COGNITION AND BRAIN THEORY, 1981, 4 (2).

The Brain, The Telephone, The Thermostat, The Computer, and The Hologram

KARL H. PRIBRAM
Neuropsychology Laboratories
Stanford University

On Abduction, the Use of Analogy

Over the past century our civilization has engineered a series of inventions that have initiated specific novel modes of thought. Each of these inventions has had extensive practical consequences that have altered our daily lives. But perhaps as significant in the long run are the modes of thought that accompanied or initiated the inventions, for these modes of thought form the context, the matrix of the future: Novelty is birthed in familiarity; inventions flow from taking inventories.

This essay addresses the impact of these modes of thought on conceptions of brain structure and functioning, especially in their relationship to psychological organization in general, and thought processing in particular. The essay is therefore largely an attempt to trace the manner in which human brains go about understanding themselves. Skeptics have suggested that any such understanding in a non-trivial sense is impossible. Here, the view is pursued that on the basis of past accomplishments, a certain kind of understanding can be achieved.

There appear to be no barriers to this kind of understanding of brain which can be called "scientific." As in all other scientific endeavors, such understanding comes from a propitious blend of three modes of reasoning that guide research and provide some understanding of its results. These three modes are the induction of principles from data; the deduction of logical relationships among principles; and abductive reasoning by analogy that attempts to place these relationships into wider contexts. This essay is concerned especially with reasoning by analogy, the abductive mode, because, as pointed out by Peirce (1934), innovation stems almost exclusively from the proper use of analogy. Induction systematizes the familiar; deduction casts it into formal relationships. Abduction,

---

Requests for reprints should be sent to Karl H. Pribram, Professor Head, Neuropsychology Laboratories, Stanford University, Jordan Hall, Stanford, California 94305.

on the other hand, brings to bear on the familiar a new perspective derived from another realm of inquiry.

The brain sciences have been subject to such abductive reasoning since their inception. Often the analogical thinking is implicit. Sometimes it is explicit as when the brain is compared to a telephone switchboard, or a central processing unit of a computer. In either case, the analogy provides a step in the understanding of how the human brain is attempting to understand itself scientifically.

The Telephone and the Thermostat: Information and Error

~~On the Telephone and Information Measurement~~

The conceptual contribution of the telephone as the initial example of an extensively used system of telecommunications came in the form of measurement of the flow of signals. The justly famous contribution of Bell Laboratory's scientist Claude Shannon and his collaborator Warren Weaver (1949) are classics in the development of modern thinking. Shannon and Weaver developed a measure on the patterns of energy transmitted over a given time in a limited channel. The measure related the number of possible understandings (alternatives) to those that were actualized. Thus, when the possibilities (uncertainties) were reduced by half, one BIT of information had been transmitted.

The impact of this formulation has been paradoxical. On the one hand the *idea* has taken root that a level of organization beyond that of energy exchange exists and can be dealt with in quantitative terms as "information." On the other, specific contributions to the understanding of brain function or to psychology have been meager. Ross Ashby, one of the foremost exponents of information measurement theory, remarked that the strength of the theory was not that it had provided answers but that it had allowed the reformulation of questions in more precise terms (Ashby, 1963).

Two critical examples of such failures of information measurement theory to provide answers while sharpening the framing of questions concern the concepts of channel capacity and cybernetics. The theory was developed to handle the organization of energy patterns in channels of fixed capacity. But fixed channels of limited capacity do not exist in the brain (Pribram, 1976), nor do they operate in personal communication (Miller, 1953), where the context of the interaction is continually updated by the information exchanged. Biological and psychological systems operate within flexible constraints, within contexts that shift, expand and contract as when attention becomes focused. Thus, such concepts as the attribution of processing limitations due to restricted channel capacity, though extremely popular at the moment (Kahneman, 1973), are in error. The central brain processing limitations are real (Broadbent, 1974; Pribram, 1974). They are, however, better handled within a framework of competency (Chomsky, 1963; Pribram, 1977; Pribram & McGuiness, 1975), where competency reflects contextual structuring such as that suggested by George Miller in his often quoted paper on The Magical Number Seven (1956) as amplified by Herbert Simon (1974) and Wendell Garner (1970).

The change from a concept of a restrictive processing capacity to one of a flexible competency limited only by the "programming" skill of the systems operator is not trivial. The change is as important as the change from an invertebrate constrictive exoskeleton to the vertebrate flexible endoskeleton. The change heralds a shift from viewing the brain as a telephone-like system to viewing it as computer-like. But before taking up this shift, another and related conceptual difficulty plaguing the application of information measurement theory must be clarified.

Cybernetic control systems were originally devised on the principle that (1) the current state of a system is compared with a "desired" potential state and (2) adjustments are achieved by virtue of repetitions of an error reducing signal whose magnitude reflects the discrepancy between them. Basically, the design of such systems is centered around the desired stable state, is achieved by progressively reducing the discrepancy or error signal, a process called "negative feedback." Norbert Wiener, the author and chief architect of Cybernetics (1948) spent time in the Harvard laboratories of Walter Cannon who conceptualized the neural regulation of the metabolic and physiological environment, the *milieu interieur* (Bernard, 1858), as dependent on negative feedback. The systems of neural regulation of the internal environment were labeled *homeostatic systems*. Wiener took these concepts, spawned by studies on brain function, and related them to his World War II work on engineering applications of what were called servosystems or servomechanisms in the service of aircraft gunnery.

The homeostat, familiar to all in its most popular servosystem engineering form, the thermostat, proved to be as powerful a conceptual tool as information measurement theory, and more generally applicable to the brain sciences, perhaps reflective of its origin. Whereas the homeostatic concept was originally developed to handle the neural regulation of the internal environment, more recent experimental results showed that the negative feedback principle also applied to the neural regulation of sensory input from the external environment (Pribram, 1967), and to the neural regulation of action (Matthews, 1964; Pribram, 1977).

