measure of information involves uncertainty *reduction* and is therefore more appropriately related to the opposite of entropy. This view has become prevalent: Information is now conceived as the measure of order, and entropy as the measure of disorder, of a system.

In the brain sciences the information measurement concepts became especially powerful in the hands of Warren McCulloch and his collaborators (see McCulloch, 1945). They described the brain as an organ where communication functioned both internally in the network of neurons and

as a means of providing the order of external (psychological) communications among individuals.

The impact of these formulations has been paradoxical. On the one hand, the idea has taken root that a level of organization beyond that of electrical nerve impulses exists and can be dealt with in quantitative terms as "information." On the other, specific contributions of information measures to the understanding of brain function or to psychology have been meager. Ross Ashby (1963), one of the foremost exponents of information measurement theory, has remarked that the strength of the theory lies not in providing answers but in allowing the reformulation of questions in more precise terms.

The concept of channel capacity is an example of the failure of information measurement theory to provide specific answers while sharpening the framing of questions. This concept was devised to handle the organization of energy patterns in fixed channels of limited capacity. But this is an oversimplification in brain science, because fixed channels of limited capacity do not exist in the brain (Pribram, 1976), nor do they operate in personal communication, in which the context of transactions is continually influenced by information received (Miller, 1953). Neurological and psychological systems operate within flexible constraints that shift, expand, and contract, as they do, for instance, when attention becomes focused. It is a common mistake at present to attribute *all* processing limitations to restricted channel capacity (see, e.g., Kahneman, 1973). Although central-brain-processing limitations are real (Broadbent, 1974; Pribram, 1974), the idea of "competency" based on contextual structuring (Chomsky, 1963; Pribram, 1977b; Pribram & McGuinness, 1975) or "chunking" (Garner, 1970; Miller, 1956; Simon, 1974) is more productive.

The move from a concept of a restricted channel capacity to the concept of a flexible competency capable of being "reprogrammed" to meet changing conditions heralds a shift from viewing the brain as a telephone-like system to regarding it as computer-like. Before discussing this shift we must clarify another related problem plaguing the application of information measurement theory.

The impact of control systems engineering

Cybernetics, "the science of information and control," raises the new problem. Intuitively, we may feel that the greater the amount of information available to a system, the more precisely that system can be controlled. However, since information can be defined as a measure of the amount of uncertainty in a system (as suggested earlier), it would appear that the more information there is in a system, the harder that system is to control.[1]

The difficulty is resolvable. Shannon in his original paper (Shannon & Weaver, 1949) distinguished between two types of information: The first reduces uncertainty; the second is concerned with repetitions. In a telephone communication disturbed by excessive noise, the receiver often shouts, "What did you say? I can't hear you. Please repeat." When the sender hears this, he or she repeats the message. The effect of repetitions is to reduce noise and error, which is not the same as reducing the uncertainty contained in the original communication. Error reduction is accomplished by repetition, or redundancy, rather than by changing the structure of the communication. Since error-reducing signals were not an intrinsic part of uncertainty-reducing communications, they were of secondary concern to Shannon and Weaver. However, error-reducing signals are, as we shall see, the critical operators in control systems.

The original idea behind cybernetic control systems is twofold: (1) The current state of a system can be compared with a desired state, and (2) the current state can be brought closer to the desired state through adjustments (repetitions) based on the magnitude of an "error signal" that denotes the discrepancy between the current state and the desired state. The process of adjustment that reduces the error signal is called "negative feedback."

Norbert Wiener in *Cybernetics* (1948) notes the relationship between cybernetics and the concept of homeostasis. Homeostasis describes the maintenance of a constant internal environment in the body by compensatory mechanisms brought into play when shifts occur in chemical or physical conditions. This is an old concept, developed originally by the physiologist Claude Bernard (1858) and given precision by Walter B. Cannon (1932). Wiener extended the concept of physiological homeostasis into control systems engineering. The thermostat, which maintains a temperature within assigned limits, is an example of such a control system.

The idea of physiological homeostasis played a role in the development of the more comprehensive ideas of cybernetics. The concept of negative feedback that developed out of control systems is, in turn, applicable to neurophysiology. In a sense, an engineering idea that was in part based on physiological observations returns to physiology on a higher level. Negative feedback is currently invoked to explain regulation by the brain of sensory input from the external environment (Pribram, 1967) and the fine tuning of muscle activity (Miller, Galanter, & Pribram, 1960; Pribram, 1977b).

The first evidence of negative feedback in the operations of the nervous system came from work on muscle spindles, receptors in the muscles that signal the degree of muscle stretch (Kuffler, 1953; Matthews, 1964). These muscle spindles are directly controlled from the spinal cord and brain, forming a loop that ensures smooth and coordinated movements.

