8
On Constructing a Reality*

HEINZ VON FOERSTER

Draw a distinction!

G. Spencer Brown[1]

The Postulate

I AM SURE YOU remember the plain citizen Jourdain in Molière's *Le Bourgeois Gentilhomme* who, nouveau riche, travels in the sophisticated circles of the French aristocracy and who is eager to learn. On one occasion his new friends speak about poetry and prose, and Jourdain discovers to his amazement and great delight that whenever he speaks, he speaks prose. He is overwhelmed by this discovery: "I am speaking Prose! I have always spoken Prose! I have spoken Prose throughout my whole life!"

A similar discovery has been made not so long ago, but it was neither of poetry nor of prose—it was the environment that was discovered. I remember when, perhaps ten or fifteen years ago, some of my American friends came running to me with the delight and amazement of having just made a great discovery: "I am living in an Environment! I have always lived in an Environment! I have lived in an Environment throughout my whole life!"

However, neither M. Jourdain nor my friends have as yet made another discovery, and that is when M. Jourdain speaks, may it be prose or poetry, it is he who invents it, and, likewise, when we perceive our environment, it is we who invent it.

Every discovery has a painful and a joyful side: painful, while struggling with a new insight; joyful, when this insight is gained. I see the sole purpose of my presentation to minimize the pain and maximize the joy for those who have not yet made this discovery; and for those who have made it, to

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let them know they are not alone. Again, the discovery we all have to make for ourselves is the following postulate.

The Environment as We Perceive It Is Our Invention

The burden is now upon me to support this outrageous claim. I shall proceed by first inviting you to participate in an experiment; then I shall report a clinical case and the results of two other experiments. After this I will give an interpretation, and thereafter a highly compressed version of the neurophysiological basis of these experiments and my postulate of before. Finally, I shall attempt to suggest the significance of all that to aesthetical and ethical considerations.

Experiments

The Blind Spot

Hold book with right hand, close left eye, and fixate star of Figure 1 with right eye. Move book slowly back and forth along line of vision until at an appropriate distance (from about 12 to 14 inches) round black spot disappears. With star well focused, spot should remain invisible even if book is slowly moved parallel to itself in any direction.

This localized blindness is a direct consequence of the absence of photo receptors (rods or cones) at that point of the retina, the “disk,” where all fibers leading from the eye’s light-sensitive surface converge to form the optic nerve. Clearly, when the black spot is projected onto the disk, it cannot be seen. Note that this localized blindness is not perceived as a dark blotch in our visual field (seeing a dark blotch would imply “seeing”), but this blindness is not perceived at all, that is, neither as something present, nor as something absent: Whatever is perceived is perceived “blotchless.”

Scotoma

Well-localized occipital lesions in the brain (e.g., injuries from high-velocity projectiles) heal relatively fast without the patient’s awareness of any perceptible loss in his vision. However, after several weeks motor dysfunction in the patient becomes apparent, for example, loss of control of arm or leg movements of one side or the other. Clinical tests, however, show that there is nothing wrong with the motor system, but that in some cases

FIGURE 1.

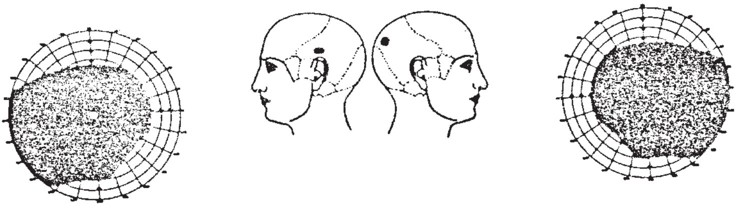

Figure 2.

there is substantial loss (Fig. 2) of a large portion of the visual field (*scotoma*).[9] A successful therapy consists of blind-folding the patient over a period of one to two months until he regains control over his motor system by shifting his "attention" from (nonexistent) visual clues regarding his posture to (fully operative) channels that give direct postural clues from (proprioceptive) sensors embedded in muscles and joints. Note again absence of perception of "absence of perception," and also the emergence of perception through sensorimotor interaction. This prompts two metaphors: Perceiving is doing, and If I don't see I am blind, I am blind; but if I see I am blind, I see.

