Introduction

Let the Problem of the Mind Dissolve in Your Mind

This is an exercise in fictional science, or science fiction, if you like that better. Not for amusement: science fiction in the service of science. Or just science, if you agree that fiction is part of it, always was, and always will be as long as our brains are only minuscule fragments of the universe, much too small to hold all the facts of the world but not too idle to speculate about them.

I have been dealing for many years with certain structures within animal brains that seemed to be interpretable as pieces of computing machinery because of their simplicity and/or regularity. Much of this work is only interesting if you are yourself involved in it. At times, though, in the back of my mind, while I was counting fibers in the visual ganglia of the fly or synapses in the cerebral cortex of the mouse, I felt knots untie, distinctions dissolve, difficulties disappear, difficulties I had experienced much earlier when I still held my first naive philosophical approach to the problem of the mind. This process of purification has been, over the years, a delightful experience. The text I want you to read is designed to convey some of this to you, if you are prepared to follow me not through a world of real brains but through a toy world that we will create together.

We will talk only about machines with very simple internal structures, too simple in fact to be interesting from the point of view of mechanical or electrical engineering. Interest arises, rather, when we look at these machines or vehicles as if they were animals in a natural environment. We will be tempted, then, to use psychological language in describing their behavior. And yet we know very well that there is nothing in these vehicles that we have not put in ourselves. This will be an interesting educational game.

Our vehicles may move in water by jet propulsion. Or you may prefer to imagine them moving somewhere between galaxies, with negligible gravitational pull. Remember, however, that their jets must expel matter in order to function at all, and this implies replenishment of the food stores within the vehicles, which might be a problem between galaxies. This suggests vehicles moving on the surface of the earth through an agricultural landscape where they have good support and can easily find the food or fuel they need. (Indeed the first few chapters here conjure up images of vehicles swimming around in the water, while later what comes to mind are little carts moving on hard surfaces. This is no accident, if the evolution of vehicles 1 to 14 in any way reflects the evolution of animal species.)

It does not matter. Get used to a way of thinking in which the hardware of the realization of an idea is much less important than the idea itself. Norbert Wiener was emphatic about this when he formulated the title of his famous book: *Cybernetics, or Control and Communication in Animals and Machines.*

Vehicle 1

Getting Around

Vehicle 1 is equipped with one sensor and one motor (figure 1). The connection is a very simple one. The more there is of the quality to which the sensor is tuned, the faster the motor goes. Let the quality be temperature and let the force exerted by the motor be exactly proportionate to the absolute temperature (the temperature above zero degrees Kelvin) measured by the sensor. The vehicle will move, wherever it is (the absolute temperature is nowhere equal to zero), in the direction in which it happens to be pointing. It will slow down in cold regions and speed up where it is warm.

Here we have introduced a bit of Aristotelian physics. Aristotle, like everybody else between this ancient Greek philosopher and the less ancient Italian physicist Galileo, thought that the speed of a moving body is proportionate to the force that drives it. This is true in most instances, namely when there is friction to slow down the vehicle. Normally friction will see to it that the velocity becomes zero in the absence of any force, that it will stay at a certain small value for a certain small force, at a higher value for a higher force, and so forth.

Of course, as you all know, this is not true for heavenly bodies

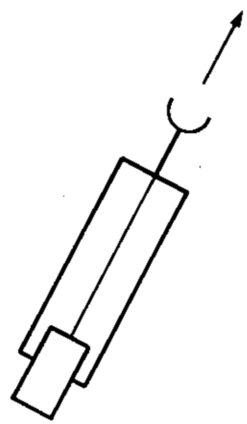


Figure 1
Vehicle 1, the simplest vehicle. The speed of the motor (rectangular box at the tail end) is controlled by a sensor (half circle on a stalk, at the front end). Motion is always forward, in the direction of the arrow, except for perturbations.

(especially if you don't invest astronomical time in observing them). Their velocity is a complicated result of all the forces that ever hit them. This is another reason for letting our vehicles move in water or on the surface of the earth rather than in outer space.