Feedback from the brain also regulates receptors of other sensory systems. Signals originating in the brain can alter the input of signals from tactile (Hagbarth & Kerr, 1954), auditory (Galambos, 1956), olfactory (Kerr & Hagbarth, 1955), and visual (Spinelli & Pribram, 1966; Spinelli & Weingarten, 1966) receptors. The association areas of the brain, which lie adjacent to the somatosensory cortex, are potential sources of these signals that influence sensory input (Lassonde, Ptito, & Pribram, 1981; Reitz & Pribram, 1969; Spinelli & Pribram, 1967).

This evidence of central control over receptors revolutionized the concept of the reflex in neurophysiology and thus affected the picture of the stimulus–response relationship that had dominated psychology for decades (see Miller et al., 1960). No longer could the organism and its brain be thought of as a passive switchboard on which environmental contingencies might play at will. A new, active image of a self-setting, homeostatically controlled organism that searched for and selectively accepted environmental events replaced the old passive stimulus–response image. Now, instead of responses elicited by discrete stimuli, as in the old physiology and psychology, the response was seen as initiating further nervous system activity that altered future responses. In biology, this change in thinking flourished in the studies of animal behavior known as ethology. In psychology, the change was reflected in an abandonment of stimulus–response learning theories in favor of the ideas of operant conditioning and cognitive conceptualization (Pribram, 1977b).

The thermostat embodies these principles. The set point of the thermostat determines the level at which changes in temperature will be sensed by the system and regulates (starts and turns off) the operation of the furnace. The operation of the furnace depends on temperature changes within chosen limits rather than on a simple on–off switch. Homeostatically controlled systems, like the thermostatically controlled furnace, provide a tremendous saving in memory load. Von Foerster (1965) called this mechanism a "memory without record." There is no need to keep track of the vagaries and variabilities of the temperatures external to the system: The homeostatic system operates on the hottest summer days and in the coldest winter months. Only the deviations of temperature from the set point need be sensed.

Cybernetics attempted to combine the insights derived from telecommunications with those derived from servocontrol. As noted earlier, this created problems. Some of these were anticipated by Shannon (Shannon & Weaver, 1949) when he used the term "information" in two technical senses, neither of which corresponds to the popular sense. As we have seen, in one technical sense information is a measure of the reduction of the number of alternative choices, that is, of uncertainty. In the second, information is a measure of the failure to reduce a discrepancy between two ongoing processes. But the distinction goes even deeper. The first measure specifies chiefly the complexity of a process. It can be precisely

and quantitatively stated in bits. The second measure is an error signal that specifies little or nothing about complexity, but deals only with discrepancy and changes in discrepancy. Usually it is measured in continuous analog terms, since it is *change* that is of central concern. As noted earlier, when digital measures are applied to this second kind of information, it is seen to be more akin to the concept of redundancy than to the concept of information! It is this redundant error signal that is the critical component of homeostatic mechanisms and is involved in the negative feedback process of cybernetic control systems.

Error signals, which specify changes in redundancy rather than in uncertainty, provide the link between cybernetic concepts and information measurement theory. Cybernetic systems use redundant error signals to maintain stability. They have little to do with "uncertainty" or complexity. Brain systems that operate solely on homeostatic principles are technically not information-processing systems in the sense of reducing or enhancing uncertainty. Information measurement theory is therefore not applicable to internal homeostasis and external sensory processing unless the homeostatic principle is supplemented in some way.

These ideas characterized the brain and behavioral sciences almost three decades ago and are detailed in *Plans and the Structure of Behavior* (Miller et al., 1960). Roger Brown (1962) rightly criticized this book for the homeostatic cast it shares with psychoanalytic theory (see Freud, 1895/1966). The notion of "drives and habits" in Hullian stimulus–response psychology (Hull, 1943) and Skinner's concept of the "conditionable operant" (Skinner, 1938) share this slant. Even ethological formulations of "eliciting stimuli" and "action-specific energies" are essentially modeled on the homeostatic principle (Hinde, 1954a, 1960; Lorenz, 1969; Tinbergen, 1951). But the capacity of homeostatic systems to alter their set points is implicit in all of these theories (Pribram & Gill, 1976). This capacity was emphasized by Waddington (1957) in his concept of homeorhesis: a flow toward an ever-changing set point rather than a return to a static stable one. Homeorhetic systems are open, helical, future-oriented, feed-forward systems (as opposed to homeo*static* systems, which are closed loops), because the changes in set point can be programmed. In biological systems, prime examples of helical organizations are the DNAs that program development. Engineers have developed nonbiological programmable systems, the currently ubiquitous computers.

