T-143

REPRINTED FROM: K. E. Boulding & L. Senesh (Eds.),
The Optimum Utilization of Knowledge: Making Knowledge Serve Human Betterment.
Boulder, Co.: Westview Press, 1983. pp. 29-40

KARL H. PRIBRAM

3

The Brain, Cognitive Commodities, and the Enfolded Order

Introduction

When certain parts of the human brain are damaged, the patient suffers an agnosia, an inability to know. Studying such patients as well as monkeys in whom similar damage is produced experimentally has gained for us considerable insight into how we know.

First, we can distinguish, on the basis of localized brain damage, three distinct types of knowing: knowing what, knowing how, and knowing that. When a patient no longer knows *what* a pencil, key, or toothbrush is he no longer knows the use of such an object. Shown a pencil and asked to demonstrate what it is, the patient may try to brush his teeth with it or try to fit the pencil into a keyhole. Such defects in *knowing what* are called the agnosias.

Deficiencies in *knowing how* are called apraxias. A patient may have no difficulty in moving about yet be extremely awkward in carrying out skilled actions. Such a patient may fumble with a key, hold his pencil in a most unusual fashion, and drop his toothbrush as he begins to brush his teeth. But if he is trying to use the object correctly, he has an apraxia, not an agnosia.

Finally, there is *knowing that*. When there is damage in another brain location the patient may be completely unaware of certain body parts or of parts of the world. Such "neglect," as it is called, may extend to one entire side of the body or may be limited to an extremity. Neglect may also encompass a portion of the visual field, so that it is often difficult to decide whether a patient ran his car into a telephone pole and sustained a brain injury or suffered a stroke that led to visual neglect and so to the accident.

On the basis of evidence from brain-damaged patients, what these cognitive processes appear to have in common is that the knower adds considerably, by means of brain processes, to that which is known. Some of the addition comes by way of inherited brain mechanisms set so that certain events, and not others, arouse interest and certain skills are more easily mastered. Other additions, like the ones that determine the form of linguistic knowledge, musical knowledge, or knowledge about sports, for example, come from experience that alters brain processes in the formation of memory mechanisms. But the additions made to events by the knower's brain are the essence of knowing. Knowing is an active, constructive process.

Representations and Computations

How does the brain operate to make such additions? Recently this question has been addressed in terms of a computer metaphor: Does the brain store representations of knowledge or does the brain compute knowledge anew every time it occurs?[1] At first glance it seems as if the storage of knowledge is uncontestable; after all, we can remember stories, pictures, and feelings, and how could we, were they not stored in the brain? There is additional evidence for this point of view. In 1981 researchers reported on patients who, when recalling scenes, would recall only half of them because their brains were damaged on the side opposite to the missing half.[2]

The issue of brain representation is unfortunately not so clear cut. There can be "memory-without-record," as von Foerster once called it.[3] We can take another technical metaphor, the thermostat. The thermostat "remembers" the temperature at which it has been set and operates a furnace or air conditioner to maintain that temperature. In a sense, the thermostat "computes" in a very simple fashion the difference between its setting and the amount of heat in the surrounding space.

We know from a good deal of research that an essential aspect of brain organization is "homeostatic"; that is, the elementary functions of the brain are carried out in a manner similar to the way thermostats operate.[4] In fact, thermostats were invented by Norbert Wiener based on the experience he had in a physiological laboratory at Harvard where the homeostatic principles of brain function were discovered.

"Memory-without-record" means that a system does not necessarily have to store as a record that which it reproduces. What may be stored is a computation that will construct the reproduction. For example, we do not store the answer to the problem, "What is 1233 divided by 3?"

5. We learn certain operations by which we can compute the answer 11), and thus we can reproduce that answer whenever the problem curs. There is, moreover, a tremendous gain in power when a comutation rather than a record is stored. Now we can divide *any* number y another and obtain a reproducible answer. The savings in storage pace of a computational memory-without-record is huge.