Alternates

A single word is spoken once into a tape recorder and the tape smoothly spliced (without click) into a loop. The word is repetitively played back with high rather than low volume. After one or two minutes of listening (from 50 to 150 repetitions), the word clearly perceived so far abruptly changes into another meaningful and clearly perceived word: an "alternate." After ten to thirty repetitions of this first alternate, a sudden switch to a second alternate is perceived, and so on.[6] The following is a small selection of the 758 alternates reported from a population of about 200 subjects who were exposed to a repetitive playback of the single word *cogitate: agitate, annotate, arbitrate, artistry, back and forth, brevity, ça d'était, candidate, can't you see, can't you stay, Cape Cod you say, card estate, cardiotape, car district, catch a tape, cavitate, cha cha che, cogitate, computate; conjugate, conscious state, counter tape, count to ten, count to three, count yer tape, cut the steak, entity, fantasy, God to take, God you say, got a data, got your pay, got your tape, gratitude, gravity, guard the tit, gurgitate, had to take, kinds of tape, majesty, marmalade.*

*Comprehension**

Into the various stations of the auditory pathways in a cat's brain microelectrodes are implanted that allow a recording (electroencephalogram)

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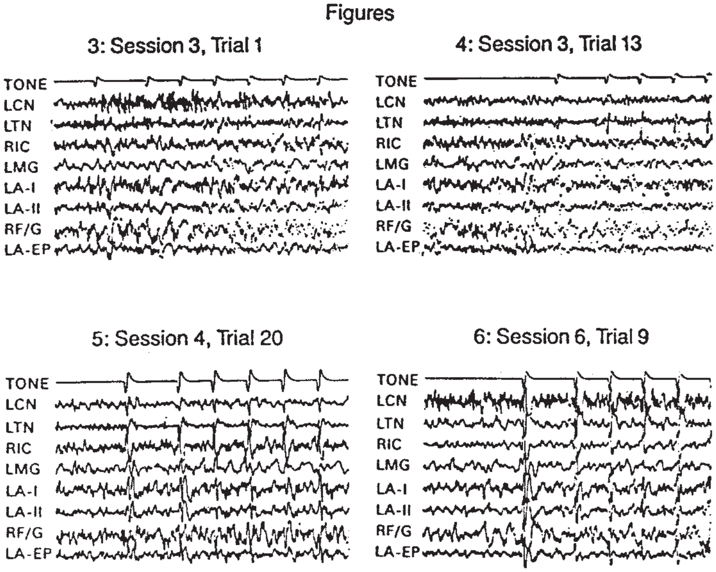
* Literally, *con* = together; *prehendere* = to seize, grasp.



Figures 3–6

from the nerve cells first to receive auditory stimuli (cochlea nucleus, CN) up to the auditory cortex.[10] The cat so prepared is admitted into a cage that contains a food box whose lid can be opened by pressing a lever. However, the lever–lid connection is operative only when a short single tone (here C_6, which is about 1000 hertz) is repetitively presented. The cat has to learn that C_6 "means" food. Figures 3–6 show the pattern of nervous activity at eight ascending auditory stations and at four consecutive stages of this learning process.[10] The cat's behavior associated with the recorded neural activity is for "random search" in Figure 3, "inspection of lever" in Figure 4, "lever pressed at once" in Figure 5, and "walking straight toward lever (full comprehension)" in Figure 6. Note that no tone is perceived as long as this tone is uninterpretable (Figs. 3,4; pure noise), but the whole system swings into action with the appearance of the first "beep" (Figs. 5,6; noise becomes signal), when sensation becomes comprehensible, when *our* perception of "beep, beep; beep" is in the *cat's* perception "food, food, food."

