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Karl Pribram turns our attention to the essential question of education: how humans learn, in terms of our emerging knowledge of the inherent operational logic of the brain.

MEANING IN EDUCATION

Karl H. Pribram
Neuropsychological Laboratories
Stanford University

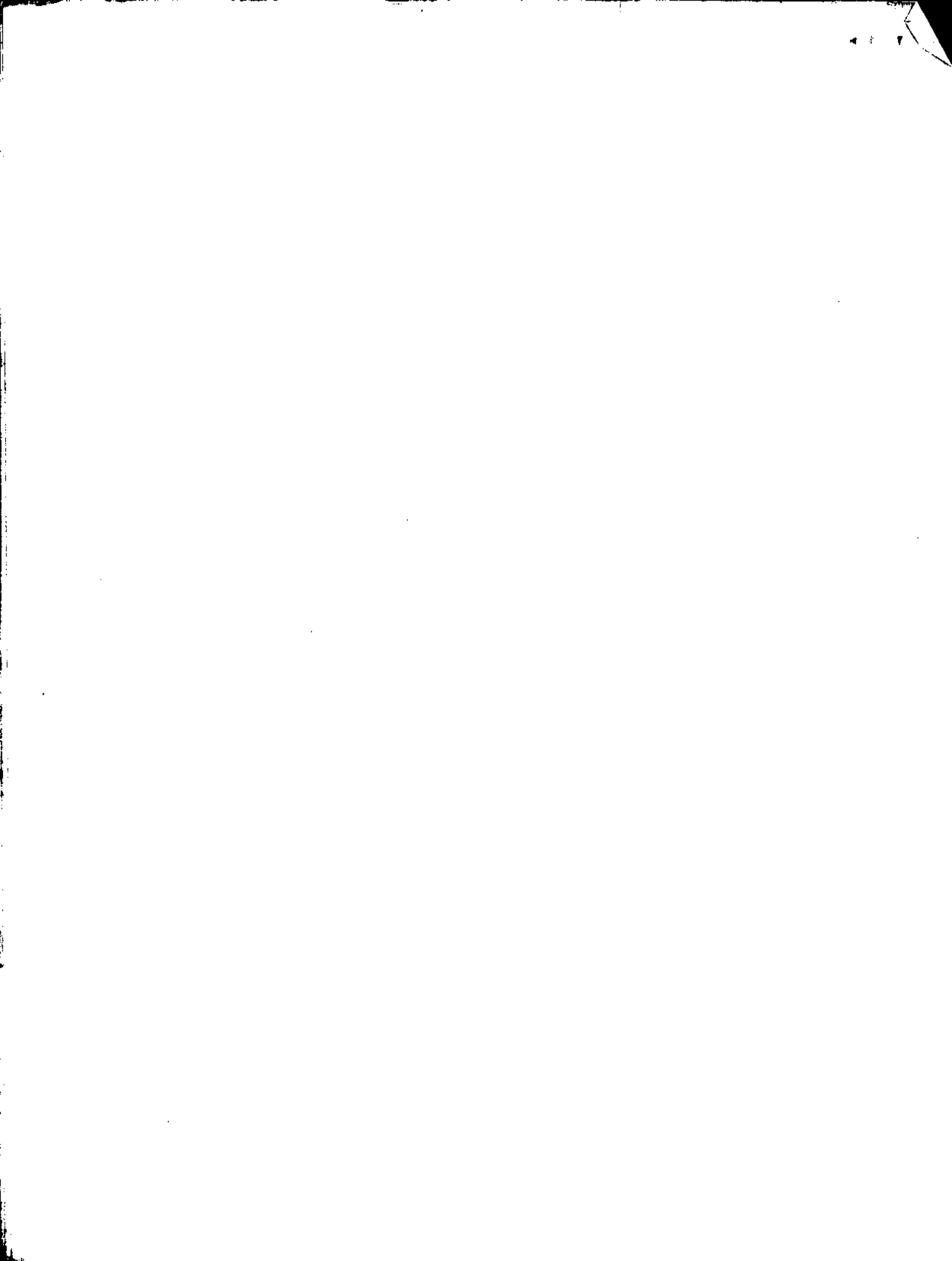
"If you ask an investigator why he does not try this or that wild theory, he will say, 'It does not seem reasonable.' It is curious that we seldom use this word where the strict logic of our procedures is clearly seen. We do [not] say that a mathematical error is not reasonable. . . ."

Charles Sanders Peirce, Collected Papers,
Vol. V, 1934, p. 107.

A briefer version of this paper was presented to the American Educational Research Association annual meeting, Chicago, Illinois, 1968.

Education: Training in Coding

We have come once again to a period in history where the difference in outlook between generations has become magnified. This "generation gap" reflects directly on education, since education entails communication between



generations. As such the job of educators is to transmit information and our schools have been occupied rightly with problems of information storage and retrieval--what ought to be taught, how often it needs repeating, how much can be crowded into a curriculum and how to examine for factual retention.

But it seems this is not enough. From those whom we presume to educate we hear rumblings of distrust, generated in part by our failure to fill their educational needs. From society as a whole we feel pressure for change, but this pressure is ill-defined for we have not provided leadership in discussing what education might be for. We are shown lacking by such devices as brain draining which place at our disposal attributes we do not sufficiently supply, but we have not asked what these attributes might be.

Whatever the specific discontents, discontent is there to probe. Could it be that preoccupation with information is self-defeating? Could it be that the mere acquisition of knowledge is sufficiently unsettling to make imperative an attempt also to impart something additional, i.e. meaning?

Information measurement theory gives an affirmative answer to these questions. In an organism endowed with memory, the acquisition of information leads by definition to storage. This stored information in turn becomes the context within which new events do or do not become informative; thus, the more this organism knows the greater his uncertainty. This ever increasing uncertainty must be countered in some fashion. My thesis will be that meaning (the gerund of an Old English word for intend, give purpose to) is what is necessary.