The initial findings in this series demonstrated that muscular control is maintained by a large feedback component which operates on muscle spindle receptors connected in parallel with the contractile muscle fibers (Kuffler, 1953; Matthews, 1964). Next it was shown that tactile sensitivity (Hagbarth & Kerr, 1954), auditory (Galambos, 1956), olfactory (Kerr & Hagbarth, 1955), and visual (Spinelli & Pribram, 1966; Spinelli & Weingarten, 1966) inputs were similarly influenced—i.e. there are connections that bring the brain's activity to bear on the functioning of sensory receptors. Even the excitations originating in the association areas of the cerebral hemispheres influence the sensory input to the brain (Lassonde, Ptito, & Pribram, ~~submitted for publication;~~ Reitz & Pribram, 1969; Spinelli & Pribram, 1967).

These midtwentieth-century results revolutionized the conception of the organization of the reflex (Miller, Galanter, & Pribram, 1960) in neurophysiology and thus also affected the concept of the stimulus-response relationship that had held sway in psychology for decades. No longer could the organism and its brain be conceived as a passive switchboard upon which environmental contingencies play at will. Instead, a self-setting, homeostatic servocontrolled organism searched for and accepted those environmental events it was set to select. In short, instead of stimuli eliciting responses as in the old physiology and psychology, stimuli now became defined by the response (homeostatic) organization of the organism. In biology this change in conceptualization flourished in the studies of animal behavior known as ethology and in psychology the change signaled an abandonment of stimulus-response learning theories in favor of operant conditioning and cognitive conceptualizations (see Pribram, 1971, Chapter 14).

The thermostat as a model brings this change of conceptualization into focus. It is the set point of the thermostat that determines which changes in temperature will be sensed by the system and thus will start or stop the operation of the furnace. Control becomes automatic by virtue of stimulus selection rather than passive reception.

An unexpected dividend accrues in the operation of a homeostatic servocontrolled system: There is a tremendous savings in memory load. Von Foerster has called the servomechanism a "memory without record." By adjusting the set-point of the thermostat one need not keep track of the vagaries and variabilities of the temperatures external to the system—the homeostatic system operates just as well on the hottest summer days and during the coldest winter months, provided it is properly connected to a heat sink and a heat source.

This was the state of conceptualization two decades ago. But, Roger Brown (1962) rightly criticized *Plans and the Structure of Behavior* for the limitations imposed by a purely homeostatic model. Psychoanalytic theory (Freud, 1966/1895), and its derivative, Hullian stimulus-response psychology, when it departed from the telephone model as in its conception of drives and habits, are at best also homeostatic, as is Skinner's conditionable operant (Skinner, 1938). Even ethological formulations of eliciting stimuli and action specific energies are essentially modelled on the homeostatic principle (Hinde, 1954; Lorenz, 1969; Tinbergen, 1951). These limitations are overcome, however, when it is realized that the capacity of homeostats to alter their set-points is implicit in all of these formulations (Pribram & Gill, 1976) and it is this capability that Waddington emphasized in his concept of homeorhesis (Waddington, 1957): a flow towards a future ever-changing set-point rather than a return to a static stable one. Homeo*rhetic* systems are open, future oriented, systems as opposed to homeo*static* systems, which are closed loop. Homeorhesis produces a feed-forward open-loop helical mechanism that is, as we shall see, considerably more consonant with the brain's parallel processing than a serially connected group of homeostats (Pribram, 1977).

On Computers and Programming

Computers as information processing devices have been heralded by the press as harbingers of the second industrial revolution, the revolution in the communication of information. Today's computers depend largely on step-wise serial processing of information (see e.g. the list structuring approach of Newell and Simon (Schank & Abelson, 1977). Despite prodigious speed, serial processing is considerably more awkward than the brain's facility, which, as noted above and detailed below, is based to a large extent on simultaneously carried out parallel procedures. Nonetheless, as a model for brain, computer programming has had a good deal to offer (Miller, Galanter, & Pribram, 1960) and as a model of cognitive computation, the computer program has served as a fruitful analogy, spawning two decades of intense research. More recently, the field of artificial intelligence has developed attempts to enhance computer capabilities, sometimes by patterning itself after natural intelligence (Schank & Abelson, 1977) or by reference to possible brain organizations (Winograd, 1977).

The revolution in information processing was initiated by devising 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. Thus, any item in any list could be addressed by any other item and in turn could address any other item. Items and lists of items therefore became endowed with the capability of addressing themselves (often after running through several other lists), a capacity for self-reflexivity—recursiveness in the technical jargon of programming.

List structures of the sort necessary for program construction have been shown to characterize the organization of brain cortex. The cerebral cortex is composed of columnar modules (lists) of cells (items), which represent a related set of stimulus parameters (Edelman & Mountcastle, 1978; Hubel & Wiesel, 1968). The representations in the somatosensory system, for example, describe adjacent portions of the body surface to compose a portion of the "homunculus" so familiar from texts on brain functioning. Interestingly, however, the relationship between modules (lists) is described by a directional selectivity of *some* of the cells to movement of stimulus from location to location—a finding that can be interpreted as providing a set of prefixes and/or suffixes to the entire columnar list (Pribram, 1977; Werner, 1970). In the visual system *each* cell (item) in the cortical column (list) appears to be endowed with such pre- and suffixes. Most cells, in addition to other selectivities (see below) are movement, direction, and even velocity specific in their selectivities (Pribram, Lassonde, & Ptito, ~~submitted for publication~~) suggesting a richer more finely grained potential network of connectivities than present in the somatosensory system.

Characterization of the representations of cortical cells as similar to items in a program list is often described as feature analysis since the item represents a feature of the entirety to be represented. In fact, the prevailing neurophysiological dogma favors the view that these cells are feature detectors (Barlow, 1972), which suggests that each brain cell is uniquely responsive to one and only one feature. However, the "detector" view is untenable since each cell has multiple selectivities and thus its output is not unique to any one as a detector view would demand: In the visual cortex, for example, a cell may select on the basis of the orientation of lines, their width and spacings, their luminance, their color, the direction of their movement, the velocity of their movement, and even to the frequency of auditory tones.