Interpretation

In these experiments I have cited instances in which we see or hear what is not "there," or in which we do not see or hear what is "there" unless coordination of sensation and movement allows us to "grasp" what appears to be there. Let me strengthen this observation by citing now the "principle of undifferentiated encoding":

The response of a nerve cell does *not* encode the physical nature of the agents that caused its response. Encoded is only "how much" at this point on my body, but not "what."

Take, for instance, a light-sensitive receptor cell in the retina, a "rod" that absorbs the electromagnetic radiation originating from a distant source. This absorption causes a change in the electrochemical potential in the rod, which will ultimately give rise to a periodic electric discharge of some cells higher up in the postretinal networks (see below, Fig. 15), with a period that is commensurate with the intensity of the radiation absorbed, but without a clue that it was electromagnetic radiation that caused the rod to discharge. The same is true for any other sensory receptor, may it be the taste buds, the touch receptors, and all the other receptors that are associated with the sensations of smell, heat and cold, sound, and so on: They are all "blind" as to the quality of their stimulation, responsive only as to their quantity.

Although surprising, this should not come as a surprise, for indeed "out there" there is no light and no color, there are only electromagnetic waves; "out there" there is no sound and no music, there are only periodic variations of the air pressure; "out there" there is no heat and no cold, there are only moving molecules with more or less mean kinetic energy, and so on. Finally, for sure, "out there" there is no pain.

Since the physical nature of the stimulus—its *quality*—is not encoded into nervous activity, the fundamental question arises as to how does our brain conjure up the tremendous variety of this colorful world as we experience it any moment while awake, and sometimes in dreams while asleep. This is the "problem of cognition," the search for an understanding of the cognitive processes.

The way in which a question is asked determines the way in which an answer may be found. Thus it is upon me to paraphrase the "problem of cognition" in such a way that the conceptual tools that are today at our disposal may become fully effective. To this end let me paraphrase (→) "cognition" in the following way:

cognition → computing a reality

With this I anticipate a storm of objections. First, I appear to replace one unknown term *cognition*, with three other terms, two of which, *computing* and *reality*, are even more opaque than the definiendum, and with the only definite word used here being the indefinite article *a*. Moreover, the use of the indefinite article implies the ridiculous notion of other realities besides "the" only and one reality, our cherished Environment; and finally I seem to suggest by "computing" that everything, from my wristwatch to the galaxies; is merely computed, and is not "there." Outrageous!

Let me take up these objections one by one. First, let me remove the semantic sting that the term *computing* may cause in a group of women and men who are more inclined toward the humanities than to the sciences.

Harmlessly enough, computing (from *com-putare*) literally means to reflect, to contemplate (*putare*) things in concert (*com*), without any explicit reference to numerical quantities. Indeed, I shall use this term in this most general sense to indicate any operation (not necessarily numerical) that transforms, modifies, rearranges, orders, and so on, observed physical entities ("objects") or their representations ("symbols"). For instance, the simple permutation of the three letters *A*,*B*,*C*, in which the last letter now goes first—*C*,*A*,*B*—I shall call a computation; similarly the operation that obliterates the commas between the letters—*CAB*—and likewise the semantic transformation that changes *CAB* into *taxi*, and so on.

I shall now turn to the defense of my use of the indefinite article in the noun phrase *a reality*. I could, of course, shield myself behind the logical argument that solving for the general case, implied by the *a*, I would also have solved any specific case denoted by the use of *the*. However, my motivation lies much deeper. In fact, there is a deep hiatus that separates the *the* school of thought from the *a* school of thought in which, respectively, the distinct concepts of "confirmation" and "correlation" are taken as explanatory paradigms for perceptions. The *the* school: My sensation of touch is *confirmation* for my visual sensation that here is a table. The *a* school: My sensation of touch in *correlation* with my visual sensation generate an experience that I may describe by "here is a table."

I am rejecting the *the* position on epistemological grounds, for in this way the whole problem of cognition is safely put away in one's own cognitive blind spot: Even its absence can no longer be seen.