In this Aristotelian world our vehicle number 1 may even come to rest. This will happen when it enters a cold region where the force exerted by its motor, being proportionate to the temperature, becomes smaller than the frictional force.

Once you let friction come into the picture, other amazing things may happen. In outer space Vehicle 1 would move on a straight course with varying speed (the gravitational pull of neighboring galaxies averages out to nothing). Not so on earth. The friction, which is nothing but the sum of all the microscopic forces that arise in a situation too messy to be analyzed in detail, may not be quite symmetrical. As the vehicle pushes forward against frictional forces, it will deviate from its course. In the long run it will be seen to move in a complicated trajectory, curving one way or the other without apparent good reason. If it is very small, its motion will be quite erratic, similar to "Brownian motion," only with a certain drive added.

Imagine, now, what you would think if you saw such a vehicle swimming around in a pond. It is restless, you would say, and does not like warm water. But it is quite stupid, since it is not able to turn back to the nice cold spot it overshot in its restlessness. Anyway, you would say, it is ALIVE, since you have never seen a particle of dead matter move around quite like that.

Vehicle 2

Fear and Aggression

Vehicle 2 is generally similar to Vehicle 1 except that it has two sensors, one on each side, and two motors, right and left (figure 2). You may think of it as being a descendant of Vehicle 1 through some incomplete process of biological reduplication: two of the earlier brand stuck together side by side. Again, the more the sensors are excited, the faster the motors run.

Of course you notice right away that we can make three kinds of such vehicles, depending on whether we connect (a) each sensor to the motor on the same side, (b) each sensor to the motor on the opposite side, or (c) both sensors to both motors. We can immediately dismiss case (c), for this is nothing but a somewhat more luxurious version of Vehicle 1. The difference between (a) and (b), however, is very interesting.

Consider (a) first. This vehicle will spend more time in the places where there is less of the stuff that excites its sensors and will speed up when it is exposed to higher concentrations. If the source of the stuff (say, light in the case of light sensors) is directly ahead, the vehicle may hit the source unless it is deflected from its course. If the source is to one side (figure 3), one of the sensors, the one nearer to the source, is excited more than the other. The corresponding

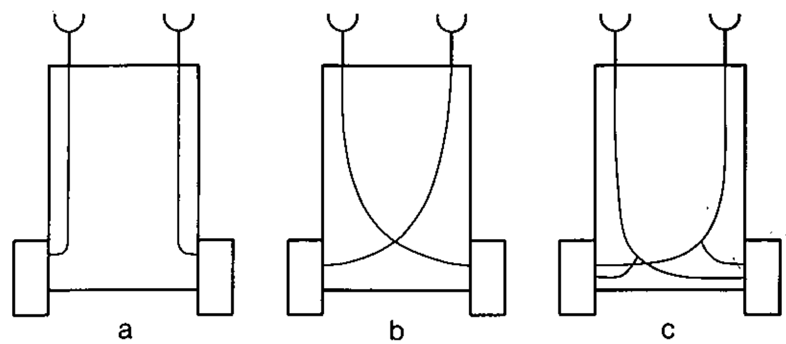


Figure 2
Vehicle 2, with two motors and two sensors; otherwise like Vehicle 1. The connections differ in a, b, and c.