I want to propose here the possibility that meaning in education can be achieved. This proposition is derived from a long series of studies performed in my laboratories aimed at the problem of how the brain works while an

organism is learning, remembering, or forgetting. Again and again my experiments showed that how much may be learned or remembered--indeed even what may be learned or remembered--is at any moment determined as much by the context, the set and setting, in which an informative item is placed as by that item per se. Further, I found that our knowledge of how to manipulate the content-context relationship, or even how to think about it, was limited; we knew that somehow repetition was essential, but knew little about which forms of repetition were effective and which were not. Finally, it became apparent that these patterns of repetition constitute codes, and that cracking the codes would be tantamount to understanding how information storage and retrieval are best accomplished.

In short, my proposal is that the extent of learning, remembering, and forgetting depends on the codes into which events are patterned, and that it is coding which determines meaning. By this I do not want to convey merely another restatement of the Sapir-Whorf hypothesis. Rather I have in mind something similar to Charles Peirce's Theory of Meaning. But more of this at the end of the paper.

First, what is a code? Not so long ago my laboratory came into proud possession of a computer. Very quickly we learned the fun of communicating with this mechanical mentor. Our first encounter involved twelve rather mysterious switches which had to be set in a sequence of patterns, each pattern to be deposited in the computer memory before resetting the switches. Twenty such instructions or patterns constituted what is called the "bootstrap" program. After this had been entered we could talk to the computer --and it to us--via an attached teletype.

Bootstrapping is not necessarily an occasional occurrence. Whenever a fairly serious mistake is made--and mistakes were made often at the beginning--the computer's memory is disrupted and we must start anew by bootstrapping. Imagine setting a dozen switches twenty times and repeating the process from beginning every time an error is committed:

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U U D D U U U D U D U D
U U U U U U U U U D D D
U U U U D U D U D U U U
U U D D U U U U U U U U
U U D D U U U D U U D D
D D U D D D U D D U U U
D D U D D D U D D U U U
U D U D D U D U U D U D
U D U D U U U U U U D U
D U D D U U U U U U U U
D U U U U U U D D U U

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and so on.

Imagine our annoyance when the bootstrap didn't work because perhaps on setting the 19th instruction an error was made in setting the eight switch. Obviously, this was not way to procede.

Computer programmers had faced this problem early and solved it simply. Conceptually, the twelve switches were divided into four triads and each combination of up-down within each triad given an Arabic numeral, thus:

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D D D became 0
D D U became 1
D U D became 2
D U U became 3
U D D became 4
U D U became 5
U U D became 6
U U U became 7

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Conceptually, switching the first toggle on the right became a 1, the next left a 2, the next after that a 4 (and the next an 8 if more than a triad of switches had been necessary, i.e. if for instance our computer had come with sixteen switches, we should have conceptually divided the array into quads). Thus the bootstrapping program now consisted of a sequence of twenty patterns of four Arabic

numerals:

e.g. 3 7 2 2
0 0 1 4
3 4 5 6
2 2 1 5
1 0 3 7
etc.,

and we were surprised at how quickly those who bootstrapped repeatedly actually came to know the program by heart. Certainly fewer errors were made in depositing the necessary configurations; the entire process was speeded and became, in most cases, rapidly routine and habitual.

Once the computer is bootstrapped it can be talked to in simple alphabetical terms: e.g. JMP for jump, CLA for clear the accumulator, TAD for add, etc. But each of these mnemonic symbols merely stand for a configuration of switches. In fact, in the computer handbook the arrangement for each mnemonic is given in Arabic notation: e.g. CLA = 7200. This, in turn, is easily translated into U U U D U D D D D D D D, should we be forced to set the switches by hand because the teletype has gone out of commission.

Programming thus is found to be in the first instance the art of devising codes, codes that facilitate learning, remembering, and reasoning. The logic of a computer is primarily a code, a set of signals which allows ready manipulation. The power of a program lies in the fact that it is a useful code. If you doubt this, try next month to check your bank statement against your record of expenditures and do it all using Roman rather than Arabic numerals. Can you imagine working out our national budget in the Roman system?

I have belabored this point because I believe educators today fail to recognize that coding is central to their task. To emphasize this view I might even go so far as to suggest that the job of education is to provide skill in

coding.

How then is such skill to be developed? What forms can coding take? How does one communicate a code? How does one learn to use it?

Here the results of research in brain function prove to be helpful. For, if we know some of the basic operations by which the brain codes signals we can facilitate the teaching of coding by making it consonant with the processes inherent in our pupils. For example, had our computer been outfitted with switches which had multiple settings, rather than only the on-off possibility, the coding problem for bootstrapping would have been somewhat different.

The nervous system, like the computer, has as its primary signalling device an on-off type of process. The nervous system, like the programmer, has to find ways by which to convert sequences of patterns of on-off events into usable, i.e. processable codes. This is accomplished in the nervous system by the arrangement of inhibitory and decremental mechanisms which act to group signals and to allow time for depositing them. Grouping is accomplished by the process of lateral or surround inhibition through which the activity in one neuron causes a reduction of activity in its neighbors; time for deposit depends on a decrementing process through which a neuron relatively quickly reduces its own activity through negative feedback. Decremental and inhibitory mechanisms allow the occurrence of an alphabet of states to supplant the restrictions imposed by coding solely by on-off patterns of nerve impulses. Thus, simple neural "words" (analogous to those composed of Arabic numerals in our initial bootstrap programming of the computer) can be manipulated by our input systems. A complex series of patterns of very simple on-off elements has been coded into a simpler series of patterns of somewhat more complex elements. The analogy with computer mechanisms can be carried even further: a hardware wiring diagram by which such transformations might be accomplished in a computer looks remarkably similar to

a diagram of the organization of the retinal structure known to organize the living visual process. This exchange between a nonrepetitive series of patterns made up of repetitive elements and a repetitive series of patterns made up of nonrepetitive elements is the essence of coding.

Images

One of the fascinating things we have learned about the operation of the brain is that, within any of its systems, information becomes distributed. Extensive removals and injuries impair performance remarkably little until some critical point is reached. I have elsewhere detailed a type of mechanism consonant with the known facts of neuroanatomy and neurophysiology which can accomplish such distribution of information (Pribram, 1969). Here it is sufficient to note that such a mechanism actually allows the construction and reconstruction of Images by a process in which only a limited number of variables need be coded. This then would be a degradation of patterns of neural signals back into simpler components. However, these components now no longer represent the presence or absence (on and off) of receptor events but are indicators of relationships among the receptor events. Imaging therefore involves a coding process by which a neural pattern can fully represent its origin. This isomorphism results from the fact that the transformations performed on receptor events are completely reversible.