Finally one may rightly argue that cognitive processes do not compute wristwatches or galaxies, but compute at best *descriptions* of such entities. Thus I am yielding to this objection and replace my former paraphrase by

$$\text{cognition} \rightarrow \text{computing descriptions of a reality}$$

Neurophysiologists, however, will tell us[4] that a description computed on one level of neural activity, say, a projected image on the retina, will be operated on again on higher levels, and so on, whereby some motor activity may be taken by an observer as a "terminal description," for instance, the utterance, "Here is a table." Consequently, I have to modify this paraphrase again to read

$$\begin{tikzcd} \text{cognition} \arrow[r] & \text{computing descriptions of} \arrow[loop right] \end{tikzcd}$$

where the arrow turning back suggests this infinite recursion of descriptions of descriptions, etc. This formulation has the advantage that one unknown, namely, "reality," is successfully eliminated. Reality appears only implicit as the operation of recursive descriptions. Moreover, we may take advantage of the notion that computing descriptions is nothing else but computations.

Hence

$$\begin{tikzcd}\text{cognition} \arrow[r] & \text{computations of} \arrow[loop right]\end{tikzcd}$$

In summary, I propose to interpret cognitive processes as never-ending recursive processes of computation, and I hope that in the following *tour de force* of neurophysiology I can make this interpretation transparent.

Neurophysiology

Evolution

In order that the principle of recursive computation be fully appreciated as being the underlying principle of all cognitive processes—even of life itself, as one of the most advanced thinkers in biology assures me[5]—it may be instructive to go back for a moment to the most elementary—or as evolutionists would say, to very "early"—manifestations of this principle. These are the "independent effectors," or independent sensorimotor units, found in protozoa and metazoa distributed over the surface of these animals (Fig. 7). The triangular portion of this unit, protruding with its tip from the surface, is the sensory part; the onion-shaped portion, the contractile motor part. A change in the chemical concentration of an agent in the immediate vicinity of the sensing tip, and "perceptible" by it, causes an instantaneous contraction of this unit. The resulting displacement of this or any other unit by change of shape of the animal or its location may, in turn, produce perceptible changes in the agent's concentration in the vicinity of these units, which, in turn, will cause their instantaneous contraction, and so on. Thus we have the recursion

$$\begin{tikzcd}\text{change of sensation} \arrow[r] & \text{change of shape} \arrow[l, bend left]\end{tikzcd}$$

Separation of the sites of sensation and action appears to have been the next evolutionary step (Fig. 8). The sensory and motor organs are now connected by thin filaments, the "axons" (in essence degenerated muscle fibers having lost their contractility), which transmit the sensor's perturbations to its effector, thus giving rise to the concept of a "signal": See something here, act accordingly there.

The crucial step, however, in the evolution of the complex organization of the mammalian central nervous system (CNS) appears to be the appear-

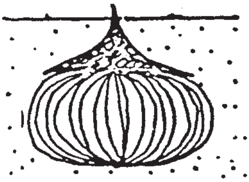
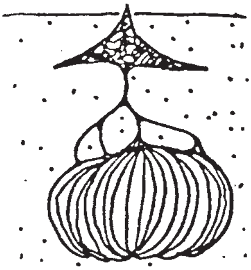


FIGURE 7.



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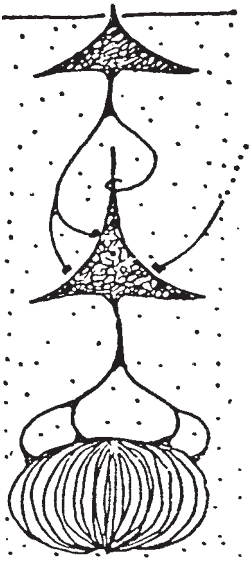

FIGURE 9.

ance of an "internuncial neuron," a cell sandwiched between the sensory and the motor unit (Fig. 9). It is, in essence, a sensory cell, but specialized so as to respond only to a universal "agent," namely, the electrical activity of the afferent axons terminating in its vicinity. Since its present activity may affect its subsequent responsivity, it introduces the element of computation in the animal kingdom and gives these organisms the astounding latitude of nontrivial behaviors. Having once developed the genetic code for assembling an internuncial neuron, to add the genetic command *repeat* is a small burden indeed. Hence, I believe, it is now easy to comprehend the rapid proliferation of these neurons along additional vertical layers with growing horizontal connections to form those complex interconnected structures we call "brains."