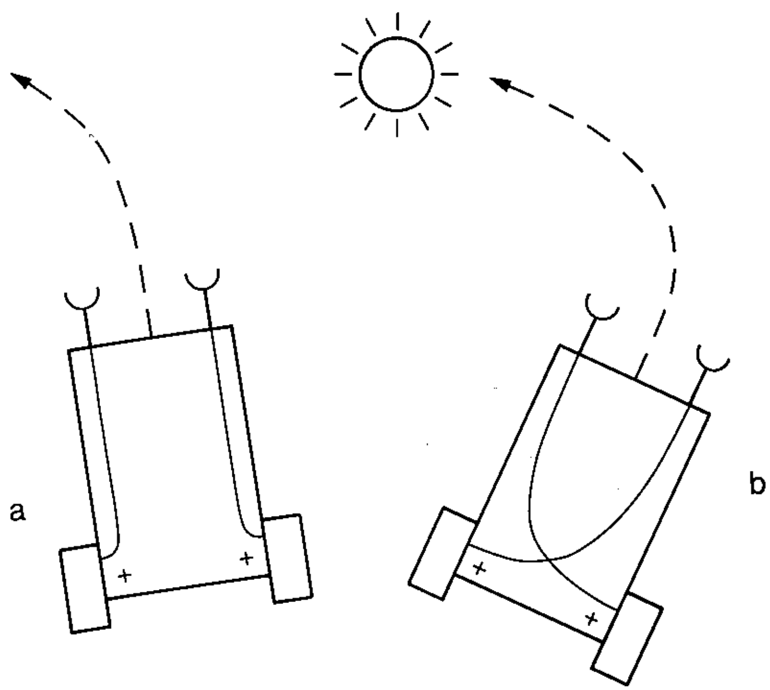


Figure 3
Vehicles 2a and 2b in the vicinity of a source (circle with rays emanating from it). Vehicle 2b orients toward the source, 2a away from it.

motor will work harder. And as a consequence the vehicle will turn away from the source.

Now let us try the other scheme of sensory-motor connections, (b) in figure 3. No change if the source is straight ahead. If it is to one side, however, we notice a difference with respect to Vehicle 2a. Vehicle 2b will turn toward the source and eventually hit it. There is no escaping: as long as 2b stays in the vicinity of the source, no matter how it stumbles and hesitates, it will hit the source frontally in the end. Only in the unlikely case that a strong perturbation in its course makes it turn exactly away from the source, and no further perturbation occurs, can it escape its fate.

Let Vehicles 2a and 2b move around in their world for a while and watch them. Their characters are quite opposite. Both DISLIKE sources. But 2a becomes restless in their vicinity and tends to avoid them, escaping until it safely reaches a place where the influence of the source is scarcely felt. Vehicle 2a is a COWARD, you would say. Not so Vehicle 2b. It, too, is excited by the presence of sources, but resolutely turns toward them and hits them with high velocity, as if it wanted to destroy them. Vehicle 2b is AGGRESSIVE, obviously.

Vehicle 3

Love

The violence of Vehicle 2b, no less than the cowardice of its companion 2a, are traits that call for improvement. There is something very crude about a vehicle that can only be excited by the things it smells (or sees or feels or hears) and knows no soothing or relaxing stimuli. What comes to mind is to introduce some inhibition in the connections between the sensors and the motors, switching the sign of the influence from positive to negative. This will let the motor slow down when the corresponding sensor is activated. Again we can make two variants, one with straight and one with crossed connections (figure 4). Both will slow down in the presence of a strong stimulus and race where the stimulus is weak. They will therefore spend more time in the vicinity of the source than away from it. They will actually come to rest in the immediate vicinity of the source.

But here we notice a difference between the vehicle with straight connections and the one with crossed connections. Approaching the source, the first (figure 4a) will orient toward it, since on an oblique course the sensor nearer to the source will slow down the motor on the same side, producing a turn toward that side. The vehicle with straight connections will come to rest facing the