The impact of computer science

Computers are information-processing devices that have been heralded as harbingers of the second industrial revolution, the revolution in the communication of information. This revolution can be compared to the communications revolution that occurred at the dawn of history with

the invention of writing or, earlier, when linguistic communication among humans began. The revolution depended largely on stepwise serial processing. Despite prodigious speed, serial processing is considerably less nimble than the brain's facility, which, as we shall see in the next section of this essay, is based to a large extent on parallel procedures carried out simultaneously. Nevertheless, as a model for brain activity, computer programming has produced three decades of intense research (Anderson & Bower, 1973; Miller et al., 1960; Neisser, 1967; Newell, Shaw, & Simon, 1958). More recently, the field of artificial intelligence has attempted to enhance computer capabilities by patterning computers after natural intelligence (Schank & Abelson, 1977) or possible brain organizations (Winograd, 1977). What has generated such sweeping changes in the way we view communication and computation?

Von Neumann (1951/1963) contributed a major innovation by devising a computational configuration that could be programmed by a system of lists in which each item in a list was prefixed by an address and suffixed by an instruction to proceed to another address. List programming was then developed by Newell and Simon (1956) to allow any item in any list to be addressed by (follow) any other item and in turn to address (precede) any other item. Items and lists of items were thereby endowed with the capacity to address themselves (often after running through several other lists). In the jargon of programming, this was called "recursiveness." As Turing (1937) pointed out, self-reflective programs endowed with recursiveness can locate any item stored in them and can associate any group of items. Such a network of lists is a far cry from the stimulus–response type of communication based on the model of the early simple telephone connection.

Structures embodying lists of the sort necessary for program construction have been shown to exist in the brain cortex. The cellular organization of the cerebral cortex of the brain shows both a vertical and a horizontal patterning. There are vertical columns of cells, perpendicular to the surface of the cortex, in which each cell responds to a different aspect of sensory input from a small group of receptor cells on the surface of the body – from a small area of the retina, for example. The columns can be thought of as lists containing items, namely, the cells (Edelman & Mountcastle, 1978; Hubel & Wiesel, 1968). The horizontal organization of the cortex reflects the arrangement of receptors on the surface of the body. The somatosensory area of the cerebral cortex, which lies directly behind the central fissure, receives sensory signals from the body surface projected in a pattern that mimics a tiny human figure, or "homunculus." The items (cells), therefore, also form horizontal lists. Interconnections between the cells in columns or arranged within a single horizontal layer enable the brain to interpret moving sensory signals. Thus, some cells in the vertical lists show sensitivity to movement of the stimulus from one

surface touch receptor to another. Movement in one direction can trigger the brain cells, while movement in another has no effect, a finding that can be interpreted as suggesting a set of prefixes and suffixes as in von Neumann's analysis (Pribram, 1977b; Werner, 1970). In the visual part of the cortex, *each* cell (item) in the cortical column (list) appears to be endowed with such prefixes and suffixes. Most of these cells respond selectively to movement, direction, and even velocity changes (Pribram, Lassonde, & Ptito, 1981), which suggests a richer, more finely grained network of connection than is present in the somatosensory system.

Characterization of cortical cells of the brain as similar to items in a program list is often described as *feature analysis*, since each item represents one feature of a sensory input. In fact, the prevailing school of neurophysiological thinking currently favors the view that these cells are feature detectors (Barlow, 1972), that is, that each brain cell is uniquely responsive to one – and only one – feature. A competing view is that each cell has multiple selectivities and that its output is not unique to any one type of stimulus, as would be required of a feature detector. In the visual cortex, for example, a cell may select on the basis of the orientation of lines, their width and spacings, luminance, color, the direction of movement, the velocity of movement, and even the frequency of auditory tones.

It appears, therefore, that each cortical cell is a member of an associative network of cells (perhaps a set of list structures, as the evidence noted above would suggest) rather than a single-feature detector. Feature analysis must therefore be a function of the entire network of cells that is addressed by the total pattern of sensory input. The brain thus differs from current computers in that the initial stages of processing occur simultaneously, that is, in parallel rather than serially. Feature analysis, therefore, results from pattern matching rather than from single-feature detection. To return to an earlier analogy, the thermostat is a primitive pattern-matching device that "selects" deviations from a set point. It thus reduces the memory load that would otherwise be required to "detect" the occasion of every new temperature that required a response. An association of homeostatic devices, that is, columns of brain cells, thus can serve as a pattern-matching device that selects features from the sensory input.

Even the concept of list structures of homeostatic devices does not solve all the problems raised by viewing the brain as an associative network of cells. Ashby (1960) noted that such associative networks tend to be hyperstable and thus intolerably slow to modify; they seem to be unable to learn. To paraphrase Lashley (1950), even though one may be driven at times to consider such a model in the classroom, it should not be forgotten that one of the brain's distinguishing features is its capacity

to learn. Two choices are open to the model builder. The evidence for homeostatic organization of the brain can be ignored, as Edelman and Mountcastle (1978) have done in their proposal for a "degenerative" (a many-to-one mapping) model in which feedback becomes a secondary rather than a primary constituent. Or, as Ashby (1960) and Miller et al. (1960) have done, one can start with an associative net made up primarily of homeostatic elements and add constraints (Pribram, 1977b). These constraints are based on invariant properties of the stimulus. The structures within the brain that recognize invariant stimuli or test–operate–test–exit units (TOTES, as Miller, Galanter, & Pribram call them) cut the associative net into pieces (to paraphrase Ashby) and can be shown to be organized hierarchically (Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; Miller et al., 1960; Pribram, 1977b; Turvey, 1973). A definition of the "invariant properties," or features, of stimuli now becomes critical. Turvey (1973) and Gibson (1979) describe such properties as localized in the environment of the organism, while nativists (e.g., Chomsky, 1972) describe them as selected by the organism in the face of an environmental cornucopia.