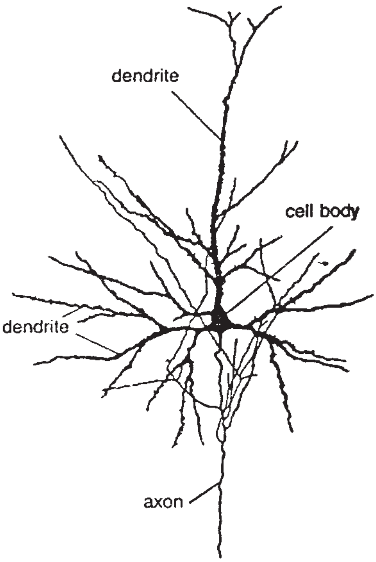

FIGURE 10.

The Neuron

The neuron, of which we have more than 10 billion in our brain, is a highly specialized single cell with three anatomically distinct features (Fig. 10): (1) the branch-like ramifications stretching up and to the side, the "dendrites"; (2) the bulb in the center housing the cell's nucleus, the "cell body"; and (3), the "axon," the smooth fiber stretching downward. Its various bifurcations terminate on dendrites of another (but sometimes—recursively—on the same) neuron. The same membrane that envelops the cell body forms also the tubular sheath for dendrites and axon, and causes the inside of the cell to be electrically charged against the outside with about $^1/_{10}$ of a volt. If in the dendritic region this charge is sufficiently perturbed, the neuron "fires" and sends this perturbation along its axon to its termination, the synapses.

Transmission

Since these perturbations are electrical, they can be picked up by "microprobes," amplified and recorded. Figure 11 shows three examples of periodic discharges from a touch receptor under continuous stimulation, the low frequency corresponding to a weak stimulus, the high frequency to a strong stimulus. The magnitude of the discharge is clearly everywhere the same, the pulse frequency representing the stimulus intensity, but the intensity only.

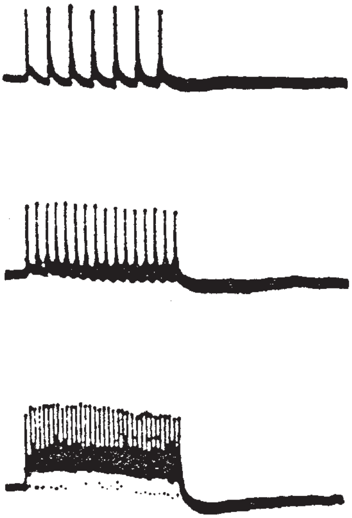

FIGURE 11.

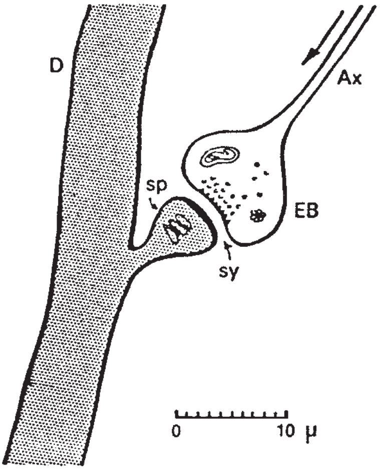

FIGURE 12.