The issues involved in Image construction have been reviewed incisively by Donald Hebb in the first three chapters of his classic volume, The Organization of Behavior (1949). He states, "One must decide whether perception is to depend (1) on the excitation of specific cells or (2) on a pattern of excitation whose locus is unimportant." Hebb makes his choice; "a particular perception depends on the excitation of particular cells at some point in the central nervous system."

As neurophysiological evidence has accumulated--

especially through the microelectrode experiments of Jung (1961), Mouncastle (1957), Maturana et al. (1960), Hubel and Wiesel (1962), this choice appears vindicated; the microelectrode studies have identified neural units responsive only to one or another feature of a stimulating event such as directionality of movement, tilt of line, etc. Today, the body of neurophysiological opinion would, I believe, agree with Hebb that one percept corresponds to one neural unit.

But Hebb's choice turns out to be a Hobson's choice; patterns of excitation must, of course, depend for their origin upon the excitation of specific cells, but the patterns become to some extent independent of cells as units and become instead the designs imposed by the junctional anatomy, the synaptic and dendritic microstructure of the brain. These designs serve, in the proper circumstance, as the neurological equivalents of percepts.

I agree with Hebb's further assumption that what one recognizes depends a good deal on the previous experience one has had, but I differentiate from this the direct immediacy of an Imaged psychological present, its existential complexity upon which the holistic Gestalt argument on perception depends. In his approach Hebb has confused the historical development of the recognition process and what is Imaged. It takes many hours of labor to construct a program which allows a computer to make calculations, but the calculations are performed by the built-in machinery of the computer in microseconds. It takes many hours to learn to recognize unfamiliar patterns, but infants a few weeks old have been shown to estimate correctly the relative size of figures placed at various distances (size constancy) and to distinguish a figure presented in various rotations (shape constancy). Learning is only part of the problem of what is recognized. The Gestaltists were in large measure correct in their nativism. Inherited built-in neural mechanisms give rise to imaging. But the Gestaltists were wrong in suggesting that this is the entire story of perception. Now, however, the pendulum has swung far in the other direction and the

danger is that a whole bevy of interesting phenomena will become neglected because of an exclusive interest in the problem of how we learn to recognize.

When Hebb wrote his book, two general views of the operation of the nervous system were dominant. One was well substantiated, the other was not. The well substantiated view dealt with the generation of nerve impulses and their transmission across connections between nerves; the other view dealt with fields of electric potentials. Wolfgang Köhler based his Gestalt arguments on these neuro-electrical fields and went out to prove their ubiquitous existence in the decade after the publication of Hebb's statement.

I was fortunate to be able to partake in these explorations. The experimental attack proved successful (Köhler, 1958), and others in my laboratory and elsewhere have recorded and imposed direct current fields and shown correlations with neural function and behavior (Guzmit, 1961; Stamm, 1964; Morrell, 1961). Direct current (D.C.) fields restricted to the appropriate region are generated when an organism is stimulated through one or another sensor portal. The imposition of D.C. fields directly on the brain can retard or speed learning, depending on the polarity of the imposed potential. When it came to publication, however, Köhler and I parted company because he insisted at the time on the connection between the D.C. fields and perception. Later, when I had finished experiments in which I implanted aluminum hydroxide cream over the cortical surface, without impairing pattern recognition, we were again able to come to terms (Kraft, Obrist, and Pribram, 1960; Stamm and Knight, 1963; Stamm and Pribram, 1960; Stamm and Pribram, 1961; Stamm, Pribram, and Obrist, 1958; Stamm and Warren, 1961). The experiments showed that pattern discrimination performance remains intact despite marked disruption of D.C. and E.G.G. activity. Köhler had never accepted experiments performed by Lashley (Lashley, Chow, and Semmes, 1951) in which gold foil was used to distort neuroelectric fields as evidence against his theory, nor did he yield to Sperry's

crosshatches (Sperry, Miner, and Meyers, 1955) into which insulating mica strips had been placed. But when faced with the evidence from the aluminum hydroxide cross-implantations, he exclaimed, "That ruins not only my D.C. fields but every other current neurological theory of perception."

Let me briefly review the evidence which has accrued since that conversation to dispel for me this dismal view of the neurology of perception. Nerve impulse generation and transmission is but one of the important electrical characteristics of neural tissue. Another characteristic is the slow potential microstructures: though slow potentials are akin to Köhler's D.C. fields, they differ importantly in that they are not diffuse but sharply localized at the junctions between neurons or in dendrites where they even may be miniature spikes that more often than not attenuate when they begin to propagate. Nerve impulse conduction leads everywhere in the central nervous system to the organization of a junctional slow potential microstructure. When nerve impulses arrive at synapses, post-synaptic potentials are generated. These are never solitary but constitute an arrival pattern. When post-synaptic potentials occur in dendritic fields of the brain they are often insufficiently large to incite immediately nerve impulse discharge. These patterns of post-synaptic potentials develop a design which can resemble a wave front. But this design of slow potentials is not some esoteric field, a mirage superimposed on known neural functions; it is a microstructure made up of classical neural slow potentials, the resultant of arrivals of nerve impulses awaiting axonic departure.

Arrival and departure patterns conceived as microstructures thus become a third force in the cell versus "floating" field argument about the possible neurological mechanism of the holistic properties of perception. The need for this third force has been recognized before: Lashley was profoundly troubled by the problem.

Here is the dilemma. Nerve impulses are trans-

mitted over definite, restrictive paths in the sensory [and] motor nerves and in the central nervous system from cell to cell through definite intercellular connections. Yet all behavior seems to be determined by masses of excitation, by the form or relations or proportions of excitation within general fields of activity, without regard to particular nerve cells. It is the pattern and not the element that counts. What sort of nervous organization might be capable of responding to a pattern of excitation without limited, specialized paths of conduction? The problem is almost universal in the activities of the nervous system and some hypothesis is needed to direct further research (Lashley, 1942, p. 306).