The computer model of brain structure and function suggests an intermediate stance. In a computer the selection of a workable program depends on a "good fit," a match between input and central processor. The brain's "central processor" may be considered to have become adapted during evolution to an ecological niche, and it should be possible to determine the "invariant properties" (features) of that niche that have effected the adaptation. But with as general purpose a computer as the human brain, the responsible environmental features may be as difficult to delimit as the specifications of the adapting mechanisms of the brain that are concerned with identifying these invariances.

The impact of holography (parallel distributed processing)

Mechanisms of extracting invariances ("features") from sensory input have been of considerable interest to neuroscientists and psychologists. As we have seen, a brain cell organization based on an associative net with hierarchic constraints can serve as a useful model. Certain problems exist with this model. There is, for example, the need to postulate an analytic mechanism that is relatively sparing in its use of neurons so that invariance can be detected without invoking a "one neuron–one feature" equivalency. A successful model must also explain the speed and immediacy with which perception occurs and its high resolving power (see Gibson, 1979).

Historically, three sorts of answers have been given to the question raised. At one extreme is the "feature detector," or "one neuron–one feature" answer, which (as just noted) is untenable in the light of current

neurological evidence. This model can also be faulted on the basis of behavioral evidence (Rock, 1970). At the other extreme is the model proposed by Wolfgang Köhler (Köhler & Held, 1949) to account for the distortions of physically measured stimulation found in illusions. Köhler emphasized the configurational aspects of perception and suggested that direct current (DC) fields result when sensory input arrives in cortical tissue. The low resolving power of the DC fields casts doubt on the efficacy of such machinery and its capacity to account for texture perception. A series of experiments was therefore set up to test the issues involved. The results of these experiments were as follows: (1) DC shifts *did* accompany the desynchronization of the cortical electrical record (EEG) induced by sensory (visual and auditory) stimulation; (2) disruption of DC electrical activity by epileptogenic agents placed on, or injected into, the cortex failed to impair pattern perception; and (3) such disruption did impair learning. Subsequently, it was shown that imposing a cathodal (negative) DC polarization across the cortex would slow learning, whereas imposing anodal (positive) DC polarization would speed learning (Stamm & Rosen, 1973). In short, DC shifts in the cortex bias learning, not perception, and are thus unlikely candidates for the critical machinery of pattern perception.

Between the extremes of the "one neuron–one feature" (usually referred to as the "pontifical" or "grandfather" cell dogma) and the DC field theory, a pair of more moderate views has been proposed. Each of these stems from one of the extreme positions. Neurophysiologist Horace Barlow (1972) has suggested that the idea of "one neuron–one feature" be dropped in favor of a set of cells that together can recognize a feature. This proposal is little different from that made by psychologist Donald Hebb (1949), who suggested that a cell assembly becomes constituted in response to sensory input. In these proposals "one neuron–one feature" is replaced by "one cell assembly–one feature." Barlow's and Hebb's proposals differ in that Barlow's cell assembly has a relatively fixed range of sensitivities – propensities to respond – whereas Hebb's "phase-sequenced" cell assemblies vary with respect to their constituent neurons and change with experience.

A quite different point of view was offered by Karl Lashley (1942) in his proposal that waves of activity are generated in the cortex by sensory input and that these waves interact to produce interference patterns. Lashley, however, did not develop his suggestion at either the neuronal or the perceptual level. He was attracted by the possibility suggested by Goldscheider (1906) at the turn of the century that the brain's organization of the perceptual field might display some of the same characteristics as the organization of embryonic developments. (Lashley was a zoologist by training.)

In several essays I have developed in detail the "interference pattern"

model for brain function (Pribram, 1966, 1977b; Pribram, Nuwer, & Baron, 1974). At the neuronal level, the model interprets electrical changes in the cell membranes of neurons on the far side of synapses (or interneuronal junctions) as constituting wave fronts. These electrical changes, known as "hyperpolarizations" and "depolarizations," are not themselves nerve impulses. Depolarizations increase the likelihood that a neuron will increase its generation of nerve impulses; hyperpolarizations decrease this likelihood. My proposal is somewhat similar to that made in quantum physics, where the wave equation is treated as a vector based on the probability of occurrences of quantal events. The neural "quantal events" are those hyperpolarizations and depolarizations that, taken as a pattern occurring in an area of the cortex, can be described in terms of nodes created by reinforcement and extinction among interfering micro-wave forms. These patterns of polarization form a microprocess of fluctuating polarizations. Molecular storage, perhaps in the form of a conformational change in the proteins of the cell membranes at neuron-to-neuron synapses, is assumed to result from repetitions of particular patterns in the neuroprocess (Pribram, 1977b; Pribram et al., 1974).