Synapse

Figure 12 sketches a synaptic junction. The afferent axon (Ax), along which the pulses travel, terminates in an end bulb (EB), which is separated from the spine (sp) of a dendrite (D) of the target neuron by a minute gap (sy), the "synaptic gap." (Note the many spines that cause the rugged appearance of the dendrites in Fig. 10). The chemical composition of the "transmitter substances" filling the synaptic gap is crucial in determining the effect an arriving pulse may have on the ultimate response of the neuron: Under certain circumstances it may produce an "inhibitory effect" (cancellation of

Figure 13.

another simultaneously arriving pulse), in others a "facilitory effect" (augmenting another pulse to fire the neuron). Consequently, the synaptic gap can be seen as the "microenvironment" of a sensitive tip, the spine, and with this interpretation in mind we may compare the sensitivity of the CNS to changes of the *internal* environment (the sum total of all microenvironments) to those of the *external* environment (all sensory receptors). Since there are only 100 million sensory receptors, and about 10,000 billion synapses in our nervous system, we are 100 thousand times more receptive to changes in our internal than in our external environment.

The Cortex

In order that one may get at least some perspective on the organization of the entire machinery that computes all perceptual, intellectual, and emotional experiences, I have attached Figure 13,[7] which shows a magnified section of about 2 square millimeters of a cat's cortex by a staining method that stains only cell body and dendrites, and of those only 1% of all neurons present. Although you have to imagine the many connections among these neurons provided by the (invisible) axons, and a density of packing that is 100 times that shown, the computational power of even this very small part of a brain may be sensed.

Descartes

This perspective is a far cry from that held, say, 300 years ago:[2]

> If the fire A is near the foot B [Fig. 14], the particles of this fire, which as you know move with great rapidity, have the power to move the area of the skin of this foot

Figure 14.

> that they touch; and in this way drawing the little thread, c, that you see to be attached at base of toes and on the nerve, at the same instant they open the entrance of the pore, d,e, at which this little thread terminates, just as by pulling one end of a cord, at the same time one causes the bell to sound that hangs at the other end. Now the entrance of the pore or little conduit, d,e, being thus opened, the animal spirits of the cavity F, enter within and are carried by it, partly into the muscles that serve to withdraw this foot from the fire, partly into those that serve to turn the eyes and the head to look at it, and partly into those that serve to advance the hands and to bend the whole body to protect it.

Note, however, that some behaviorists of today still cling to the same view,[8] with one difference only, namely, that in the meantime Descartes' "animal spirit" has gone into oblivion.

Computation

The retina of vertebrates, with its associated nervous tissue, is a typical case of neural computation. Figure 15 is a schematic representation of a mammalian retina and its postretinal network. The layer labeled 1 represents the array of rods and cones, and layer 2 the bodies and nuclei of these cells. Layer 3 identifies the general region where the axons of the receptors synapse with the dendritic ramifications of the "bipolar cells" (4) which, in turn, synapse in layer 5 with the dendrites of the ganglion cells" (6), whose

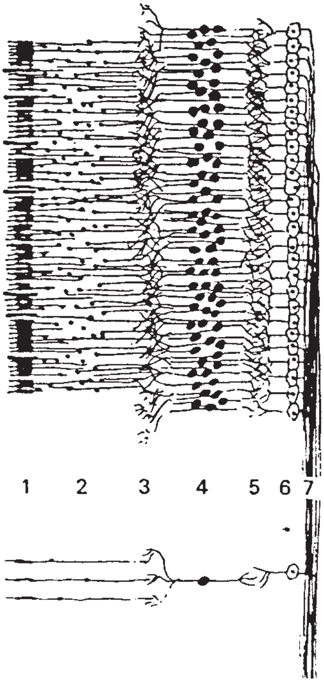

FIGURE 15.

activity is transmitted to deeper regions of the brain via their axons, which are bundled together to form the optic nerve (7). Computation takes place within the two layers labeled 3 and 5, that is, where the synapses are located. As Maturana has shown[3] it is there where the sensation of color and some clues as to form are computed.