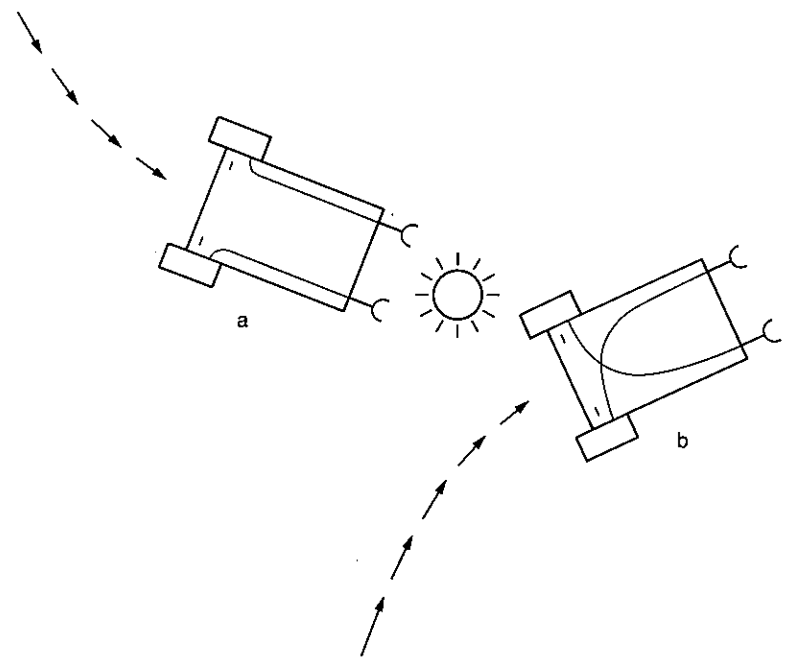


Figure 4
Vehicle 3, with inhibitory influence of the sensors on the motors.

source. The vehicle with crossed connections (figure 4b) for analogous reasons will come to rest facing away from the source and may not stay there very long, since a slight perturbation could cause it to drift away from the source. This would lessen the source's inhibitory influence, causing the vehicle to speed up more and more as it gets away.

You will have no difficulty giving names to this sort of behavior. These vehicles LIKE the source, you will say, but in different ways. Vehicle 3a LOVES it in a permanent way, staying close by in quiet admiration from the time it spots the source to all future time. Vehicle 3b, on the other hand, is an EXPLORER. It likes the nearby source all right, but keeps an eye open for other, perhaps stronger sources, which it will sail to, given a chance, in order to find a more permanent and gratifying appeasement.

But this is not yet the full development of Vehicle 3. We are now ready to make a more complete model using all the behavioral traits at our disposal. Call it Vehicle 3c. We give it not just one pair of sensors but four pairs, tuned to different qualities of the environment, say light, temperature, oxygen concentration, and amount of organic matter (figure 5). Now we connect the first pair to the motors with uncrossed excitatory connections, as in Vehicle 2a, the second pair with crossed excitatory connections, as in Vehicle 2b, and the third and the fourth pairs with inhibitory connections, crossed and uncrossed, as in Vehicles 3b and 3a.

This is now a vehicle with really interesting behavior. It dislikes high temperature, turns away from hot places, and at the same time seems to dislike light bulbs with even greater passion, since it turns toward them and destroys them. On the other hand it definitely seems to prefer a well-oxygenated environment and one containing many organic molecules, since it spends much of its time in such places. But it is in the habit of moving elsewhere when the supply of either organic matter or (especially) oxygen is low. You cannot help admitting that Vehicle 3c has a system of VALUES, and, come to

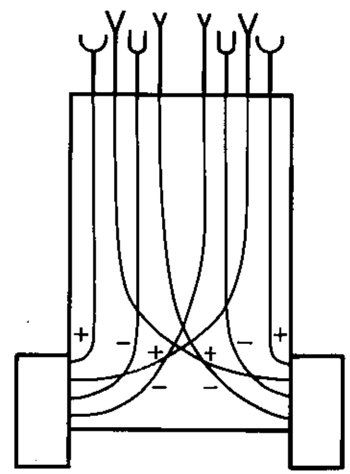


Figure 5
A multisensorial vehicle of brand 3c.

think of it, KNOWLEDGE, since some of the habits it has, like destroying light bulbs, may look quite knowledgeable, as if the vehicle knows that light bulbs tend to heat up the environment and consequently make it uncomfortable to live in. It also looks as if it knows about the possibility of making energy out of oxygen and organic matter because it prefers places where these two commodities are available.

But, you will say, this is ridiculous: knowledge implies a flow of information from the environment into a living being or at least into something like a living being. There was no such transmission of information here. We were just playing with sensors, motors, and connections: the properties that happened to emerge may look like knowledge but really are not. We should be careful with such words.