At the perceptual level, the model implies that sensory input becomes encoded in synaptic membranes by these microprocesses in such a fashion that image reconstruction can be readily accomplished. This can be done by storing the Fourier or similar transform (see later in this section) of a sensory signal, which involves storing the coefficients that represent the interference nodes of the microprocess (Pribram, 1988; Pribram et al., 1974), rather than representing it by simple point-to-point intensive dimensions. In order to read out an image from such a store, all that is necessary is to invoke the inverse transform to restore an image.

Over the past century evidence has been accumulating that such harmonic analysis of the neural process entailed in sensory processing is valid. Ohm (of Ohm's law) suggested in 1843 that the auditory system operates as a frequency analyzer, perhaps according to Fourier principles. Fourier theory states that *any* pattern, no matter how complex, can be separated into a set of component regular waves of different frequencies, amplitudes, and relations to one another. Helmholtz (1857/1971) developed Ohm's suggestion by a series of experiments that provided evidence that such separation takes place in the cochlea, the part of the inner ear where the sound receptors are located. Helmholtz proposed that the cochlea operates much like a piano keyboard, a proposal that was subsequently modified by Georg von Bekesy (1960), who demonstrated that the cochlea resembled more closely a stringed instrument brought to vibrate at specific frequencies. Nodes of excitation developing in the vibrating surface (the "strings") accounted for the piano-keyboard-like qualities described by Helmholtz.

Bekesy further developed his model by actually constructing a surface

bearing five vibrators, which he placed on the forearm of a subject. The periods of vibration of the five vibrators could be adjusted so that the five showed a variety of phase relationships to one another. The phase relationship could be adjusted so that a single point of tactile excitation was perceived (Bekesy, 1967). It was then shown that the cortical response evoked by such vibrations was also located in a single area: The pattern evoked resembled the perceptual response in its singleness rather than the multiplicity of the physical stimuli (Dewson, 1964). Somewhere between skin and cortex, inhibitory (hyperpolarizing) interactions among neurons had produced a transformation.

Bekesy went on to show that by applying two such vibrator-bearing surfaces, one to each forearm, and once again making the appropriate adjustments of phase, the subject could be made to experience the point source alternately on one arm, then on the other, until, after some continued exposure, the source of stimulation was projected outward into space between the two arms. Bekesy noted that we ordinarily "project" our somatosensory experience to the end of writing and surgical instruments. The novelty in his experiments was the lack of solid physical continuity between the perceived source and the actual physical source. Stereophonic high-fidelity music systems are based on a similar principle: By appropriate phase adjustment, the sound is projected to a location between and forward of the acoustical speakers, away from the physical source of origin.

Over the past two decades, it has been shown that the visual system operates along similar principles in its processing of spatial patterns. In an elegant series of experiments, Fergus Campbell (1974) and John Robson (1975) found anomalous responses to sets of gratings (sets of lines or bars) of various widths and spacings. The anomalies were reconciled when it was realized that the widths and spacings of the bars could be treated as having a frequency of alternation over space – that is, the width of bars and the distance between them formed a pattern that, when scanned, showed a frequency in the change from bar to spacing. The anomalous results were obtained when these "spatial frequencies" formed harmonics.

Then it was shown that certain cells in the visual cortex encode such "spatial frequencies" (De Valois, Albrecht, & Thorell, 1977; Movshon, Thompson, & Tolhurst, 1978; Pollen & Taylor, 1974; Schiller, Finlay, & Volman, 1976). Most telling are the results of experiments pitting the standard neurophysiological hypothesis that these cortical cells are line (bar or edge) detectors against the hypothesis that they are selective of one or another bandwidth of spatial frequency. De Valois and his colleagues showed that cortical cells were insensitive to bar width and that, when the bars were crossed with others in a pattern such as a plaid, the response of the cortical cells changed to reflect the total pattern. Speci-

fically, each cortical cell was shown to be selectively sensitive to lines (gratings) oriented in a particular direction, a finding that had been instrumental in generating the feature detector proposal (Hubel & Wiesel, 1959). If the cells were operating as feature detectors, additions to the initial display pattern of lines should not alter the orientation in which the display has to be shown in order to match the selectivity of the cell. Additional lines in the pattern would be processed by additional units whose orientation matched that of the additional lines. If, however, the total pattern of the plaid was being processed by the brain cell, the orientation of the whole pattern would have to be altered to match the orientation of the major components of the Fourier (i.e., spatial frequency) transform of the pattern. De Valois performed a Fourier transform by computer on each plaid displayed. Such transforms showed radii at various angles from the original perpendicular pattern of the plaid. De Valois found that all plaid display patterns had to be rotated to bring these radii into line with the special selectivity for orientation of the brain cells. Furthermore, the rotation was exactly that (to the degree and the minute of visual arc) predicted by the proposal that the Fourier transform of the total plaid (and not its separate lines) is encoded.