Subsequently, he suggested that an interference pattern model would account for the phenomena more adequately than either of the more extreme views. He did not, however, have available to him a clear model of how the mechanism might work. He never specified the fact that the "waves" generated by arrivals of nerve impulses are constituted of well known and classical neurophysiological processes: synaptic and dendritic potentials. He thus never arrived at the argument for the existence of a junctional micro-structure partially independent of nerve impulse conduction developed here. This left his wave forms both too much tied to the neuronal circuitry he found unsatisfactory and at the same time disembodied when flexibility was accounted for, and he was discouraged from pursuing his insight.

The advantage of this interference pattern view of image construction is that a formal similarity to optical information processing procedures can be drawn. These procedures have been called holographic because of their holistic properties. The coding of information in such holographic systems is a linear transformation of the pattern of light not only in terms of its intensity as in an ordinary photographic process, but also in terms of neighborhood interactions (spatial phase). The most intensively studied holograms have been those in which these phase relationships can be expressed mathematically

as Fourier transforms. These are special forms of convolutional integrals which have the property that the identical equation convolves and de-convolves. Thus any process represented by the spatial Fourier transforms can encode and subsequently decode simply by recurring at some second stage!

All holograms have some interesting properties in common which make them potentially important in understanding brain function. First, the information is replicated and distributed throughout the hologram, making the record resistant to damage. Each part of the hologram can reproduce the entire image; thus the hologram can be broken into small fragments each of which can be used to construct a complete image. As the pieces become smaller, some resolution is lost. As successively larger parts of the hologram are used for reconstruction, the depth of field of the image decreases, i.e. focus becomes narrowed, so that an optimum size for a particular use can be ascertained (Leith and Upatneiks, 1965). Second, the hologram has a fantastic capacity usefully (i.e. retrievably) to store information. Information incorporated in a suitable retrieval system can be located immediately and reconstructed accurately. The density of information storage is limited only by the wave length of the coherent light (the shorter, the greater the capacity) and the grain size of the film used. Furthermore, many different patterns can be stored simultaneously, especially when holograms are produced in solids.--each image stored throughout the solid, yet each image individually retrievable. As Leith and Upatneiks (1965) describe it:

. . .several images can be superimposed on a single plate on successive exposures, and each image can be recovered without being affected by other images. This is done by using a different spatial-frequency carrier for each picture. . . . The gating carriers can be different frequencies. . .and there is still another degree of freedom, that of angle (p. 31).

Some ten billion bits (a measure of the amount) of

constructed by brain processes about which we know a considerable amount.

Two operations fundamental to communicative enactment can be distinguished: the formation of Signs, and of Symbols. Signs are constructed by identifying aspects of the Image; Symbols are constructed arbitrarily through use. The characteristic of Signs is that their meaning is consistent over a variety of transformations of the context in which they are made: a rose is a rose whether in a vase, a corsage, or the garbage pail. By contrast, the meaning of Symbols is characteristically sensitive to the context in which they appear: the Symbol V can stand for the numeral 5, for victory, or for peace, depending on the occasion in which it is produced.

Studies performed in my laboratories have explored the neurological mechanisms involved in the construction of Signs and Symbols. These studies have shown that those parts of the brain which had earlier been thought to serve associative functions are more likely involved in the coding operations which lead to significant and symbolic communications. We have evidence that the so-called cortical association areas of the brain work primarily to control input--in the visual and auditory modes, this control is exerted as far peripherally as the retina and the cochlea (Pribram, 1960a; Spinelli and Pribram, 1967; Spinelli and Pribram, 1966). Two cortical controls over sensory input have been shown to exist: one originating in the posterior, the other in the frontal cortex. The two processes act reciprocally: one codes the input by increasing, the other by diminishing spatial "redundancy" in the input mechanisms. This means that the number of nerve fibers which at any one time are engaged in the transmission of a particular signal can vary and that the variation is under central control. An increase in channel redundancy indicates that a greater number of fibers are engaged in processing the signal; redundancy reduction indicates that the signal is transmitted over fewer fibers. Ordinarily, an organism's input channels have sufficient reserve so that redundancy reduction does not impair the information

handling capacity of the channel (Attneave, 1954). What, then, do redundancy reduction and enhancement accomplish?

Perhaps the easiest way to explain the functions of a redundancy control mechanism is to resort to an analogy. The suggestion has been made that a redundancy controlling process is similar to that engaging a newspaper editor (Barlow, 1961). The editor asks, "Is this news, i.e. information, or is it familiar, i.e. redundant"? If news, the editor orders, "Communicate"; if familiar, he orders, "Reject." The evidence cited suggests that input channels of the organism serve not only as transmission, i.e. communication systems, but also as mechanisms which can suppress, i.e. reject signals. A precise model of this mechanism has been detailed elsewhere (Pribram, 1967) and behavioral evidence supporting the model has been presented (Douglas and Pribram, 1966). This model and its behavioral supporting data suggest further that the function of the input channels is truly "editorial." After brain lesions that reduce redundancy, the admitted novelty becomes overwhelming and meaning is not achieved; after other lesions that increase redundancy, only a very limited amount of novelty can be processed.

These extremes are, of course, caricatures of normal function. Nonetheless some extrapolation to everyday situations is warranted, if for no other reason than to suggest hypotheses likely to bear fruit in testing. Here are my thoughts: When a student is operating in the redundancy-reducing mode he takes in a great deal of information, handles a large number of facts. However, these facts must be repeated often, i.e. redundancy must be provided if the facts are to become significant. Further, simple repetition is not necessarily the best form in which the redundancy is to be provided. Some sort of organized redundancy in the form of classification is far superior. And when the student becomes engaged actively himself in classifying, in indexing, meaning will evoke detailed images when on subsequent occasions he is exposed to only parts of the material.

Thus one way meaning can be achieved is by Imaging through indexing by Signs. The relationship between Image and Index provides intrinsic meaning; in a sense it goes beyond the given by denoting, structuring the variety encompassed in the Image. Meaning is imposed on the events by indexing them; the imposition is derived from relationships between sensory events. I indicate to you by an identifying Sign that I know Jerome Bruner; this indication is meant to call forth the richness and complexity of your Image of the person indicated. When it does not, the indicator has failed to be meaningful.