You are right. We will explain in a later chapter (on Vehicle 6) how knowledge may enter a system of connections. And we will introduce an alternative way of incorporating knowledge into the system in our chapter on Vehicle 7. In any case, once knowledge is incorporated, the resulting vehicle may look and behave quite like our Vehicle 3c.

Meanwhile I invite you to consider the enormous wealth of different properties that we may give Vehicle 3c by choosing various sensors and various combinations of crossed and uncrossed, excitatory and inhibitory, connections.

If you consider the possibility of strong and weak influences from the sensors to the motors, you realize that the variety becomes even greater. The vehicle may not care much about light but care very much about temperature. Its sense of smell may be much keener for organic matter than it is for oxygen or vice versa. And there may be many more than just four pairs of sensors and four sensory qualities: the vehicles may be equipped with all sorts of shrewd detectors of energy and of chemicals. But this is best discussed in connection with a new idea incorporated in the vehicles of the next chapter.

Vehicle 4

Values and Special Tastes

We are now in a position to create a new brand of vehicle, starting from all the varieties of Vehicle 3, by working on the connections between sensors and motors. They were, up to now, of two very simple kinds: the more the sensor was excited, the faster the corresponding motor ran, or, alternatively, the more the sensor was excited, the slower the motor ran. We did not care what the rules of the dependence were, as long as they were of the nature "the more, the more" or "the more, the less." The vast class of mathematical functions describing such dependences is sometimes called monotonic. Obviously, there is something very simple-minded about creatures governed by such unconditioned likes or dislikes, and we can easily see how such the-more-the-merrier behavior could lead to disaster. Think what happens in the case of a tendency to follow downhill slopes!

Let us consider the following improvement. The activation of a certain sensor will make the corresponding motor run faster, but only up to a point, where the speed of the motor reaches a maximum. Beyond this point, if the sensor is activated even more strongly, the speed will decrease again (figure 6). The same sort of dependence, with a maximum efficiency at a certain level of sensor

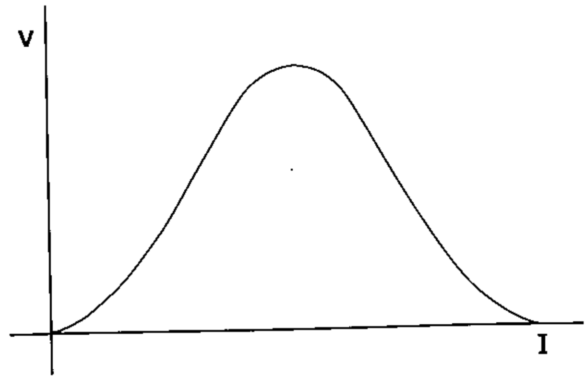


Figure 6
A nonlinear dependence of the speed of the motor V on the intensity of stimulation I, with a maximum for a certain intensity.

activation, can be engineered for the inhibitory connections between sensor and motor. We may set the maximum efficiency of the various sensors at any level we choose, and we may even play with dependences having more than one maximum. Any vehicle constructed according to this prescription we will assign to a new brand, labeled 4a. Of course, if you like, you can keep some of the connections of the old monotonic type and mix them with the nonmonotonic ones in every possible combination.

You will have a hard time imagining the variety of behavior displayed by the vehicles of brand 4a. A 4a vehicle might navigate toward a source (as Vehicle 2b would) and then turn away when the stimulus becomes strong, circle back and then turn away over and over again, perhaps describing a trajectory in the form of a figure eight. Or it might orbit around the source at a fixed distance, like a satellite around the earth, its course being corrected toward the source by a weaker stimulus and away from the source by a stronger stimulus, depending on whether the stimulus intensity is

on one side or the other of the maximum describing the sensory-motor dependence (figure 7). Vehicle 4a might like one sort of stimulus when it is weak but not when it is too strong; it might like another stimulus better the stronger it becomes. It might turn away from a weak smell and destroy the source of a strong one. It might visit in alternation a source of smell and a source of sound, turning away from both with a change of temperature.