There thus remains little doubt that descriptions in terms of harmonic analysis are valid models of the processing of sensory stimuli in audition, touch, and vision. Such descriptions can also be compared to image formation in the processing devices called holograms. Holograms were so named by their inventor, Dennis Gabor (1948), because each part of the hologram is representative of the whole. In a hologram each quantum of light acts much like a pebble thrown into a pond. The ripples from one pebble spread over the entire surface of the pond. (The mathematical expression for this is, in fact, called a spread function, and the Fourier transform is a prime example of such a function.) If there are several separate pebbles, the ripples produced by one pebble will originate in a different location than those produced by another pebble. The ripples will intersect and form interference patterns, with nodes where the ripples add, and sinks where they cancel. If "ripples" are produced by light falling on film (instead of pebbles falling into water), the nodes can be captured as reductions of silver grains on the film. Note that the information from the impact of each pebble or light ray is spread over the "recording" surface; thus, *each portion* of that surface can be seen as encoding the whole. And as noted earlier, performing the inverse Fourier transform reconstructs the image of the origin of that information. Thus, the whole becomes enfolded in each portion of the hologram since each portion "contains" the spread of information over the entire image.

The principle of the hologram is different from the earlier Gestalt view that wholes develop properties in addition to the sum of their parts. The properties of holograms are expressed by the principle that "the whole is

contained or enfolded in its parts," and the very notion of "parts" is altered, because parts of a hologram do not have what we think of as boundaries.

The following properties of holograms are important for brain function: (1) the distribution and parallel content-addressable processing of information – a characteristic that can account for the failure of brain lesions to eradicate any specific memory trace (or engram); (2) the tremendous storage capacity of the holographic domain and the ease with which information can be retrieved (the entire contents of the Library of Congress can currently be stored on holofische, or microfilm recorded in holographic form, taking up no more space than is contained in an attaché case); (3) the capacity for associative recall that is inherent in the parallel distributed processing of holograms because of the coupling of separate inputs; and (4) the provision by this coupling of a powerful technique for correlating (cross-correlations and autocorrelations are accomplished almost instantaneously).

It is important to realize that holography is a mathematical invention and that its realization in optical systems through the use of laser beams is only one product of this branch of mathematics. Fourier transforms also play a role in modern computer technology as in the parallel distributed processing algorithms of neural network simulations of cognitive processing (Rumelhart, McClelland, & the PDP Research Group, 1986), in X-ray tomography, and (as demonstrated by the evidence described earlier) in understanding the results obtained in experiments on brain function.

Let us return for a moment to the classes of neural models that have been proposed for perception. Recall that the holographic model (i.e., of interference pattern processing of Fourier coefficients) was derived from dissatisfaction with both the "feature detector" and "cell assembly" theories. John (1967) and Uttal (1978) have also developed sophisticated statistical correlation models, which differ from the holographic model, however, in that they do not rely primarily on harmonic analysis of brain function. The most efficient manner of achieving statistical correlations is to transform the data (the sensory input, in the case of the nervous system) into the Fourier domain. There is thus a convergence of the statistical and harmonic models when they are followed to their logical and neurological conclusion: Nerve impulses arriving at synaptic junctions are converted to postsynaptic depolarizations and hyperpolarizations, which can best be described as Fourier transforms of those impulses. Repetitions of impulse patterns result in information storage of as yet undetermined nature, possibly alterations in the cell membranes of neurons. Subsequent sensory stimuli are cross-correlated with the stored residual from former inputs, and the inverse transform of the results of the correlation form our perceptions. The perceptions are then projected

away from the brain itself by appropriate phase relationships, as in Bekesy's experiments, in stereophonic sound equipment, and in holograms.

There are important differences between the brain process and the optical information procedure, however. First, in an ordinary hologram the wave form is spread more or less over the entire surface of the film. In the brain each individual cortical cell reflects a particular pattern of depolarizations and hyperpolarizations in the dendritic network. If this is compared to encoding in a hologram, it is seen that the cortical "hologram" must be a patchwork (Robson, 1975) in which the Fourier transform of any specific input pattern becomes encoded in an overlapping set of patches, each patch corresponding to the receptive field of a particular cortical neuron. But such composite holograms, called strip or multiplex holograms, are commonly employed to provide three-dimensional *moving* images (see Leith, 1976). The process of adding together strips representing Fourier-transformed sections of space was invented by Bracewell (1965) to compose a high-resolution image of the heavens by radio astronomy. Pollen and Taylor (1974) interpreted some of their neurophysiological results in terms of a strip hologram in which each elongated receptive field served as a strip in the total pattern. Thus, the neural hologram, because of its patchwork nature, shows properties that are purely holographic (discussed later) as well as properties that are due to the spatial arrangement of the patches or strips. These spatial arrangements form the basis of the list structures described earlier and account for such nonholographic properties of perception as location and movement in the space and time domain.