By now I may have convinced you that knowledge is stored in the rain as a set of computations somewhat similar to those carried out y thermostats. Brain computations are, of course, more complex than hermostatic ones. Instead of simple set points, a series of computational rocedures, such as arithmetical division, must be stored. Often these procedures can be described in terms of mathematical equations; if not, omputer simulations allow *in vitro* manipulation and experimentation. "In vitro" means "in glass"; in biochemistry it indicates an experiment arried out in the test tube rather than in vivo, in the live organism.) Research on "artificial intelligence" has shown the utility of this type of experimentation.

Imaging and Isomorphism

Though you may have become convinced by the arguments for a computational, procedural memory—and rightly so—there is still more to be said regarding the complexity of the brain's knowledge systems. Roger Shepard initiated another line of research by showing that when we imagine a three-dimensional object and rotate it in space, the time it takes to rotate the image of an object is proportional to the time it takes to rotate an actual object.[5] Now if there were no resemblance between the brain procedure and the actual procedure, such proportionality ought not to hold. Shepard therefore reasoned that, in some instances at least, brain procedures and actual procedures were analogous—that whatever is happening in the brain is in some sense a facsimile, a copy or record, of actual occurrences. In the brain/behavioral sciences the idea that a brain copy is made of external actuality is called *isomorphism* ("iso" meaning same, "morphism" meaning form). This geometric definition of isomorphism is, however, not the only one. In mathematics, isomorphism is said to exist whenever the transformations between descriptions are linear, i.e., when the transformations are readily reversible. Shepard, therefore, has distinguished between primary isomorphism of the geometric kind and secondary isomorphism, which is algebraic and transformational.

Which kind of isomorphism between knowledge-in-the-world and knowledge-in-the-brain exists? Many years ago, B. F. Skinner asked me, while I was teaching a class at Harvard, whether I believed in isomorphic brain representations. He meant representations in the geometric sense and I understood his meaning. I answered "Yes" to his question. He then suggested that I imagine some green grass growing. I did this. Next he said, "Now mow the lawn!" I clutched my head in response—and the absurdity of the geometric isomorph position struck me full force.

Why had I then and why do other neuroscientists today still entertain the geometric isomorph or representational (rather than computational) alternative? For two reasons. The first is that the body surface *is* more or less isomorphically represented in the arrangement of connections to the brain cortex. This is true of skin receptors, the receptors of the cochlea of the ear, the receptors in the retina and the muscle system. There *is* an overall topological correspondence between sensory and motor organization in the periphery of the body on the one hand and the overall organization of the sensory and motor "projection" cortex on the other. Thus "knowing where" and "knowing whither" are sketched out within a framework that is characterized by a rough geometric correspondence between body surface and brain. Our phenomenal subjective experience reflects this body-brain geometry in the where and whither dimensions.

But, as the lawn-mowing example portrays so forcefully, there is considerably more to phenomenal experience than can be accounted for by geometrical isomorphy. Constructional procedures *must* be involved. However, as in the Shepard figures, some of these procedures are secondarily, i.e., algebraically isomorphic and described by linear transformations; others, such as the production of languages, seem to involve nonlinearities. As the powers of language and languagelike systems have been universally extolled as *the* unique characterization of mankind, I want to concentrate on the linear operations to show something of the surprising range of human knowledge systems and the cognitive processes that these linearities (secondary isomorphisms) can encompass.

Not long ago—in the 1950s—brain/behavioral scientists had no inkling as to the existence of such linear transformations, which literally make the form of brain processes utterly different from the form we experience while maintaining the proportionality between the forms. Brain/behavioral scientists did know, however, that they were faced with very serious problems for which they had no explanation. One of these problems was imaging, the other memory. I have already discussed both of these problems from a current vantage point, but it is useful to go back a quarter-century to see the importance of the discovery of a specific procedural operation that, at one stroke, resolved the most puzzling aspects of both problems.