Watching vehicles of brand 4a in a landscape of sources, you will be delighted by their complicated trajectories. And I am sure you will feel that their motives and tastes are much too varied and intricate to be understood by the observer. These vehicles, you will say, are governed by INSTINCTS of various sorts and, alas, we just don't know how Nature manages to embody instincts into a piece of brain.

You forget, of course, that we have ourselves designed these vehicles.

But instincts are a lowly sort of behavior anyway. We can do better. Let us improve on type 4a by adding a new sort of connection between sensors and motors. This time the influence of the sensor on the motor is no longer smooth; there are definite breaks. There might be a range of intensities of sensory stimulation for which the motor is not activated at all and then, under stronger stimuli, the motors are running at full speed. Or else, there might be smooth changes of motor activation for certain ranges, with abrupt changes in between. A very lifelike pattern would be: no activation up to a threshold value of the stimulus, and increasing activation beyond the threshold, starting with a certain fixed minimum (figure 8). You are by now experienced in the art of creative invention and will have no difficulty dreaming up more schemes of this sort.

In a way these new vehicles, which we call 4b, are already contained in the vast class of vehicles 4a, since abruptness of behavior can of course be simulated with any degree of approximation by functional dependences that are in reality, mathematically speak-

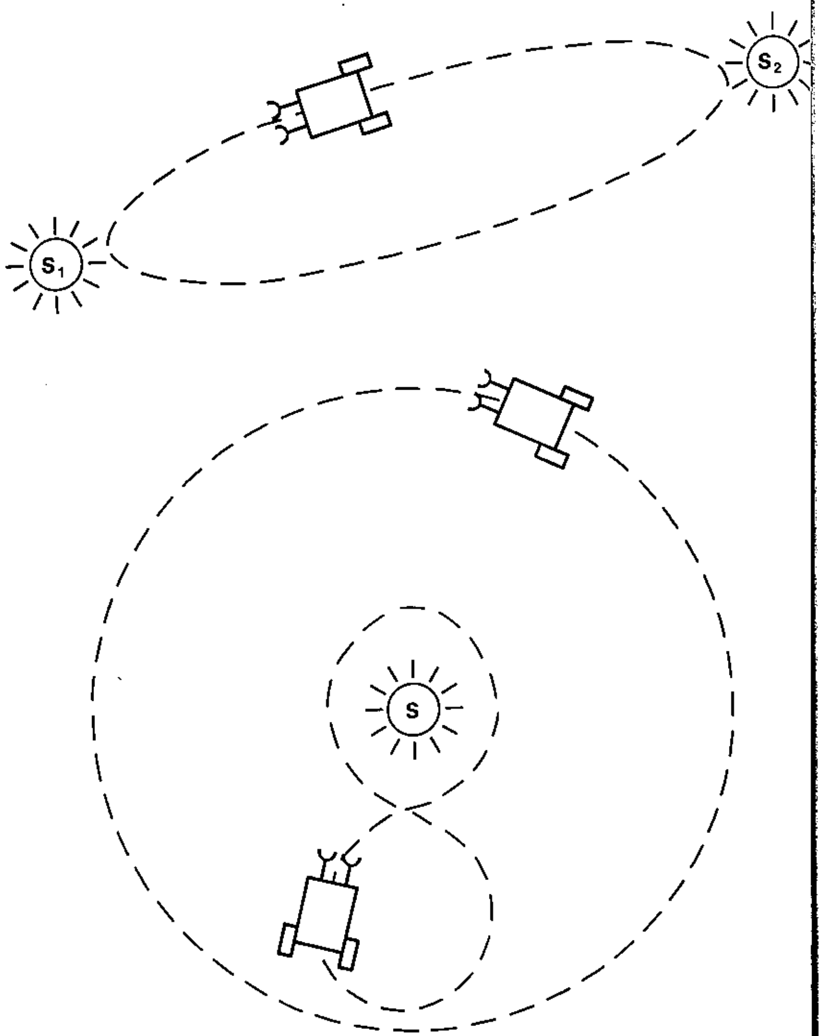


Figure 7
Trajectories of vehicles of brand 4a around or between sources.