Further, as noted earlier, each cortical cell is selective of several features of a stimulus. In the visual system these can include spatial frequency, color, directional movement, and velocity. Recordings from small groups of neurons in the visual cortex suggest that other aspects of situations are also encoded: In a problem-solving task, wave forms indicating the presence or absence of expected reinforcement are recorded (Pribram, Spinelli, & Kamback, 1967). The aspects of brain function that are encompassed by the neural holographic model are not exhaustive of all that the brain accomplishes, and the relationship of the model to the information and control models presented earlier must not be forgotten. The holographic model does, however, account for hitherto unexplained aspects of brain functioning, and it brings brain science into relationship with the revolution in modern physics occasioned by quantum and relativity theory (Pribram, 1988).

This relationship to physics is brought out when a particularly vexing question is faced. In all of the holographic systems other than neural that have been described here, an observer is assumed. Who and where is the observer of the image constructed by the neural hologram? Where is

the little man or woman in the head? Who is the "I," the "self," that experiences the results of the holographic process?

To try to answer this question one must first ask what it is that is being observed. The assumption has been that an isomorphism (identical form) exists between a sensory perception and some physical "reality" (Köhler & Held, 1949). But as the Bekesy experiment with multiple vibrators makes clear, physical reality and perceptual reality may differ substantially. The sensory apparatus appears to be lenslike as it focuses an input, but the focusing produces an image that is decomposed by subsequent neural activity into the Fourier transform domain – that is, into a distributed holographic form. In view of the invertibility of *image domain $\rightleftarrows$ holographic domain*, one may ask in what form the input to the senses arrives. Is this input holographic, and does it become organized into images (thereby revealing the objects of which the images are formed) only by the lenslike capabilities of our senses?

This view is probably too extreme. The only way we can answer these questions is through the evidence of the senses and the instruments devised to augment them. This evidence suggests an ordinary level of reality to which the senses have become adapted through evolution. "Ordinary reality" is the reality of Newton's mechanics and Euclid's geometry. It is grasped through consensual validation – by bringing to bear the several senses and inferring a reality that partakes of them all. We see a moon in the sky and send a man to palpate it. We bump into unseen obstacles and invent radar and sonar to discover them. As infants, we hear our mothers, and see and touch them. At another level, smell and taste are based on our perceptions of dissolved molecules – a chemical level of an unseen, unheard, and untouched reality.

More recently, physicists have probed ever smaller components and have taken a new look at the evidence about a spatially distant reality presumably palpable but beyond our reach. The evidence about this macrouniverse comes to us by way of the very same electromagnetic components that make up the microuniverse. It should come as no great surprise, therefore, that the laws that relate to us the nature of the macrouniverse, such as the special and general laws of relativity, and those that relate the nature of the microuniverse, that is, quantum and nuclear mechanics, provide a somewhat similar conception of reality. This reality, highly mathematical in nature, departs considerably from ordinary sensory experience.

David Bohm (1971, 1973) has noted that, although the mathematics of relativity and of quantum theory are thoroughly worked out, the conceptual representation of what that mathematics might mean has lagged seriously. He has suggested that this lag is caused by our propensity to use lens systems to construct our conceptual reality. He proposed that the hologram might provide a better conceptual model for understanding

both the macrouniverse and microuniverse! His proposal strikes a responsive chord in the neuroscientist, who has also found a level of organization in the nervous system that is more appropriately modeled by the hologram than by the senses (i.e., lenses). After all, the brain is a part of physical reality.

What are the characteristics of this holograph-like order of reality? First, it does not correspond to sense perception and is thus counterintuitive. Second, this order, which Bohm calls "implicate" to distinguish it from the ordinary "explicate" sensory order, is nonobjective. The objective, explicate order is made up of the images by which we know objects. These images are constructed by lenses: the lenses and lenslike characteristics of our senses as well as the lenses, often called "objectives," of our microscopes and telescopes. By contrast, the holograph-like implicate nonobjective reality is not composed of things but of quantally constituted microwaves and their interactive constituents such as constructive (nodal) and destructive interferences. Leibniz (1714/1973) described such a reality in his *Monadology*, in which the whole universe was represented in each monad, a windowless portion of the whole. Substitute lensless for windowless, and the monad becomes holographic.