Perception and Reality

At first glance, the problem of the brain mechanisms involved in imaging may not be obvious. After all, we image the objects in the "real" world and the imaging is "direct," i.e., we are not aware of any steps intermediate between object and image; the object and image appear to be one. This directness has led scientists such as James Gibson to suggest that all we need to know are the attributes that make objects, objects—the "information" in external stimulation that reaches the senses and so becomes imaged.[6] From a brain scientist's viewpoint this sort of "naive" realism—even when it becomes "critical" in the sense that the "information" may not be what it initially appears to be—begs a number of important questions. Certainly the structure of the ambient array of information is important; but sensory transduction and transformation of this array is not to be ignored. We have already noted that transformations are truly trans-forms, that the form present at any particular stage of processing may not look at all similar to that present at another, even if the transformations are linear and invertible and secondarily "isomorphic" in the algebraic sense. For the brain physiologist the puzzle is *how* image and object correspond despite the *variations* in the ambient array that strike the sensory receptors. Whatever the "information" provided by these variations, it must be computed by correlating across the variations. Thus the "information" is not just a property of the array but is also a function of the transforming and correlating powers of the organism. This is an extremely important point to grasp: In one view (Gibson's) the organism is a passive gatherer in an object world; in the other (the brain scientist's) the organism is actively involved in the construction of this object world.

Those who take the view that perception is direct would argue that a distinction must be made between perception and cognition. In perception (and in action), they would hold, the brain process "complements" the ambient array rather than representing it. The brain scientist, on the basis of considerable evidence, notes that cognitions enter into perceptions by way of preprocessing: The parts of the brain involved in knowing actively alter the functions of the sensory projections at several stages.[7]

Despite this evidence of cognitive preprocessing in sensory channels, there is a hierarchy that can be made out in our perceptual-cognitive processing. There is, first, a level of "complementation" in which images of objects are present in experience. This presentational level appears to be directly related to phenomenal experience. At the other extreme is the linguistic level, which is obviously re-presentational and in which the connection between re-presentation and what is re-presented is largely arbitrary.

Cognitive Commodities

In between, however, is a level of perceiving and knowing that has been almost completely ignored. This aspect of the perceptual-knowledge process can most easily be understood in terms of the construction of environmental representations of the results of brain/behavioral processes. Such "realizations" of brain/behavioral processes in the environment are *cognitive commodities.* It is with these constructions that the active, inventive, and creative aspect of processing becomes especially evident.

Take, for example, your perception of a chair. How do you know that it is a chair? What "information" do you perceive to be the chairness of chairs? What is in the "direct" perception of an array of stimulations coming from a chair that makes it a chair? Is it the flatness of the seat at a certain elevation from another surface, the floor? The chairback? What about Eames chairs, which are highly contoured? Isn't it the use made of particular objects that helps define them as chairs rather than just their physical conformation? And isn't use a cognitive process, one that involves memory? I see the chairness of a chair as "directly" and immediately as I see its shape, texture, and color (unless the chair is something "totally modern"—something out of the world of my experience of chairs).

Realizing the constructive aspect of direct phenomenal experience, of perception, makes explanations of creativity and invention possible. Not only does the cognitive mechanism preprocess the events in sensory channels to construct perceptions, but the same mechanisms have been found to operate in the motor systems.[8] Here the images-of-achievement are constructed that, when they become realized in action, result in *cognitive commodities.* Chairs, computer programs, and the like join what Karl Popper has called World III, the world of cultural inventions and artifacts.[9] Sports equipment, musical instruments, furniture, telecommunication devices, and economic exchange media such as money are all cognitive commodities. Though language and languagelike processes may play a significant role in constructing these cognitive commodities, two at least equally important aspects of their construction are perceptual iconicity (geometric isomorphism) and proportional fittingness (algebraic or secondary isomorphism).

Holography and Brain Theory

The second major seemingly unsolvable problem facing brain scientists in the 1950s was the question of the brain mechanisms responsible for learning and memory storage. Lashley stated the problem succinctly: "After a lifetime of search for an engram [any trace of a specific memory] the only conclusion that I can reach from the evidence is that learning is just not possible."[10] The issue that Lashley and other brain/behavioral scientists faced was that damage to the brain, no matter how extensive, does not impair any memory for a specific event in isolation. A patient having suffered a stroke does not return to his family, recognize his children, but turn to his wife and find her a total stranger. Memory storage appears to be distributed within the brain and at the same time of a piece. No wonder brain/behavioral scientists were puzzled. When disturbances in remembering do occur, they usually involve a time period (the antegrade and retrograde amnesias following head injuries) or a retrieval mode (the aphasias, apraxias, and agnosias described earlier).