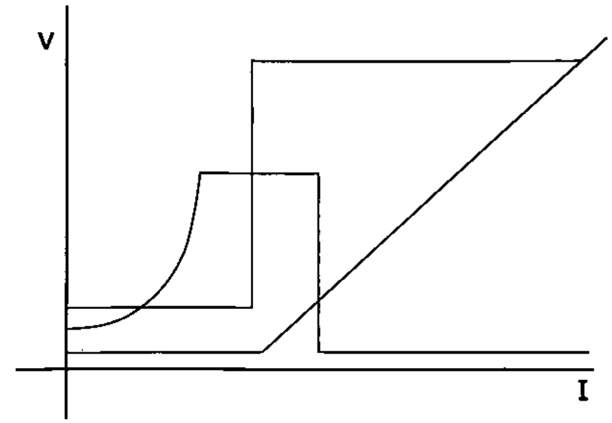


Figure 8
Various bizarre kinds of dependence of the speed of the motor (ordinate) on the intensity of stimulation (abscissa) in Vehicle 4b.

ing, continuous. Moreover, if friction plays a role, as we have already decided it should, thresholds in motor activation would ensue naturally: the vehicle will start moving only when the force exerted by the motor exceeds a certain value, sufficient to overcome the initial friction.

Whatever their origin, thresholds in some behavior patterns make a lot of difference in the eye of the observer. These creatures, the observer would say, ponder over their DECISIONS. When you come close to them with a lure, it takes them some time to get going. Yet once they have decided, they can act quite quickly. They do indeed seem to act in a spontaneous way: none of this passive being attracted one way or the other that was so obvious in the vehicles of the more lowly types. You would almost be tempted to say: where decisions are being made, there must be a WILL to make them. Why not? For all we know, this is not the worst criterion for establishing the existence of free will.

Vehicle 5

Logic

At this point we are ready to make a fundamental discovery. We have gathered evidence for what I would like to call the "law of uphill analysis and downhill invention." What I mean is this. It is pleasurable and easy to create little machines that do certain tricks. It is also quite easy to observe the full repertoire of behavior of these machines—even if it goes beyond what we had originally planned, as it often does. But it is much more difficult to start from the outside and to try to guess internal structure just from the observation of behavior. It is actually impossible in theory to determine exactly what the hidden mechanism is without opening the box, since there are always many different mechanisms with identical behavior. Quite apart from this, analysis is more difficult than invention in the sense in which, generally, induction takes more time to perform than deduction: in induction one has to search for the way, whereas in deduction one follows a straightforward path.

A psychological consequence of this is the following: when we analyze a mechanism, we tend to overestimate its complexity. In the uphill process of analysis, a given degree of complexity offers more resistance to the workings of our mind than it would if we encoun-

tered it downhill, in the process of invention. We have already seen this happen when the observer of Vehicle 4b conjectured that the vehicle does some thinking before it reaches a decision, suggesting complicated internal processes where in reality there was nothing but a threshold device waiting for sufficient activation. The patterns of behavior described in the vehicles of type 4a undoubtedly suggest much more complicated machinery than that which was actually used in designing them.

We may now take pleasure in this and create simple "brains" for our vehicles, which will indeed (as experience shows) tax the mind of even the most playful analyst. All we have to do is introduce special elements, called threshold devices, which will be either interposed between sensors and motors or connected to each other in complexes that receive some input from the sensors and give some output to the motors.

The individual threshold device is of the simplest sort: it gives no output if its input line carries a signal below the threshold, and it gives full output beyond the threshold. We will also use another variety giving output all the time unless the input carries a signal above the threshold. Each of these devices is fitted with a knob which may be turned to set the threshold, so that the input would become effective with one, two, or any specified number of input activation units. (The word threshold of course implies that, for a given threshold value, any input stronger than the one specified would also be effective.)