It appears therefore that each cortical cell is a member of, or a node in, a associative network of cells, (perhaps a set of list structures as the evidence noted above would suggest) and not the sole detector of a solitary feature. Feature analysis must therefore become a function of an entire network of cells addressed by the total pattern of sensory input. The brain thus differs from current computers to some extent: The initial stages of processing are largely parallel rather than serial, and feature analysis results from pattern matching rather than from feature detection. To return to an earlier analogy, the homeostat is a primitive (pattern) matching device in that the thermostat "selects" deviations from a set point. It thus minimizes the memory load, which otherwise would need to "detect" the occasion of each and every temperature that had to be reacted to. An associative net made up of homeostats readily fulfills the requirements of a feature or pattern analyzer based on the matching (or as it is often called, the "template matching") principle.

But there are problems with simple multiply interconnected associative networks of cells even when they are arranged as list structures or homeostats. 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 in the classroom one may be driven at times to consider such a model, it is our capacity to learn that is one of our distinguishing features. Two choices are open to the model builder. One can ignore the evidence for the homeostatic organization of the modules composing the neuropsychological process. Mountcastle and Edelman have done this in their otherwise interesting proposal for a "degenerative" (a many-to-one mapping) as opposed to a redundant associative network model (Edelman & Mountcastle, 1978). In their model, feedback becomes a secondary rather than a primary constituent. Other models such as those of Ashby (1960), Miller, Galanter, and Pribram (1960), and Pribram (1977), place constraints on an associative net made up primarily of homeostatic elements. These constraints take advantage of the modularization of the cortex (and the reflex organization of subcortical structures) by suggesting that each module coordinates with invariant properties of the stimulus. Such coordinate structures (or test-operate-test-exit units, TOTES as Miller, Galanter, and Pribram called they) "cut the associative net into pieces" (to paraphrase Ashby) and can be shown to be organized hierarchically. (Gel'fand, Gurfinkel, Tsetlin, et al. 1971; Miller, Galanter, & Pribram, 1960; Pribram, 1977; Turvey, 1973) For example, as noted earlier, representations of receptor surfaces, homunculi, are constructed in the brain and these are more intimately connected with stimulus properties (features) than with other parts of the brain. A definition of features, "invariant properties" of stimuli thus becomes critical. Gibson (1979) and Turvey (1973) tend to "localize" such properties in the environment of the organism, while nativists (for example, Chomsky, 1972) emphasize the selective nature of the organism's competencies in the face of an environmental cornucopia. The computer model of brain structure and function suggests an intermediate stance: The selection of a workable program depends on a good fit, a match between input and central processor. The computer model thus agrees with evolutionary theory in that adaptation to an ecological niche is implied—albeit with as general purpose a computer as the human brain, that niche may well be more difficult to delimit than the specification of the computer "wetware," i.e., the brain.

On the Hologram and Pattern Analysis

Possible forms of the machinery for extracting invariances ("features") from sensory (including muscle sensory) input have been of considerable interest to neuroscientists and psychologists for a century. As the foregoing discussion has developed, a telephone + homeostat = computer programming model based on a hierarchically constrained associative net, meets most of the requirements such machinery must display. But certain specifications and problems remain. What type of analytic mechanism might spot consistencies—the constancies and "invariances"—in a relatively parsimonious manner without invoking a principle such as "one neurone for one feature"? What sort of machinery would allow for the extremely rapid, practically instantaneous process of perception, its immediacy (Gibson, 1979), and at the same time assure its high resolving power, which provides the fine texture of the images that are so immediately perceived?

Historically, only three classes of answers have been given to these questions. At one extreme is the "feature detector," one neuron for one feature answer, which, as noted above is untenable in the light of currently available neurological evidence. This "detector" model can also be faulted from behavioral evidence (Rock, 1970). At the other extreme is the model proposed by Wolfgang Köhler to account for the distortions of physically measured stimulations in illusions. Köhler emphasized the configurational aspects of perception and suggested that when sensory input arrives in cortical tissue direct current (D.C.) fields result. However, direct current shifts in the cortex were shown experimentally to bias learning and not to influence perception (Stamm & Rosen, 1973), and were thus ruled out as the critical machinery for pattern perception.

Between the extremes of "one neuron one percept" (usually referred to as the "pontifical" or "grandfather" cell dogma) and the D.C. field theory, two more moderate views were proposed. Each of these stemmed from one of the extreme positions. Neurophysiologist Horace Barlow (1972) suggested that the "pontifical" cell be dropped in favor of a set of "cardinal" cells that formed a responsive "college" responsible for a percept. This proposal is little different from that made by psychologist D. O. Hebb (1949) regarding a cell assembly constituted by a response to input (called a phase sequence) and responsible for a percept. In these proposals, the one neuron–one percept is replaced by one cell assembly–one percept. Barlow's and Hebb's proposals differ in that Barlow's college of cardinals has relatively fixed selectivities, i.e., propensities to respond, while Hebb's phase sequenced cell assemblies are more labile both with respect to constituent neurons and to change by experience.

Coming from the field "extreme" of proposals to a more intermediate view is Karl Lashley's proposal that waves are generated in the cortex by sensory input and that these waves interact to produce interference patterns. Lashley, however, did not develop his suggestion either at the neuronal or at the perceptual level. He was, however, 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 characteristics that describe the organization of the morphogenetic field during the development of embryos (Lashley was a zoologist by training). Morphology, the form that various structures take, was considered to be a result of stress lines set up by cleavages that divided the initially homogenous tissue into differentiated parts.