Finally, in the reality described in this domain, the ordinary dimensionalities of space and time become enfolded (implicated). Thus, a different set of dimensions must be invoked in order to specify its characteristics. Time and space can be read out, but the readout may show peculiarities such as the complementary nature of measures of location in space and of moment (momentum), so that in specifying one, the other becomes elusive. "Particles," or rather events, in this microuniverse appear to influence one another in situations where a causal connection between them cannot be traced (see d'Espagnat, 1971). An implicate order composed of the probabilities of fluctuations in interference nodes, related by their wave equations, was proposed to account for the peculiarities resulting from observations of the microuniverse. The implicate order is therefore not static, and "holographic" is a somewhat inappropriate term. A hologram is only a frozen record of an ever-changing scene. The term "holonomic," used in physics to describe linear dynamical processes, would be preferable (Pribram, 1977a).

The fact that the holonomic implicate order is without boundaries, that every part enfolds or "contains" the whole, and that therefore the distinction between observer and observed is blurred so that observations no longer result in objects (i.e., observables) has led some physicists to note the intrinsic interweaving of perception and consciousness on the one hand and macrophysical and microphysical reality on the other. Thus, Bohm includes an appendix titled "Perception" in his book *The Special Theory of Relativity* (1965), and Wigner (1967) exclaims that modern physics deals with "relations among observations," not among "observables." An observable is characterized by invariance across observations;

in his famous principle Heisenberg (1930/1984) pointed out that, in microphysics, the observed varies with the instrumentation of the observer. Bohr (1928/1985) enunciated his principle of complementarity on the same grounds. And, of course, Einstein (1917/1961) made the same point with regard to the macrouniverse in his general theory of relativity.

This enfoldment of observation into the observable has led some physicists and some philosophers (e.g., Whitehead, 1938) into a panpsychism in which consciousness is a universal attribute rather than an emergent property of brain organization. Such views have interesting consequences for the analysis of the mind–brain issue (Pribram, 1979, 1986), bringing the concept of consciousness closer to that enunciated in the Eastern mystical tradition and the spiritual religious views of the West. Thus, Capra (1975) can proclaim a Tao of Physics in which the details of modern macrophysics and microphysics are matched to those of the mystical tradition. Science of this sort appears far removed from the objective operationism of the positivist and critical ˉphilosophers of the Vienna circle (e.g., Carnap, 1939; Feigl, 1954) and of likeminded psychologists (e.g., Hull, 1943; Skinner, 1938).

Summing up: how human beings go about understanding themselves

It is incredible to think that the major impacts on neuropsychology and the brain sciences that we have reviewed have occurred in less than half a century. Of course, the modes of thought that made these advances possible could be traced much further back in time, but enough history has been covered to allow a return to the issue raised at the beginning of this essay. If you will recall, I said that I would review the impact of certain modes of thought, which had been stimulated by several new inventions, in an attempt to trace the manner in which human brains go about understanding themselves. I also foreshadowed my thesis, stating that reasoning by analogy is one of the most powerful tools for innovative thought and scientific progress. The subsequent historical review of major developments in neuropsychology should have provided ample illustration of this claim, even for the most intractable skeptic. Now I want to review this thesis.

I find it useful to distinguish between *metaphor* (the larger concern of this volume), *analogy* (a way of reasoning about metaphor), and *model* (a precise coupling of an organization of data to another mode of organization such as a mathematical formulation). It seems to me that the historical episodes I have just recounted show (1) how a group of investigators can begin with a general metaphor – a broad and somewhat undefined sense of the similarities between two things (in our cases between some newly invented technological device or concept and some aspect of brain function), (2) how they can "trim" this metaphor into

more and more precise shape, primarily through reasoning by analogy back and forth between the two things being compared, and (3) how, once they have gone far enough, the original metaphor is transformed into a precise scientific model, a theoretical framework that can be shared with and tested by the larger scientific community. I submit that my historical account of developments in the brain sciences over the past half-century shows that this simple scheme is a straightforward and accurate way of tracing the manner in which human brains have gone about understanding themselves.

So, in sum, metaphorical insight, reasoned analogy, and empirical modeling are woven together in the fabric of scientific innovation, in the "hard" areas of psychology as in the "soft" areas. I have emphasized the process of proper analogical reasoning – the process leading from metaphor to model – because, although metaphorical insight is fundamental, it will not get us far in achieving scientific understanding unless we subject it to the sort of sustained reasoning by analogy that has been illustrated throughout this essay.

Looking to the future, there is no reason to expect that the sort of reasoning by analogy that has wrought current scientific understanding in neuropsychology will cease. New developments, technical and theoretical, in engineering, chemistry, interpersonal psychology, and other yet unspecified domains, will continue to cross-fertilize the brain sciences – leading from vague but pregnant metaphors to more precise and testable models – provided that scientists continue to reason, carefully, by analogy.

Acknowledgment

Note

1 I once posed the problem of specifying the relationship between information measurement and the control of systems to Norbert Wiener, Warren McCulloch, Don Mackay, and other cyberneticians. After many hours of discussion, everyone agreed that it was indeed a most perplexing issue that had at that time no direct answer.

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