When, on the other hand, a student is operating in the redundancy-enhancing mode, he becomes easily overloaded with a plethora of facts. The educational process must somehow draw him out (educere, from *educere*) if it is to make an impact. The key to meaning here is the familiarity, the consonance of the input to what he already knows. This requires that the educator become aware of the student's knowledge and that the student himself be allowed to arbitrate new entries through his own action. When re-communicated, these entries become tokens that represent the special conditions, the context in which the original communication occurred. Thus, tokens are Symbols derived from some referent, some context, external to the material symbolized. Their effectiveness depends on the readiness, the purposes of the person using the Symbol. We use Symbols to evoke meaning; such evocation depends, however, on the background of the communicants using the Symbol.

The Construction of Signs

Most of the evidence for these views on significant and symbolic communication comes from experiments performed with non-human primates. Meynert (1867-8) and Flechsig (1896) in the latter part of the nineteenth century attributed an associative function to all those parts of the brain cortex that do not connect relatively directly with peripheral receptors and effectors. They were

guided by both fact and theory: the fact that all parts of the cortex are highly interconnected, and the theory stemming from the then prevailing empiricist doctrine of the association of ideas. This associationistic view of brain function is still important when the language and thought of man are scrutinized. However, with respect to discrimination learning, pattern recognition, and the like, the early empiricist approach to brain function, that the association cortex merely "associates," merely integrates inputs from a variety of primary sensory receiving areas, has proved wanting.

Specifically, many experiments done with monkeys have shown that discrimination learning and pattern recognition is still possible after removal of large expanses of cortex surrounding the primary projection areas (Pribram, Spinelli, and Reitz, 1969). Yet much more restricted removals made at some distance from the primary cortex produce severe deficiencies in both sign learning and recognition (Mishkin and Pribram, 1954). Simply disconnecting the intracortical pathways that join these areas with the primary has no effect. On the other hand, cutting the pathways that connect the cortex with subcortical structures produces as severe a disturbance as does removal of the cortical tissue itself (Pribram, Blehert, and Spinelli, 1965).

For the associationistic view these results pose one of those paradoxes which have been so stimulating to research in the neurobehavioral sciences during the past century and a half. How can a sector of the brain cortex "associate" the effects of inputs to other primary parts of the brain when disconnection from those parts has no effect?

The puzzle was compounded by the finding that the impairments were not all-of-a-piece. Localization of function on the basis of sense modality was found within the so-called association cortex. A sector of the parietal lobe affects somesthetic discrimination, and no other; a sector in the anterior portion of the temporal lobe concerns only

taste (gustation); a mid-temporal sector is selectively involved with audition; and a sector in the inferior part of the temporal lobe serves vision. Further, no inter-sensory association defects are produced by lesions in this so-called association cortex (Pribram, 1969a).

The problem thus becomes that of identification of the functions of these sensory specific regions. Most of the experimental work attempting to solve this problem has been performed in the visual sphere and therefore concerns the cortex of the inferior part of the temporal lobe. Enough has been done with auditory and somatosensory procedures, however, to know that the results obtained in vision research are applicable to the other parts of the "association cortex" serving other sensory modalities.

Initially the question arose whether resections of the inferior temporal cortex of monkeys would impair all forms of visual performance. It was quickly established that the tracking of a visual object, such as a flying gnat, remained undisturbed by the lesion. This finding was later confirmed with the use of an eye camera, photographing the reflections of the cornea of objects looked at (Bagshaw, Mackworth, and Pribram, 1970).

Only when choices, discriminations, were undertaken by the brain-injured monkeys did deficits show up. Impaired performance was recorded on a great variety of visual choice procedures: color, form, pattern, brightness were all affected (Mishkin and Pribram, 1954). The only common denominators in these tasks were that they were visual, that choices were involved, and the degree of behavioral impairment was proportional to the difficulty experienced by normal monkeys in learning the tasks.

These results immediately led the investigators to ask whether the difficulty shown by the brain-injured monkeys centered on their inability to learn and to remember the problem rather than their inability to perceive the cues that guide problem solution. In order to test this hypothesis, comparisons were made on a variety of different

visual performances of monkeys with resections of the inferior temporal cortex and of others with partial removals of the primary visual area. On the whole, the hypothesis that learning and perceiving could be separated by making lesions in different parts of the cortex was supported by the evidence. Perceptual problems, such as being able to pull in a peanut attached to a string that crosses several other unbaited strings, were adversely affected by lesions in the primary visual area but not by those in the inferior temporal cortex; the reverse picture was obtained when learning tasks were used (Wilson and Mishkin, 1959).

In terms of the language of Signs and Images, the results of these experiments can be interpreted as follows. Some aspects of Images take on meaning, become significant and are therefore learned and remembered. In the monkey discrimination experiments, a painted pattern takes on meaning, becomes significant, becomes a Sign, as a consequence of the monkey's behavior. Signs are achieved, thus, through action and, anatomically, the pathways from the inferior temporal cortex lead through motor structures (Reitz and Pribram, 1969). It is this active aspect of signing that generates meaning and produces perceptual learning through reinforcement.

An exciting result obtained by Robert and Beatrice Gardner (1969), working with a young female chimpanzee named Washoe, dramatize this dependence on behavior. Because of previous failures to enable chimpanzees to talk they decided to try to teach Washoe to communicate by using her hands rather than her vocal cords. American Sign Language devised for the deaf and mute was chosen as the ideal vehicle since it is easy to learn because of its iconicity; the hand and fingers are maneuverable to resemble, to some considerable degree, the object or action described by the sign. Washoe, about three and one half years old at the time of this writing, has learned over 150 signs of the American Sign Language system. The Gardners and Washoe readily communicate with each other using this method. Washoe has, in fact, invented several

new signs which now are in common use by humans being taught the system.

The Mechanism of Attention

The meaningfulness of signs, according to neurobehavioral and neurophysiological data, depends not so much on preprogramming some specific attribute that is to be signed, but on a mechanism that allows attention to a large range of alternatives. Monkeys deprived of inferior temporal cortex select from a restricted range of alternatives (display less uncertainty) when making visual choices, whether the alternatives are separated clearly in the form of dime store junk objects (Pribram, 1960b) or are features that distinguish patterns from each other (Butter, 1968). These results gave rise to the next experimental question: How does this temporal lobe cortex function to facilitate the process of making the choice necessary to learning and remembering? As already noted, one of the most striking aspects of Images is their richness. As a rule, this richness cannot be apprehended all at once but must be sampled piecemeal, attribute by attribute. Now color, now shape, now texture, now content are selected for emphasis. This limitation of the attentive process does not, however, diminish the immediacy or the kaleidoscopic nature of Imaging; if anything, both are enhanced by proper attending. How?