The "interference pattern" proposal was developed for brain function in detail by Pribram (Pribram, 1977, 1966; Pribram, Nuwer, & Baron, 1974). At the neuronal level, the model is based on viewing the hyperpolarizations and depolarizations that are generated in receptive branches (dendrites) on the far side of junctions (synapses) between neurons as constituting wave fronts. Such hyper- and depolarizations are not themselves nerve impulses nor do they invariably result in nerve impulses. They may, however, modulate the patterns of nerve impulses that are separately generated at the origins of axons (in axon hillocks of those neurons that possess axons—many neurons do not, and therefore do not generate nerve impulses; they have been called by Rakic [1976] *local circuit neurons*). The proposal is somewhat similar to that made in quantum physics where the wave equation is treated as a vector on the probability of occurrences of quantal events. The neural "quantual events" are those hyper- and depolarizations that express themselves in some coherent fashion that can be described in wave form terms. These coherent polarizations compose microwaves that are not to be confused with the macro waves that compose the electroencephalogram (which do not have the resolving power necessary to account for the richness of texture of perception). The EEG wave forms reflect the sum of many such microwave processes as well as the synchronized nerve impulse activity that lies within the recording field of the electrode placement (Crueutzfeldt, 1961; Fox & O'Brien, 1965; Verzeano, Dill, Vallecalle, et al., 1968). Molecular storage, perhaps a conformation change in the membrane proteins constituting the junctions and receptive branches of neurons, is assumed to result from repetitions of the microwave structure (Pribram, 1977; Pribram, Nuwer, & Baron, 1974).

At the perceptual level the model implies that sensory input becomes encoded in the quantal microwave structure in such a fashion that image reconstruction can be readily accomplished. This can be done by storing the Fourier or similar transform (see below) of a signal rather than representing it in its simple point-to-point intensive dimensions. (Technically, this involves storing the square of the intensity of a point of stimulation and its complex conjugate, i.e. its phase relationship to the intensity of its neighbors [Pribram, et al. 1974]) What this amounts to is storing the ripples produced on a film (or cortical) surface by the impact of a set of signals (as might be done by filming the ripples as they are produced in a pond by a set of pebbles thrown in). In order to read out an image from such a store, all that is necessary is to invoke the inverse transform (actually the identical mathematical operation in the Fourier procedure) and an image is produced (much as the pebbles again become visible when the film is reversed).

Evidence has been accumulating for almost a century that such wave form descriptions of sensory processing are valid. Helmholtz proposed that the cochlea operates much like a piano keyboard, a proposal subsequently modified by Georg von Bekesy (von Bekesy, 1969, 1967; Dewson, 1964), on the basis of further experimentation that showed the cochlea to resemble more a stringed instrument brought to vibrate at specific frequencies. Nodes of excitation that develop in the vibrating surface (the "strings") account for the piano keyboard-like qualities described by Helmholtz.

Bekesy further developed his model by actually constructing a multiply vibrating surface that he placed on the forearm of a subject. When the phase relationship between the vibrators (there were five in the original model) are appropriately adjusted, a single point of excitation is tactually perceived (von Bekesy, 1967). It was then shown that the cortical response evoked by such vibrations is also single: The percept rather than the physical stimulus (Dewson, 1964) is reflected in the cortical response.

Over the last decade 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, and Robson (Campbell, 1974) found that visual processing of gratings (sets of lines or bars) of various widths and spacings produced apparently anomalous results until the experimenters realized that the system adapts not only to a particular grating "frequency" but its harmonics. The "frequency" of a grating is determined by its spacing—the width of bars and the distance between them—and is thus called a "spatial frequency."

Currently, it has been shown that cells in the visual cortex encode in this "spatial frequency" domain (Movshon & Thompson, 1978; DeValois, Albrecht, & Thorell, 1978; Schiller, Finlay, & Volman, 1976). Most telling are the results of experiments that pitted the neurophysiological "dogma" that the cortical cells were line (bar or edge) detectors against the proposal that they encoded in the wave form (spatial frequency) domain. DeValois showed that the cortical cells were insensitive to bar width and that when crossed with others running perpendicular as in a plaid, the encoding changed dramatically to include the total pattern. Specifically, the cortical cells are selectively sensitive to lines (gratings) presented at a particular orientation—a finding (Hubel & Wiesel, 1959) instrumental in generating the feature detector proposal. If the cells operate as detectors, additions to the pattern of lines (as in a plaid) should not alter the orientation with which the pattern must be presented; the additional lines in the pattern ought to be processed by additional units selective of that orientation. But if, on the other hand, the total pattern of the plaid is being processed by the cell, the orientation of the stimulus presentation would have to be altered. DeValois performed a Fourier transform by computer on each plaid presented. Such transforms show radii at various angles from the original perpendicular arrangement of the lines of the plaid. DeValois found that *all* stimuli had to be rotated to bring these radii into line with the orientation selectivity of the cells when a grating was changed to a plaid. 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 plaid (not its separate lines) is encoded.

There thus remains little doubt that descriptions in the quantal microwaveform domain are valid accounts of sensory processing in audition, touch, olfaction (Freeman, 1975), and vision. Such descriptions also fit the constructions of optical image processing devices called holograms. Holograms were so named by their inventor, the mathematician Dennis Gabor, because each part of the hologram is representative of the whole. In a hologram each quantum of light acts much as a pebble thrown into a pond. The ripples from such pebble spread over the entire surface of the pond (the mathematical expression for this is in fact called a *spread function*, of which the Fourier transform is a prime example). If there are several pebbles, the ripples produced by one pebble originate in a different location from those produced by another pebble, thus the ripples intersect and form interference patterns with nodes where the ripples add and sinks where they cancel. The nodes can be captured on film as oxidations of silver grains if the ripples are produced by light falling on film instead of pebbles falling into water. Note that the information from the impact of each and every pebble or light ray is spread over the "recording" surface, thus the property that each portion of that surface is encoding the whole. And as noted earlier, performing the inverse transform reconstructs the image of the origin of that information.

The holistic properties of holograms are expressed in 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 have no specifiable boundaries.

The properties of holograms that are important for brain functioning are (1) the distribution of information that can account for the failure of brain lesions to eradicate any specific memory trace (engram); (2) the tremendous readily retrievable storage capacity of the holographic domain—the entire contents of the Library of Congress can currently be stored on holofische (microfilm recorded in holographic form) taking up no more space than an attache case; (3) the capacity for associative recall that is inherent in holograms because of the coupling of inputs when they become distributed; and (4) this coupling also provides a powerful technique for correlating—crosscorrelations and autocorrelations are accomplished almost instantaneously. This is why the Fast Fourier Transform (FFT) is so useful in computer operations when statistical correlations are needed or when image construction, as in X-ray tomography, is required.