Early in the 1960s engineers developed optical information-processing devices based on a mathematical proposal made by Dennis Gabor.[11] Gabor suggested that, instead of being used to make photographs in the ordinary way, film be treated as an interferometer, recording the interference patterns created when two different electromagnetic beams interact.[12] One beam of electrons or photons would reach the film directly from a generating source; the other would be bounced off an object. The wave forms generated on the film would resemble those produced in a calm-surfaced pond when two (or more) pebbles are thrown in. The ripples produced around each pebble spread away from the source, and where they intersect they interfere with or reinforce each other. If one took a movie of the whole process, from pebble to interference patterns, one could show the film in reverse so that the pebbles would seem to be produced from the ripples. Gabor's insight was that the mathematical processes (called spread functions) that describe the "rippling" process of making interference patterns can be applied a second time to reverse the process, creating images of the objects that produced the ripples. Gabor named the new type of photography "holography" because the interference patterns stored on the film displayed novel and interesting properties, among them the fact that the entire image could be reconstructed from any portion of the film. Whole and part were related in a unique fashion, a fashion very like that which appears to relate memory storage in the brain to the recognition and recall of events in phenomenal experience.

In the fifteen or more years since this striking resemblance between holography and certain brain/behavioral processes was noted, much evidence has accumulated to show that what began as a metaphorical simile has been developed into a precise neurological model. Now based on evidence, this holographic brain model continues to be sharpened as relevant results from tests of various hypotheses (only some of which are derived from the model) have accrued. There is little remaining doubt that some brain processes are characterized by holonomic transformations that result in algebraic isomorphisms between the image/object domain on the one hand and the holographic transform domain on the other.

What advantage does this transform domain contribute to processing? One obvious advantage is resistance to damage. Others include enhanced storage capacity and ready associative recall. But perhaps the most relevant to our purpose here is that extensive correlations can be carried out much more simply and rapidly. Since invertibility insures that no information is lost, the steps involved in transforming and retransforming enhance efficiency. This is why statisticians use the FFT program (the Fast Fourier Transform, an invertible spread function) when they use computers to do their calculations, and why image reconstruction by computerized X-ray tomography relies heavily on these computations.

The peculiarity of holograms is that because information becomes stored throughout, each part of the hologram encodes the whole. The relationship between whole and part is therefore both distributed and enfolded. In fact, the holographic representation enfolds the coordinates of space and time as well as the specific images of objects that are extended in space and time. Thus the memory store is organized neither in space (in any place in the brain) nor in time (in a sequence as if it were registered on a tape), though spatial and temporal markers may well accompany any specific to-be-remembered episode. The feasibility of rapid and extensive correlation stems from the distributed nature of the transformed store.

Holonomy and Education

The discovery of the holonomic organization of memory has important consequences. As noted earlier, the brain has mechanisms for organizing retrieval from the distributed store, and we might properly call the operations of these gnostic mechanisms "thinking." According to the holonomic hypothesis, the operations involved in thinking must invert the distributed memory into images—not necessarily visual images but also kinesthetic/tactile, olfactory/gustatory, and auditory/linguistic. An experiment by Wallach and Averbach in 1955 showed that thinking had to be carried out in one or another sensory mode, that there is no such process as "pure" nonmodal thought.[13]

The problem for education is to communicate the enfolded memory store of the educator to the enfolded memory store of the student. Two separate thought processes must be engaged in order to accomplish this. First the educator must be clear in his unfolding, in his thinking, to establish meaningful, useful images. Second, the teacher must engage the student's enfolding/unfolding mechanism, the student's modes of thinking. If the student is primarily a visual imager and the educator is using primarily auditory/verbal thinking processes there is a mismatch. If the student has tactile/kinesthetic mechanical abilities and the educator is highly auditory/verbal there is a mismatch. There is good evidence that as a group males and females differ considerably in their preferred modes of thinking: females are primarily auditory/verbal; males are often visual and kinesthetic.[14] Since much elementary and secondary education is provided by female instructors, there is a considerable opportunity for mismatching with the thinking processes of their male students.

Holonomic storage per se allows myriad novel combinations to be extracted from the brain. Images of unicorns, changes in interpretation of history, departures from accepted theory in science, inventions of new machines and of other *cognitive commodities* become possible. Whether any particular novel combination is useful and viable is another matter. But in the classroom one must not severely prejudge viability lest the creative process become permanently stifled.