The answer to the question lies, of course, in the continuous interaction between Imaging and attending. As we have seen, processes originating in the so-called association areas have access to the functions of the input systems. Evidence suggests that this access utilizes the subcortical and perhaps cortical inhibitory organizations within the input systems to control what is attended to.

The evidence accrued from experiments using techniques of estimating the rapidity with which excitability recovers within the input channels mentioned above. When responses

are evoked in a sensory system by some fairly abrupt event in the environment, say a flash of light or a click of sound, the response of the system takes a finite period. Should a second flash or click occur before the system has "recovered" from its reaction to the initial event, the response to the later event will be affected by the earlier one. The duration of the reaction to excitation is therefore an important dimension in determining the manner in which input becomes processed. In our experiments we were able to show that electrical stimulation (or even ablation) of the so-called association cortex could alter this duration.

Slowing of recovery in the primary visual system is in fact observed when the inferior temporal cortex is electrically stimulated (Spinelli and Pribram, 1966). As noted this result was especially welcome because it indicated the neurological mechanism by which the so-called association cortex exerts its control over the primary input systems. We explored this mechanism further, but as often happens at the laboratory bench, we found we had incomplete knowledge of the variables involved in the phenomenon under observation. When we tried to replicate, we could not. Because the problem was so important, we persisted, however, and found a way to gauge the conditions necessary to obtain the effect.

Needing a more stable indicator of excitability, we abandoned, for the moment, the multiple flash presentations. We reasoned that the retina was the site of instability and that electrically stimulating a more central location in the visual system by means of an implanted probe would produce more reliable results. The cost of achieving stability might be that we no longer would be able to influence the excitability of the system, but we had to take this risk. Indeed, electrical stimulation of the inferior temporal cortex failed to influence excitability as tested with the cortical probe.

Lauren Gerbrandt, a postdoctoral fellow, extricated us from this dilemma with a simple observation. He showed

that the amplitude of the responses evoked by electrical probe stimulations within the visual system were a function of the attentiveness of the monkey during the experiment. When the monkey was enclosed in a box, the response evoked was small. When the box was opened and the monkey was looking around, the response evoked was large. Further, inferior temporal cortex stimulation could make the small response obtained in the closed box into a large response, but had no influence on the large response. Finally, using the size of this probe-evoked response as a monitor, Garbrandt could predict in the closed box situation whether inferior temporal cortex stimulation would or would not affect the recovery function of the visual system.

Whenever the monkey was attentive, the effects we had earlier obtained were not observed. When, however, the monkey became "bored," tended to nod into sleep, etc., the effect on the recovery function was clear-cut. In our initial experiments we had daily performed a long routine of procedures: paired flashes, paired clicks, click-flash and flash-click combinations, patterned flashes, etc. were presented in regular order, day-in, day-out, week-in, week-out. Not only the monkeys, but also Spinelli and I, who were performing the experiments, became disenchanted with the routine. Spinelli and I took turns keeping watch on the other two to see to it that sleep would not intervene. We watched the monkey through a peephole; when he nodded, we tapped the enclosure gently. A small displacement of the stool of the nodding investigator accomplished the same end. In short, we got our results because the monkeys were not attentive. Subsequent teams testing monkeys only on the recovery cycle phenomenon, working with monkeys fresh to the situation and apparently interested in the goings-on of the experiment, obtained different results. Only when, through repetition, the situation became boring to us and to the monkey did the recovery-cycle effects again emerge.

Taken together, these experiments show that the effects of electrical stimulation of the inferior temporal

cortex and those produced when a monkey is "attending" are similar, and that the two processes show a considerable amount of convergence onto some final common mechanism. I may suggest reasonably, therefore, that the process of attention involves the influence exerted, via motor structures, by the inferior temporal "association" cortex on the input mechanism. This influence is not necessarily the specification of a particular operation but the production of a setting in which certain operations are enhanced.

The Construction of Symbols

The story that leads me to view Symbols as context dependent constructions is equally well worked out and begins shortly after World War I in the psychological laboratories of the University of Chicago. The then new functionalism in psychology raised many procedural questions. One of these was asked by Walter Hunter (1913), a graduate student at the time: Was it possible that children and animals really had "ideas"? And would it be possible to prove that they did? He devised a test during which, in full view of the child, a tidbit, such as a piece of chocolate, was hidden in different locations on successive occasions (trials). In each trial either the child was relocated or a screen was interposed between him and the hiding place. Some minutes (or even hours) later, the child was exposed to the hiding place which over successive trials was shifted, and so, contrary to what occurs in sign discrimination, had lost any consistent distinctiveness. If the child finds the tidbit, he must have carried the "idea" of the hidden tidbit and its location in his head during the delay between hiding and finding. Children and a host of animals were shown to be proficient at this task, which became an indicator of their ability to recall.

During the 1930s, Carlisle Jacobsen at Yale became interested in devising a procedure to test for the impairment produced in nonhuman primates when the frontal cortex

of the brain is damaged. Clinical studies and laboratory observations of monkeys had suggested that frontal injury destroyed some sort of thought processes. It seemed reasonable to Jacobsen, therefore, to use the test which had become the scientists' indicator of recall to study the effects of frontal brain damage.

By this time several versions of the test had become standardized. The first involved the hiding of a tidbit in one of two identical boxes within view of the animal, closing the lids, interposing a screen between the subject and boxes for a few seconds (usually 5-15), raising the screen, and allowing the subject to choose between the boxes. Sometimes the screen was transparent, sometimes opaque. Only the opaque trials constituted the true test, which was called the "delayed reaction task." In one modification of this test, the "indirect method," a cue such as a colored object temporarily shown over the actual hiding place of the tidbit indicated which box would, after the delay, contain the reinforcement. After the delay the animal was allowed to choose between hiding places that now were indistinguishable. Another modification, the "delayed alternation" procedure, did not signal the hiding place at all. The location of the reinforcement simply was alternated from one box to the other from trial to trial.