It is important to realize that holography was a mathematical invention and that is realization in optical systems (as with laser beams) is only one form the mathematics can take. Another common realization is by computer as noted above, and another may well be by brain tissue.

To return for a moment to the classes of neural models that have been proposed for perception: Recall that the quantal microwaveform model (of interference patterns, i.e., holography) derived from a dissatisfaction with both the feature detector and field theoretic stances. E. Roy John (1967) and Uttal (1978) have also developed sophisticated statistical correlation models (Uttall's is based on a spatial autocorrelation function), which differ from the holographic model, however, in that they ignore the quantal microwave domain of brain function. If the computer analogy of brain function is taken seriously, 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 these models when they are followed to their logical, neurological, and psychological ends: nerve impulses arriving at synaptic junctions become pre- and postsynaptic potentials in dendritic receptive fields, which can best be described as Fourier transforms of those inputs. Repetitions of input patterns result in storage (of as yet undetermined nature). A match, i.e., a correlation, is then computed between subsequent inputs and the stored residual from former inputs and the inverse transform of the results of this correlation are our perceptions. The perceptions are then projected away from the computational machinery by appropriate phase relationships as in Bekesy's experiments, in stereophonic sound equipment, and in holograms.

However, the fact that descriptions in the quantal microwaveform domain are valid for both brain function and holography does not automatically assure the validity of the holographic hypothesis of brain function. There are important differences between the brain process and that which makes up the optical information procedure. First, in an ordinary hologram, the wave form is spread more or less over the entire surface of the film. In the brain, the wave form encoding is restricted to the receptive field of a particular cortical cell—in the visual system, for example, a receptive field subtends at most some 5° of visual angle. Thus 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 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 stripping together Fourier-transformed elongated sections of space was invented by Bracewell (1965) to compose a high resolution image of the heavens by radio astronomy. Pollen and Taylor (1974) intepreted some of their neurophysiological results in terms of a strip hologram in which each elongated receptive field (the original, so-called *line detector*) served as a strip in the total. Thus the neural hologram because of its patchwork characteristic shows properties that are purely holographic (discussed below) and also properties 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 non-holographic properties of perception as location and movement in the space and time domain.

Further, as noted earlier, each cortical cell is selective of a variety of stimulus dimensions, which, in the visual system for instance, can range from spatial frequency through color, directional movement, and velocity of a visual stimulus to a highly specific tuning to an auditory tone. Recordings from small groups of neurons in the visual cortex suggest that other aspects of situations are also encoded (Pribram, Spinelli, & Kamback, 1967). The neural holographic properties of brain cortex are therefore only one set among many; they are, however, a powerful set that not only accounts for hitherto unexplained aspects of brain functioning but brings these into relationship with the revolution in modern physics occasioned by quantum and relativity theory.

What are the characteristics of this holographic-like quantum order of physical reality? It is first of all non-sensical (i.e. it does not correspond to sense perception), thus counterintuitive. Second, this order—which Bohm (1965) calls *implicate* to distinguish it from the ordinary *explicate* sensory order—is non-objective. The objective, explicate order is made up of the images by which we know objects. These images are constructed by lenses: THE LENSES AND LENS/LIKE CHARACTERISTICS OF OUR SENSES, THE LENSES, OFTEN CALLED "objectives," of our microscopes and telescopes. By contrast, the holographic-like implicate non-objective reality is not composed of things; it is filled with no-thing but with quantally constituted microwaveforms and their interactive constituents such as constructive (nodal) and destructive interferences. Leibnitz described such a reality in his *Monadology* (1965), in which the universe was represented in each monad, a windowless portion of the whole. Leibnitz, of course, was with Newton, the originator of the calculus that Gabor used to devise the hologram. Substitute "lens-less" for "windowless" and the monad becomes holographic.

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

The fact that the holonomic implicate order is boundariless, that every part enfolds or "contains" the whole, that therefore the distinction between observer and observed is blurred so that observations no longer result in objects (i.e., observables) has led physicists to note the intrinsic interweaving of perception and consciousness on the one hand and macro- and microphysical reality on the other. Thus Bohm includes an appendix on "Perception" in his book on the Special Theory of Relativity (1951), and Wigner exclaims that modern physics deals with "relations among observations" not among "observables." An observable is characterized by invariance across observations; Heisenberg (1959) in his famous principle pointed out that in microphysics, the observed varies with the stance and instrumentation of the observer. Bohr enunciated his principle of complementarity on the same grounds (1966). And, of course, Einstein made the same point with regard to the macro-universe in his general theory of relativity. This intimate enfoldment of observation into observable has led some of these physicists, and some philosophers, e.g. Whitehead (1958), 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), 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 macro- 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 philosophers of the Vienna circle, e.g. Carnap (1940), Feigel (1954), and their scientist heirs (e.g. Bridgeman, 1938, Skinner, 1938) of only a few decades ago.

The impact on society of this new science is hard to anticipate. For example, the changed views of the mind/brain relationship resulting from the dematerialization of matter in modern physics and the holonomic implicate nature of the relationship of observer and observed can have dramatic consequences on man's view of himself, his nature, and his relationship to nature. It is certain that a spiritual resurgence is to come, but just what form it will take and how it will affect our daily lives is harder to predict. Medical practice may be completely revamped by holistic (i.e., holy) procedures: e.g., it is already established that placebos generate the secretion of endorphins in patients—endorphins being morphine-like substances endogenously produced; economics may take a new turn when holonomic principles are brought to bear; even politics, the practice of the possible, may find the limits of the possible expanded beyond any current horizons.

Nor is there any reason to expect abductive reasoning that has wrought the current revolution in science to cease. New developments, technical and theoretical, in engineering, chemistry, and psychology will continue to fertilize the brain sciences provided careful reasoning by analogy is fostered. Scientific abduction is not loose analogizing. Rather, it is the first step in taking a metaphor, using it to construct a precise model from inductively systematized data and testing that model deductively. If the past presages the future, exciting discoveries, abductively induced, lie ahead.