You may object that the educator already has enough trouble just transmitting the current culture to the next generation without the distraction of novelties that can lead to classroom anarchy. My own special remedy for this is to distinguish clearly between education and instruction. Education (from the Latin *ex ducere*) means to lead out; instruction (*in structura*) means to put structure in. Education should, in my view, portray the exciting panorama of knowledge humankind has fashioned so students can then fashion their own visions within the framework of that panorama. In contrast, instruction trains in a discipline that preordains how to function within the panorama of knowledge. Without the three Rs, students will become limited because they can't acquire the knowledge stored in books; they can't progress to other portals of the knowledge system if they can't write; they can't take advantage of sales and other accesses to the culture of consumer goods if they can't handle money.

A physican *must* know drug dosages, a dentist *how to* straighten and fill teeth, a physicist *how to* solve equations, a psychologist *how to* use statistics. Ideally, instruction follows the decision to explore one or another vision achieved through education. That decision must of necessity be made by parents and the educational system when the students are younger; but this does not mean that the separate goals of education and instruction cannot be made clear to the student. I believe a great deal of negativity toward schooling would disappear if students were made aware of this distinction by having each classroom exercise clearly labeled as either necessary although perhaps temporarily uncomfortable training or a widening of the horizons of knowing.

Holonomy and Economics

A final point: Are there any cognitive commodities that embody the holonomic transform domain or display an enfolded order? There is a commonly experienced cognitive commodity that operates within an enfolded order—the economy. Hayek pointed out that every transaction in the marketplace contains within it information about what is taking place over the entire reach of that market.[15] What a dollar will buy reflects the skill of the Japanese, the industriousness of the Germans, the availability of a Ford product during a strike, the size and efficiency of the Washington bureaucracy, your and my needs and desires, the monetary policy of the U.S. Treasury, the availability of gold, of Eurodollars, of oil, of grain—one could go on and on. The marketplace is an enfolded order; the value of money encodes and distributes information within that order. Given this insight, the question is whether the economic enfolded order is holonomic: Are the transactions of the marketplace invertible transformations, and if so, what significance does this have for managing our economic cognitive commodities?

With this question I defer to the economists and educators, for, as noted earlier, I believe that the educational as well as the economic establishment can profit from an examination of the enfolded orders that characterize the construction of cognitive commodities.

Conclusion

The problem of representation in the brain/behavioral sciences has no simple solution. Brain research allows us to distinguish (1) receptor-brain geometric isomorphisms within which image/object complementations and iconicity in phenomenal experience become implemented; (2) secondary algebraic isomorphisms that depend on linear invertible (holonomic) transformations that enhance efficient correlations and the constructive aspects of experience; and (3) possibly nonlinear procedures such as language and languagelike operations. These procedures are involved not only in the phenomenal experiences of knowing but in the production of the cognitive commodities that compose our social/cultural/economic world. The holonomic transformations and their characteristics are the least familiar of these processes. Examining the enfolded orders produced by such transforms and embodied in some of the cognitive commodities could reveal principles interesting and useful in economics and education.

Notes

1. For example, see *The Brain and Behaviorial Sciences*, Spring 1980 (entire issue).

2. Bisiach, E.; E. Capitani; C. Luzzatti; and D. Perani. Brain and conscious representation of outside reality.

3. von Foerster, H. Memory without record. In D. P. Kimble (ed.) *The Anatomy of Memory*.

4. Ashby, W. R. *An Introduction to Cybernetics*; Cannon, W. B. *Bodily Changes in Pain, Hunger, Fear and Rage*; Pribram, K. H. *Languages of the Brain*; Pribram, K. H. The role of analogy in transcending limits in the brain sciences.

5. Shepard, R. N. Cognitive processes that resemble perceptual processes. In W. K. Estes (ed.) *Handbook of Learning and Cognitive Processes*.

6. Gibson, J. J. *The Ecological Approach to Visual Perception*.

7. Pribram, K. H. Computations and representations. In T. W. Simon (ed.) *Symposium on Language, Mind and Brain, Gainesville, Florida, April 1978*.