Jacobsen's approach (1928, 1936) to the study of the frontal cortex was successful; resection of the frontal pole of the brain interfered with adequate performance of all versions of the delayed reaction task. Therefore, the frontal lobes must in some way be responsible for an organism's ability to recall recent occurrences.

The indirect form of the delayed reaction task is of special interest here. The indirectness of the method signaling the hiding place led some of Jacobsen's colleagues to devise other tasks to explore the ability to use tokens. The most famous of these is the Chimpomat. Chips like those used in poker are provided by a slot machine and the entire "game" is played with the chips,

which only later and in a remote location could be "turned in" for peanuts. Normal chimpanzees readily use these chips, these tokens, but chimpanzees whose frontal lobes have been resected fail entirely to take the steps that lead from token to reinforcement (Jacobsen, Wolfe, and Jackson, 1935).

This method of training has been enhanced recently in another experimental effort to teach a chimpanzee to communicate. We have already described Washoe's ability to use signs. David Premack (1970) at the University of California in Santa Barbara has trained his chimpanzee, Sarah, very differently from the manner used by the Gardners with Washoe. Premack applied operant conditioning methods to determine exactly how complex a system of tokens can be used to guide Sarah's behavior. The Chimponat had already shown that chimpanzees would work for tokens. Premack's chimpanzee has demonstrated that behavior dependent on tokens is not only possible but that hierarichical organizations of tokens can be responded to appropriately.

In all of these experiments the crux of the problem is that a token does not call forth a uniform response. Depending on the situation (the context in which the token appears), the token must be apprehended, carried to another location, inserted into a machine or given to someone, traded for another token, or traded in for a reward. Or, as in the original delayed response situation, the token stands for a reward which is to appear in one location at one time, in another location at another time.

I will use the term Symbols to describe these context-dependent tokens. (This distinction is consonant with that made by Chomsky (1963) and is used here to indicate that the primordia of rules that govern human language are rooted in what are here called "significant" and "symbolic" processes.)

As indicated earlier, a large body of evidence indicates that the cortex lying between the classical

sensory projection areas in the posterior part of the brain is involved in discriminating context-free Signs. The evidence which shows that the frontal cortex lying anterior to the motor areas is involved in context-dependent symbolic processes follows.

Jacobsen believed that the processes tested by these procedures had to do with memory (short-term recall) and that these processes were attributable exclusively to frontal lobe functions. Later studies have shown that, with two exceptions, his belief was justified. One exception is that lesions of the caudate nucleus of the basal ganglia, a part of the motor system of the brain, also disrupt performance in the delayed reaction task. Here again we have evidence of the involvement of the motor mechanisms which produce action in a higher order brain process. The other exception concerns performance in the delayed alternation task, which, though it does not use tokens, is disrupted by frontal lesions. Performance of this task also is impaired by ablations of all parts of the limbic system (Pribram, Wilson, and Connors, 1962).

Thus behavioral as well as anatomical reasons are shown for grouping the frontal pole of the brain with the limbic formations (Pribram, 1958). Removals of tissue in these systems does not impair Sign discrimination but does impair performance on such tasks as delayed alternation (Pribram, et al., 1952; Pribram, et al., 1966, Pribram, Wilson, and Connors, 1962), discrimination reversal (Pribram, Douglas, and Pribram, 1969), and approach-avoidance (commonly called "passive" avoidance, McLeary, 1961). In all of these tasks some conflict in response tendencies, conflict among sets is at issue. The appropriate response is context-dependent (i.e. state-dependent) and the context is varied as part of the problem presented to the organism. Thus a set of contexts must become internalized (i.e. become brain states) before the appropriate response can be made. Building sets of contexts depends on a memory mechanism that embodies self-referral, rehearsal, or, technically speaking, the operation of sets of recursive functions. (The formal properties of memory systems of this

type have been described by Quilliam, 1967.) The closed loop connectivity of the limbic systems has always been its anatomical hallmark and makes an ideal candidate as a mechanism for context dependency (Pribram, 1961; Pribram and Kruger, 1954).

As an aside, it is worth noting that much social-emotional behavior is to a very great extent context dependent. This suggests that the importance of the limbic formations in emotional behavior stems not only from anatomical connectivity with hypothalamic and mesencephalic structures but also from its closed-loop, self-referring circuitry. It remains to be shown (although some preliminary evidence is at hand: Fox, et al., 1967; Pribram, 1967) that the anterior frontal cortex functions in a corticofugal relation to limbic system signals much as the posterior cortex functions to preprocess sensory signals.

But back to Jacobsen's delayed reaction task and his interpretation of it as an indicator of short-term memory. Could it be simply that frontal (and limbic) resection hastens the fading of memory traces? I tested this hypothesis in the following experiment (Pribram and Tubbs, 1967). Ordinarily trials are separated by equal intervals (right box 5 second, left box 5 seconds, right box 5 second, left box 5 seconds, etc.) in the delayed alternation task. Instead, I changed this so that couplets were formed: right box 5 seconds, left box 15 seconds; right box 5 seconds, left box 15 seconds, etc. Almost immediately, frontally lesioned monkeys began to perform properly, despite the insertion of the longer (15 second) interval. Thus the hypothesis of a more rapid fading of memory traces is disconfirmed.

The idea for doing the experiment came from a pet example used by Warren McCulloch to demonstrate the power of coding. When words are run together, as in the song "Marzey Dotes and Dozy Dotes," or in the phrases,

INMUDEELSARE
INCLAYNONEARE

it is difficult, if not impossible, to find meaning. But when the proper stops are put in, coding the string of letters into separate chunks, words can be discerned immediately: mares eat oats, in mud eels are, etc. To the frontally lesioned monkey the alternation task may appear all run together, one response interfering with the next and the one past. Imposing the grouping resolves the difficulty. Organizing events into groups is a simple way to provide the context necessary to fundamental forms of coding as well as more complex programming (as in teaching mathematics via simple set theory).