Conclusion

In this essay I have related to brain processes the conceptualization developed in studying communications, control, computational, and imaging systems. In each instance I have reviewed the recent history of these relationships, the issues to which the conceptualizations were brought to bear, some problems that developed, and some current tentative resolutions of these problems. Communication systems such as the telephone gave rise to a quantitative measure of the information transmitted in terms of a reduction in uncertainty. When applied to brain function and psychology, difficulties arose. These difficulties suggested a shift of emphasis from an externally constrained channel capacity to a flexible internal programmed channel competency.

A second problem that arose was that of relating communication to control. Cybernetics purported to provide such a relationship but failed to specify how this was to be accomplished. In this essay it was suggested that an early distinction between "good" and "bad" information be recognized and that "bad" information, i.e. error signals, are in fact measures of redundancy rather than of uncertainty reduction. Error signals are generated through negative feedback in the cybernetic unit, the servomechanism. Thus, the relationship between information measures and control is suggested to be the relationship between uncertainty reduction and the enhancement of redundancy.

Measures of information and redundancy were quickly found to be of limited use in the neural and behavior sciences because additional indices of structure were necessary to describe cognitive organizations.

Parallel processing forms much of the brain's sensory and motor capabilities. The essentials of the needed parallel processing were found in image constructing devices such as holograms. In addition to image processing, holograms also accounted for the distributed nature of memory traces. Evidence was reviewed to show that, among other attributes, the auditory, somatosensory, olfactory, and visual systems encode holistically in the wave domain—i.e., cells in the sensory cortex can be shown to resonate to bands of temporal and spatial frequencies in the sensory input. The import for psychology for such image constructive operations was shown to be far reaching. Not only could the mechanisms of ordinary perception and memory be more precisely modeled, but that extraordinary order usually relegated to mystical and religious experience could be firmly apprehended.

As noted in the introduction, these advances in understanding have been prodigious, and one can take the stance that we have seen the last coming before Armageddon—a last glimpse of truth and beauty before our hubris destroys us. But, as we reviewed them, the brain facts themselves and the theories derived from the interactive functioning of human brains suggest a different more optimistic stance. What we have already learned, when assimilated into our culture, will undoubtedly change the context within which further brain facts will be gathered and viewed. Such contextual changes through abductive reasoning have in the past continually renewed the human endeavor. The way our brains are constructed gives every expectation that such renewals will continue.

insert ACKNOWLEDGMENT (courtesy)

~~NOTES~~ References

re-set in alphabetical order — see typed pages

1. C. S. Peirce, *Collected Papers* (Cambridge, Mass.: Harvard University Press, 1934).

2. C. E. Shannon and W. Weaver, *The Mathematical Theory of Communications* (Urbana: The University of Illinois Press, 1949)

3. W. R. Ashby, *An Introduction to Cybernetics* (New York: John Wiley & Sons, 1963)

4. K. H. Pribram, "Self-consciousness and intentionality," In: G. E. Schwartz and D. Shapiro (Eds) *Consciousness and Self-Regulation, Vol. 1* (New York: Plenum, 1976), pp. 51-100.

5. G. A. Miller, "What is Information Measurement?" *American Psychologist*, 8 (1953): 3-11.

6. K. Kahneman, *Attention and Effort* (Englewood Cliffs, New Jersey: Prentice-Hall, 1973)

7. D. E. Broadbent, "Division of Function and Integration," *Neurosciences Study Program, III.* (New York: MIT Press, 1974)

8. K. H. Pribram, "How Is It That Sensing So Much We Can Do So Little?", Neuroscience Third Study Program, III. (New York: MIT Press, 1974): pp. 249-261.

9. N. Chomsky, "Formal Properties of Grammars," In: R. D. Luce, R. R. Bush, and E. H. Galanter (Eds) *Handbook of Mathematical Psychology*, (New York: John Wiley and Sons, 1963): 323-418.

10. K. H. Pribram, *Languages of the Brain*, (Englewood Cliffs, New Jersey: Prentice-Hall, 1971; 2nd edition, Monterey, Calif.: Brooks/Cole, 1977)

11. K. H. Pribram and D. McGuinness, "Arousal, activation and effort in the control of attention." Psychology Review, 82(2) (1975): pp. 116-149.

12. G. A. Miller, "The Magical Number Seven, Plus or Minus Two, or, Some Limits on Our Capacity for Processing Information." *Psychology Review*, 63 (2) (March, 1956): 81-97.

13. H. A. Simon, "How Big is a Chunk?", *Science*, 183 (1974): 482-488.

14. W. R. Garner, "The Stimulus in Information Processing," *American Psychologist*, 25 (1970): 350-358.

15. N. Wiener, *Cybernetics or Control and Communication in the Animal and the Machine* (New York: John Wiley & Sons, 1948)

16. C. Bernard, *Lecons sur la Physiologie et la Pathologie du Systeme Nerveux* (Paris: J. B. Bailliere et fils, 1858)

17. K. H. Pribram, "The New Neurology and the Biology of Emotion," *American Psychologist*, 22 (10) (1967): 830;838.

18. G. A. Miller, E. Galanter, and K. H. Pribram, *Plans and the Structure of Behavior* (New York: Henry Holt & Co., 1960)

19. P. B. C. Matthews, "Muscle Spindles and Their Motor Control," *Physiological Review*, 44 (1964): 219-288.

20. S. W. Kuffler, "Discharge Patterns and Functional Organization of Mammalian Retina," *Journal of Neurophysiology* 16 (1953): 37-69.

21. K. E. Hagbarth and D. I. B. Kerr, "Central Influences on Spinal Afferent Conduction," *Journal of Neurophysiology*, 17 (3) (May, 1954): 295-307.

22. R. Galambos, "Suppression of Auditory Nerve Activity by Stimulation of Efferent Fibers to Cochlea," Journal of Neurophysiology, 19 (1956): 424-437.