8. Pribram, K. H. *Languages of the Brain*. Chaps. 12, 13, and 14.

9. Popper, K. R., and Eccles, J. C. *The Self and its Brain*.

10. Lashley, K. S. In search of the engram. In *Physiological Mechanisms in Animal Behavior*.

11. Leith, E. Holography's practical dimension; Goodman, J. W. *Introduction to Fourier Optics*; Bracewell, R. *The Fourier Transform and its Applications*.

12. Gabor, D. Information processing with coherent light.

13. Wallach, H., and Averbach, E. On memory modalities.

14. McGuinness, D. Sex differences in the organization of perception and cognition. In J. Archer and B. Lloyd (eds.) *Explorations in Sex Differences*; McGuinness, D., and Pribram, K. H. The origins of sensory bias in the development of gender differences in perception and cognition. In M. Bortner (ed.) *Cognitive Growth and Development: Essays in Memory of Herbert G. Birch*.

15. Hayek, F. A. *Individualism and Economic Order*.

Bibliography

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

Bisiach, E.; Capitani, E.; Luzzatti, C.; and Perani, D. Brain and conscious representation of outside reality. *Neuropsychologia* 1981, 19(4): 543–551.

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

Cannon, W. B. *Bodily Changes in Pain, Hunger, Fear and Rage.* New York: D. Appleton & Co., 1929.

von Foerster, H. Memory without record. In D. P. Kimble (ed.) *The Anatomy of Memory.* Palo Alto, Calif.: Science & Behavior Books, 1965, pp. 388–433.

Gabor, D. Information processing with coherent light. *Optica Acta* 1969, 16: 519–533.

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

Goodman, J. W. *Introduction to Fourier Optics.* San Francisco: McGraw-Hill, 1968.

Hayek, F. A. *Individualism and Economic Order.* Boston: Routledge & Kegan Paul, 1977.

Lashley, K. S. In search of the engram. In *Physiological Mechanisms in Animal Behavior.* New York: Academic, 1950, pp. 454–482.

Leith, E. Holography's practical dimension. *Electronics* 1966, 39: 88–94.

McGuinness, D. Sex differences in the organization of perception and cognition. In J. Archer and B. Lloyd (eds.) *Explorations in Sex Differences.* Brighton, England: Harvester Press, 1975.

McGuinness, D., and Pribram, K. H. The origins of sensory bias in the development of gender differences in perception and cognition. In M. Bortner (ed.) *Cognitive Growth and Development: Essays in Memory of Herbert G. Birch.* New York: Bruner/Mazel, 1978, pp. 3–56.

Popper, K. R., and Eccles, J. C. *The Self and its Brain.* New York: Springer International, 1977.

Pribram, K. H. Computations and representations. In T. W. Simon (ed.) *Symposium on Language, Mind and Brain, Gainesville, Florida, April 1978.* New York: Erlbaum, 1981, pp. 213–224.

Pribram, K. H. *Languages of the Brain.* Englewood Cliffs, N.J.: Prentice-Hall, 1971 (2d ed. Monterey, Calif.: Brooks/Cole, 1977).

Pribram, K. H. Localization and distribution of function in the brain. In J. Orbach (ed.) *Neuropsychology Since Lashley.* New York: Erlbaum, 1981.

Pribram, K. H. The role of analogy in transcending limits in the brain sciences. *Daedalus* 1980, 109 (2): 19–38.

Pribram, K. H. Some dimensions of remembering: Steps toward a neuropsychological model of memory. In J. Gaito (ed.) *Macromolecules and Behavior.* New York: Academic Press, 1966, pp. 165–187.

Pribram, K. H.; Nuwer, M.; and Baron, R. The holographic hypothesis of memory structure in brain function and perception. In R. C. Atkinson, D. H. Krantz, R. C. Luce, and P. Suppes (eds.) *Contemporary Developments in Mathematical Psychology.* San Francisco: Freeman, 1974, pp. 416–467.

Shepard, R. N. Cognitive processes that resemble perceptual processes. In W. K. Estes (ed.) *Handbook of Learning and Cognitive Processes.* Hillsdale, N.J.: Erlbaum, 1978.

Wallach, H., and Averbach, E. On memory modalities. *American Journal of Psychology* 1955, 68 (2): 249–257.