Form computation: Take the two-layered periodic network of Figure 16, the upper layer representing receptor cells sensitive to, say, "light." Each of these receptors is connected to three neurons in the lower (computing) layer, with two excitatory synapses on the neuron directly below (symbolized by buttons attached to the body) and with one inhibitory synapse (symbolized by a loop around the tip) attached to each of the two neurons, one to the left and one to the right. It is clear that the computing layer will not respond to uniform light projected on the receptive layer, for the two excitatory stimuli on a computer neuron will be exactly compensated by the inhibitory signals coming from the two lateral receptors. This zero response will prevail under strongest and weakest stimulations as well as for slow or rapid changes of the illumination. The legitimate question may now arise: "Why this complex apparatus that doesn't do a thing?"

Consider now Figure 17, in which an obstruction is placed in the light path illuminating the layer of receptors. Again all neurons of the lower layer will remain silent, except the one at the edge of the obstruction, for it

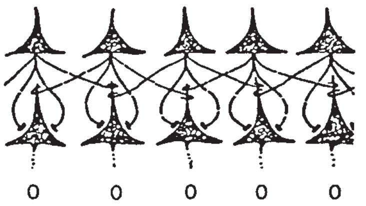

FIGURE 16.

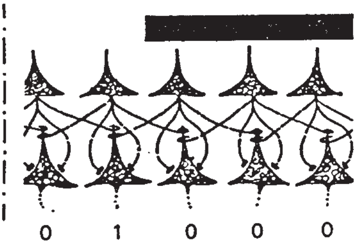

FIGURE 17.

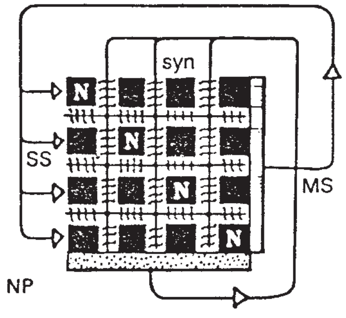

FIGURE 18.

receives two excitatory signals from the receptor above, but only one inhibitory signal from the sensor to the left. We now understand the important function of this net, for it computes any spatial *variation* in the visual field of this "eye," independent of the intensity of the ambient light and its temporal variations, and independent of place and extension of the obstruction.

Although all operations involved in this computation are elementary, the organization of these operations allows us to appreciate a principle of considerable depth, namely, that of the computation of abstracts, here the notion of "edge."

I hope that this simple example is sufficient to suggest to you the possibility of generalizing this principle in the sense that "computation" can be seen on at least two levels, namely, (1) the operations actually performed and (2) the organization of these operations represented here by the structure of the nerve net. In computer language (1) would again be associated with "operations," but (2) with the "program." As we shall see later, in "biological computers" the programs themselves may be computed on. This leads to the concepts of "metaprograms," "meta-metaprograms," and so on. This, of course, is the consequence of the inherent recursive organization of those systems.

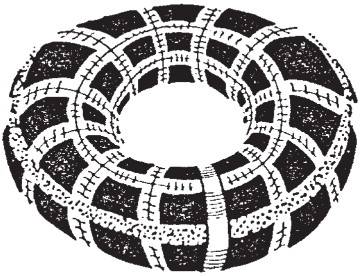

FIGURE 19.

Closure

By attending to all the neurophysiological pieces, we may have lost the perspective that sees an organism as a functioning whole. In Figure 18 I have put these pieces together in their functional context. The black squares labeled *N* represent bundles of neurons that synapse with neurons of other bundles over the (synaptic) gaps indicated by the spaces between squares. The sensory surface (SS) of the organism is to the left, its motor surface (MS) to the right, and the neuropituitary (NP), the strongly innervated master gland that regulates the entire endocrinal system, is the stippled lower boundary of the array of squares. Nerve impulses traveling horizontally (from left to right) ultimately act on the motor surface (MS) whose changes (movements) are immediately sensed by the sensory surface (SS), as suggested by the "external" pathway following the arrows. Impulses traveling vertically (from top to bottom) stimulate the neuropituitary (NP), whose activity release steroids into the synaptic gasp, as suggested by the wiggly terminations of the lines following the arrow, and thus modify the *modus operandi* of all synaptic junctures, hence the *modus operandi* of the system as a whole. Note the double closure of the system that now recursively operates not only on what it "sees," but on its operators as well. In order to make this twofold closure even more apparent I propose to wrap the diagram of Figure 18 around its two axes of circular symmetry until the artificial boundaries disappear and the torus (doughnut) in Figure 19 is obtained. Here the "synaptic gap" between the motor and sensory surfaces is the striated meridian in the front center, the neuropituitary the stippled equator. This, I submit, is the functional organization of a living organism in a (dough) nut shell.