23. D. I. B. Kerr and K. E. Hagbarth, "An Investigation of Olfactory Centrifugal Fiber System," *Journal of Neurophysiology*, 18 (1955): 362-374.

24. D. N. Spinelli and K. H. Pribram, "Changes in Visual Recovery Functions Produced by Temporal Lobe Stimulation in Monkeys," *Electroencephalography and Clinical Neurophysiology*, 20 (1966): 44-49.

25. D. N. Spinelli and M. Weingarten, "Afferent and Efferent Activity in Single Units of the Cat's Optic Nerve," *Experimental Neurology*, 3 (1966): 347-361.

26. D. N. Spinelli and K. H. Pribram, "Changes in Visual Recovery Function and Unit Activity Produced by Frontal and Temporal Cortex Stimulation," *Electroencephalography and Clinical Neurophysiology*, 22 (1967): 143-149.

27. S. L. Reitz and K. H. Pribram, "Some Subcortical Connections of the Inferotemporal Gyrus of Monkey," *Experimental Neurology*, 25 (1969): 632-645.

28. M. C. Lassonde, M. Ptito, and K. H. Pribram, "Intracerebral Influences on the Microstructure of Visual Cortex" ~~(Submitted)~~, Experimental Brain Research (1981, in press)

29. H. von Foerster, "Memory Without Record," In: D. P. Kimble (Ed.) *The Anatomy of Memory*, ([illegible], 1965), pp 388-433.

30. R. Brown, "Models of Attitude Change," In: R. Brown, E. Galanter, E. Hess, and G. Mandler (Eds) *New Directions in Psychology* (New York: Holt, Rinehart & Winston, 1962), pp 1-85.

31. S. Freud, *Project for a Scientific Psychology*, 1895. (Standard Edition, Vol. I, London: The Hogarth Press, 1966)

~~32. B. F. Skinner, *The Behavior of Organisms*, (New York: Appleton-Century-Crofts, 1938)~~

33. K. Lorenz, "Innate Bases of Learning," In: K. H. Pribram (Ed) *On the Biology of Learning* (New York: Harcourt, Brace & World, 1969), pp 13-94.

34. N. Tinbergen, *The Study of Instinct* (Oxford: University Press, 1951)

35. R. A. Hinde, "Factors Governing the Changes in Strength of a Partially Inborn Response, as Shown by the Mobbing Behavior of the Chaffinch (Fringilla Coelebs)," *Proceedings of the Royal Society*, B 142 (1954): 306-358.

36. K. H. Pribram and M. M. Gill, *Freud's Project Re-Assessed* (New York: Basic Books, 1976)

37. C. H. Waddington, *The Strategy of the Genes* (London: George Allen & Unwin, 1957)

38. A. Newell, J. C. Shaw and H. A. Simon, "Elements of a Theory of Human Problem Solving," Psychology Review, 65 (1958): 151-166.

39. R. C. Schank and R. P. Abelson, *Scripts, Plans, Goals and Understanding* (Hillsdale, New Jersey: Lawrence Erlbaum Assoc., 1977)

40. T. Winograd, "Framework for Understanding Discourse," *Stanford University Intelligence Monograph* (June, 1977)

41. G. M. Edelman and V. B. Mountcastle, *The Mindful Brain* (Cambridge, Mass.: The MIT Press, 1978)

42. D. H. Hubel and T. N. Wiesel, "Receptive Fields and Functional Architecture of Monkey Striate Cortex," *Journal of Physiology*, 195 (1968): 215-243.

43. G. Werner, "The Topology of the Body Representation in the Somatic Afferent Pathway," In: G. C. Quarton, T. Melnechuk and F. O. Schmitt (Eds) *The Neurosciences, Vol. II* (New York: Rockefeller University Press, 1970): pp. 605-616.

44. K. H. Pribram, M. Lassonde and M. Ptito, Classification of Receptive Field Properties," Experimental Brain Research (1981, in press).

45. H. B. Barlow, "Single Units and Sensation: A Neuron Doctrine for Perceptual Psychology?" *Perception*, 1 (1972): 371-394.

46. W. R. Ashby, *Design for a Brain: The Origin of Adaptive Behavior*, (New York: John Wiley & Sons, 1960)

47. K. S. Lashley, "In Search of the Engram," *Physiological Mechanisms in Animal Behavior* (New York: Academic Press, 1950), pp. 454-482.

48. I. M. Gel'fand, V. S. Gurfinkel, H. L. Tsetlin, et al. "Some Problems in the Analysis of Movements," In I. M. Gel'fand, V. S. Fomin and M. T. Tsetlin (Eds) *Models of the Structural-Functional Organization of Certain Biological Systems* (Cambridge, Mass.: The MIT Press, 1971), pp. 329-345.

49. M. T. Turvey, "Peripheral and Central Processes in Vision: Inferences from an Information Processing Analysis of Masking with Pattern Stimuli," *Psychology Review*, 80 (1) (1973): 1-52.

50. J. J. Gibson, *The Ecological Approach to Visual Perception* (Boston: Houghton Mifflin, 1979)

51. N. Chomsky, *Language and Mind* (New York: Harcourt, Brace & Jovanovich, 1972)

52. J. J. Gibson, *The Ecological Approach to Visual Perception* (Boston: Houghton and Mifflin, 1979)

53. I. Rock, "Perception from the Standpoint of Psychology," In: K. H. Pribram, D. A. Hamburg and A. J. Stunkard (Eds) *Vol. XLVIII*, Association for the Research of Nervous and Mental Disease (1970) pp. 1-11.

54. J. S. Stamm and S. C. Rosen, "The Locus and Crucial Time of Implication of Prefrontal Cortex in the Delayed Response Task," In: K. H. Pribram and A. R. Luria (Eds) *The Psychophysiology of the Frontal Lobes* (New York: Academic Press, 1973) pp. 139-153.

55. D. O. Hebb, *The Organization of Behavior: A Neuropsychological Theory* (New York: John Wiley, 1949)

56. A. Goldscheider, "Uber die materiellen veranderungen bei der associationsbildung," *Neurologie Zentralblatt*, 25 (1906): 146.