Perhaps in man this propensity to chunk and organize, to provide and maintain a context within which experience takes place, can grow out of bounds and result in disturbances such as obsession and compulsion neuroses. A diminution of this propensity by a limited frontal lobotomy would account for the success of lobotomy in such conditions. Perhaps also the change produced by lobotomy in the duration of the frustration reaction of monkeys and the duration of pain is attributable to this same change in the ability to impose and maintain on experience one or another context (see Ornstein, 1970). What is past experience becomes short lived and at the mercy of the current situation. In the clinic the expression "stimulus-bound" has been coined to describe this aspect of the lobotomized patient's behavior.

Symbolic processes thus appear to be derived from the interaction of motor mechanisms with the brain's frontal cortex and limbic formations. These parts of the cerebrum are characterized by a multiplicity of interconnections, an organization which in computer programming leads to context-sensitive communications. Context dependent behavior is necessary to the solution of certain problems that involve short-term memory (recall) such as delayed reaction and alternation and also to a variety of appropriate communicative, interpersonal responses usually described as motivational/emotional. The involvement of frontal cortex and limbic formations in both intellectual (problem solving) and emotional (interpersonal)

communication is therefore attributed to their function in context dependent processes.

Reasoning and Meaning

To summarize what I have covered so far, the results of experiments performed in my laboratories over the past two decades have led me to believe that the issue central to effective learning and remembering is coding. The nervous system turns out to be a magnificent instrument for efficient coding. The hypothesis is that meaning is derived from these coding operations. Elementary coding operations are found in the nervous system. From these Images are formed by a further coding process--this one of relationships among sensory events. Through enactment which involves the motor mechanisms of the brain, Signs are constructed when a redundancy-reduction mechanism controlled by the so-called association areas of the brain becomes engaged. A reciprocal mechanism originates in the frontal formations of the forebrain. This mechanism constitutes Symbols when redundancy enhancement limits coding to representations useful to the organism.

When is a student apt to be functioning in the significant (redundancy reducing) mode? Perhaps the most common occasion is when he is motivated to acquire perceptual, motor, and professional skills. In such situations he looks externally to authority, to machines, to programs and tests against which he pits his learning abilities. What he remembers primarily are facts that will apply to a large variety of situations. Rarely does the student of clinical medicine fail to remember the dosage of aspirin because its mechanism of action remains obscure. Rarely does the musician refrain from the practice of a difficult phrase on his chosen instrument because the theory of music has not yet been made clear to him.

And when is a student apt to be operating in the symbolic mode? Perhaps the most common occasion is when he is motivated by a search for meaning. In such

situations he looks internally, he is his own authority, he pits his current environment against his knowledge, what he already remembers. What becomes meaningful appears arbitrary with respect to the material itself, but makes sense within the context that the student brings to the instructor. To this mode, memorization of drug dosages would be anathema, while the dramatization of a dream or the writing of a term paper of his own choosing becomes a challenging experience.

My question to educators is this: Could we more often identify occasions when predominantly one or the other mode of receptivity is in operation? Could we then usefully control redundancy in the classroom so that the student's predominant neural redundancy process is engaged? Could we, in this fashion, make more effective use of our educational armamentarium? Would the student, set to acquire skills, be spared the explanations which are to him meaningless and only delay his push toward competence? Would the student in search of meaning learn to remember, instead of cramming to forget once the test is done? And would the proper timing of these techniques in the student's life help to make his education what it should be, an exciting adventure in self and social fulfillment?

This brings me to the relationship between the processes of signifying and symbolizing described here and to Peirce's theory of meaning. Peirce (1934) makes the statement that "we are too apt to think that what one means to do and the meaning of a word are quite uncorrelated measurements of the meaning." Peirce's analysis appears to be validated by the fact that Sign and Symbol are codes constructed by brain processes involving motor mechanisms. Thus, the importance of the phrase "what one means to do" centers on the fact that the doing lies in the attempt to communicate an internal representation through action. Even the most abstract indexing efforts of the mathematician concern (or should if they are to be meaningful) his vision of relationships. Even the most earthy of symbols, the phallic Hindu lingam, takes its meaning from the imagery evoked by the stories of divine powers.

Thus meaning takes on its pragmatic mantle. But Peirce goes one step further in emphasizing the effectiveness and utility of Symbols in generating meaning. In doing this he underplays significance; thus the normative, context dependent emphasis of pragmatism on "expediency. [This is too harsh a judgment on Peirce, though perhaps applicable to William James and Dewey. Editor] This seems to me unnecessary. I would suggest that Signs and Symbols derive meaning also to the extent that they evoke Images and Actions other than those undertaken for communicative purposes--e.g. those taken purely for self expression. Peirce, when discussing reasoning rather than memory, recognizes this. He does in fact give primacy to what he calls "abductive" reasoning: hypothesis formation and testing by analogy as against reasoning by deduction or induction. In science, abduction takes the form of modelling. A fascinating example of the careful and proper use of abductive reasoning was displayed by Watson and Crick (1968) in their discovery that the structure of DNA is a double helix. This is not to deny the importance of deduction and induction, only to deny them primacy.

For education the message of these views is clear. We have altogether too long and too exclusively focussed on the logical operations involved in deductive and inductive coding per se without asking that they be pertinent to Imaging and expressive Acting. For a long time only the intuitive teacher allowed himself the license of abduction and expression, and then only informally. More recently, the introduction of audio-visual aids and the emphasis on play ameliorated the situation somewhat, but only as an ancillary, not an integral part of our teaching. For we have not clearly recognized abductive coding as a legitimate educational procedure. According to the analysis presented here, not only is the abductive process of Imaging and expressive Acting legitimate; it becomes an essential component of learning if Signs and Symbols are to be made meaningful.

The young generation which faces us begs for meaning. In our concern with information processing, with rote

indexing and with logical symbol manipulation, we have excluded imaging and expressive Acting and therefore one important path to meaning. The young have over-reacted and taken refuge in pure abduction and expression--Image production through psychadelic drugs or Esalin-like group contactual encounter and happenings. Though momentarily meaningful, these primitive experiences will fail to provide other, more enduring ways toward a meaningful life unless the disciplines of indexing and symbolization also are cultivated. Nonetheless, the current cultural revolt has redressed an imbalance and we as educators will do well to take heed of this development. Let us, hereafter, along with our proper concern for the indexing and logical manipulation of information, always also provide full meaning by the less constrained, more primal process of evoking Images and expressive Acts.

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