The computations within this torus are subject to a nontrivial constraint, and this is expressed in the postulate of cognitive homeostais:

> The nervous system is organized (or organizes itself) so that it computes a stable reality.

This postulate stipulates "autonomy," that is, "self-regulation," for every living organism. Since the semantic structure of nouns with the prefix *self-* becomes more transparent when this prefix is replaced by the noun, *autonomy* becomes synonymous with *regulation of regulation*. This is precisely what the doubly closed, recursively computing torus does: It regulates its own regulation.

Significance

It may be strange in times like these to stipulate autonomy, for autonomy implies responsibility: If I am the only one who decides how I act, then I am responsible for my action. Since the rule of the most popular game played today is to make someone else responsible for *my* acts—the name of the game is "heteronomy"—my arguments make, I understand, a most unpopular claim. One way of sweeping it under the rug is to dismiss it as just another attempt to rescue "solipsism," the view that this world is only in my imagination and the only reality is the imagining "I." Indeed, that was precisely what I was saying before, but I was talking only about a single organism. The situation is quite different when there are two, as I shall demonstrate with the aid of the gentleman with the bowler hat (Fig. 20).

He insists that he is the sole reality, while everything else appears only in his imagination. However, he cannot deny that his imaginary universe is populated with apparitions that are not unlike himself. Hence he has to

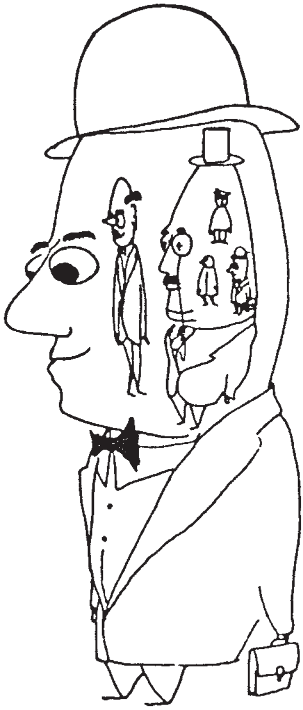

FIGURE 20.

concede that they themselves may insists that they are the sole reality and everything else is only a concoction of their imagination. In that case their imaginary universe will be populated with apparitions, one of which may be *he*, the gentleman with the bowler hat.

According to the principle of relativity, which rejects a hypothesis when it does not hold for two instances together, although it holds for each instance separately (Earthlings and Venusians may be consistent in claiming to be in the center of the universe, but their claims fall to pieces if they should ever get together), the solipsistic claim falls to pieces when besides me I invent another autonomous organism. However, it should be noted that since the principle of relativity is not a logical necessity—nor is it a proposition that can be proven to be either true or false—the crucial point to be recognized here is that I am free to choose either to adopt this principle or to reject. If I reject it, I am the center of the universe, my reality is my dreams and my nightmares, my language is monologue, and my logic monologic. If I adopt it, neither I nor the other can be the center of the universe. As in the heliocentric system, there must be a third that is the central reference. It is the relation between Thou and I, and this relation is *identity*:

$$\text{reality} = \text{community}$$

What are the consequences of all this in ethics and aesthetics?

The ethical imperative: Act always so as to increase the number of choices.

The aesthetical imperative: If you desire to see, learn how to act.

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