57. K. H. Pribram, "Some Dimensions of Remembering: Steps Toward a Neuropsychological Mode of Memory," In J. Gaito (Ed) *Macromolecules and Behavior* (New York: Academic Press, 1966), pp. 165-187.

58. K. H. Pribram, M. Nuwer and R. Baron, "The Holographic Hypothesis of Memory Structure in Brain Function and Perception," In: R. C. Atkinson, D. G. Krantz, R. C. Luce and P. Suppes (Eds) *Contemporary Developments in Mathematical Psychology* (San Francisco: W. H. Freeman & Co., 1974) pp. 416-467.

59. P. Rakic, *Local Circuit Neurons* (Cambridge, Mass.: The MIT Press, 1976)

60. S. S. Fox and J. H. O'Brien, "Duplication of Evoked Potential Waveform by Curve of Probability of Firing a Single Cell," *Science*, 147 (1965): 888-890.

61. O. D. Creutzfeldt, "General Physiology of Cortical Neurons and Neuronal Information in the Visual System," In: M. Brazier (Ed) *Brain and Behavior* (Washington, D.C.: American Institute of Biological Sciences, 1961) pp. 299-358.

62. M. Verzeano, R. C. Dill, E. Vallecalle, et al., "Evoked Responses and Neuronal Activity in the Lateral Geniculate," *Experentia*, 24 (1968): 696-698.

63. G. von Bekesy, *Experiments in Hearing* (New York: McGraw Hill Book Co., 1960)

64. G. von Bekesy, *Sensory Inhibition* (Princeton, N.J.: Princeton University Press, 1967)

65. J. H. Dewson, III. "Cortical Responses to Patterns of Two-Point Cutaneous Stimulation," *Journal of Comparative and Physiological Psychology*, 58 (1964): 387-389.

66. Campbell, F. W. The transmission of spatial information through the visual system. In F.O. Schmitt and F.G. Worden (Eds) *The Neurosciences Third Study Program*, Cambridge, Mass.: (The MIT Press, 1974) pp 95-103.

67. Schiller, P. H., Finlay, B. L., and Volman, S. F. Quantitative studies of single-cell properties in monkey striate cortex. *Journal of Neurophysiology*, (1976) 39: 1288-1374.

68. Movshon, J. A., Thompson, I. D., and Tolhurst, D. J. Rceptive field organization of complex cells in the cat's striate cortex. *Journal of Physiology*, (1978)

69. De Valois, R. L., Albrecht, D. G., and Thorell, L. G. Spatial tuning of LGN and cortical cells in monkey visual system. In H. Spekreijse (Ed) *Spatial Contrast*, (Amsterdam: Monograph Series, Royal Netherlands Academy of Sciences, 1978.)

70. Hubel, D. H. and Wiesel, T. N. Receptive field of single neurones in the cat's striate cortex. *Journal of Physiology*, 1959, *148*, 574-591.

71. Freeman, W. *Mass Action in the Nervous System* (New York: Academic Press) 1975.

72. John, E. Roy, *Mechanisms of Memory*, New York: Academic Press, 1967.

73. Uttal, W. R., *Psychobiology of Emotion*, Hillsdale, N.J.: Erlbaum, 1978.

74. Robson, J. G. Receptive fields: Neural representation of the spatial and intensive attributes of the visual image. In E. C. Carterette (Ed) *Handbook of Perception, Vol. V, Seeing*, New York: Academic Press, 1975.

75. For reference to Ross, see Leith, E. N. White-light holograms. *Scientific American*, 1976, *235*(4), 80.

76. Bracewell, R. *The Fourier Transform and its Applications*. New York: McGraw-Hill, 1965.

77. Pollen, D. A. and Taylor, J. H. The striate cortex and the spatial analysis of visual space. In F.O. Schmitt and F.G. Worden (Eds) *The Neurosciences Third Study Program*. Cambridge, Mass.: The MIT Press, 1974, pp 239-247.

78. Pribram, K. H., Spinelli, D. N., and Kamback, M. C. Electrocortical correlates of stimulus response and reinforcement. *Science*, 1967, *157*,94-96.

79. Bohm, D. *The Special Theory of Relativity*, (New York: W. A. Benjamin, Inc., 1965), pp. 236.

80. Leibnitz *Monadology and Other Philosophical Essays*. 1965 translation by P. and A. Schrecker (Indianapolis: Bobbs-Merrill Co.)

81. For review of the Einstein, Podolsky and Rosen Experiment and Bell's Theorem see B. d'Espagnat, "The Quantum Theory and Reality," Scientific America, 241(1971):158-81

82. Pribram, K. H. Holonomy and structure in the organization of perception. In J. H. Nicholas (Ed) *Images, Perception and Knowledge* (Dordrecht-Holland: C. Reidel, 1977) p. 4

83. Bohm, D. *Quantum Theory*, (Englewood Cliffs, N.J.: Prentice-Hall, Inc. 1951), pp 646.

84. Heisenberg, W. *Physics and Philosophy*, (London: G. Allen and Unwin, 1959).

85. Bohr, N. *Atomic Physics and Human Knowledge*, (New York: Vintage Press, 1966).

86. Whitehead, A. N. *Modes of Thought*, (New York: Capricorn Books, 1958).

87. Pribram, K. H. Transcending the mind/brain problem. *Zygon* (1979) 14(2): 19-30.

88. Capra, F. *Tao of Physics*, (Boulder, Colorado: Shambhala, 1975).

89. Carnap, R. Science and analysis of language. *Journal of Unified Science*, (1940) p. 401.

90. Feigl, H. Scientific methods without metaphysical presuppositions. Philosophical Studies (1954), p. 406.

91. Bridgeman, B. Operational analysis. *Philosophy of Science*, (1938), p. 399.

92. Skinner, B. F. *The Behavior of Organisms*, (New York: Appleton-Century-Crofts, 1938).

Acknowledgements:

[illegible] revised and [illegible] version of an address [illegible] and first published in [illegible] [illegible] supported by a life time research career award [illegible]