We are not limited to the types of connections through which the threshold devices activate each other. We can also use another kind, call them "inhibitory," which counteract the activation that comes from other sources (figure 9).

In order to make a brain out of threshold devices, we may connect them together one to one, or many to one, or one to many, or many to one and one to many, in whichever way we like. When you are designing brains, it is important for you to know that in one of

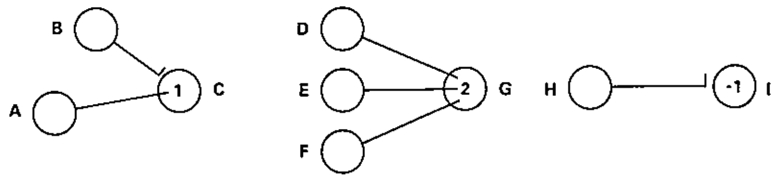


Figure 9
How threshold devices act on each other. Explanation of symbols: The circles stand for threshold devices. The L-shaped fiber between B and C stands for inhibition; the penetrating fiber from A to C means activation. Each active element contributes one unit of activation to the element (threshold device) to which it sends an activating connection. The threshold device becomes active when the activation reaches at least the threshold value indicated within the circle. An inhibitory connection from an active element subtracts 1 from the sum of all the units of activation reaching the same target element. A negative threshold (or threshold 0) implies activity in the absence of external activation. Such an element can be silenced by a corresponding amount of inhibition.

these threshold devices the output does not appear immediately upon activation of the input, but only after a short delay, say one tenth of a second. During this time the gadget performs its little calculation, which consists of comparing the quantity of its activation with its threshold.

You can already guess some of the things that a vehicle fitted with this sort of brain can do, but you will still be surprised when you see it in action. The vehicle may sit there for hours and then suddenly stir when it sights an olive green vehicle that buzzes at a certain frequency and never moves faster than 5cm/sec. Since our brand 5 vehicle is not interested in any other vehicles, you might say that the olive green vehicle is its special friend. You will have to conclude that Vehicle 5 has something like proper nouns in his mind, NAMES that refer to very particular objects, like James, Calcutta, or Jupiter.

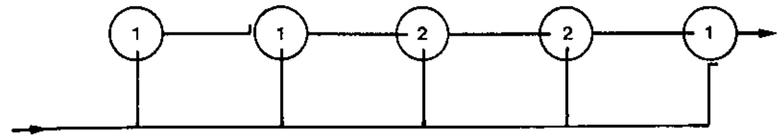


Figure 10a
A network that gives a signal when a burst of 3 pulses presents itself, preceded and followed by a pause.

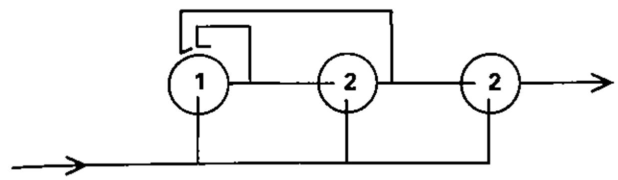


Figure 10b
A network of threshold devices that emits a pulse for every third pulse in a row in the input.

But Vehicle 5 can do much more than that. It can count (figure 10). It may associate only with groups of four vehicles, not more and not less, to make a party of five. Or it may visit every tenth source it encounters on its way. Or it may turn away from a vehicle whose number of sensors is a multiple of seven, implying that such vehicles bring bad luck. In some way, it seems to operate with NUMBERS.

If you fit such a vehicle with a very large number of shrewdly connected threshold devices, you may get it to play a passable game of chess. Or you may make it solve puzzles in LOGIC or prove theorems in euclidean geometry. You realize what I am driving at: with enough threshold devices it can do anything a computer can do, and computers can be made to do almost everything.

But where is the memory, some of you will ask, realizing that most of the activities of a digital computer consist of putting data into memory, taking the data out again to perform some calculation, putting the results back into the memory, and so forth. The answer: there is room for memory in a network of threshold devices, if it is large enough. Imagine a threshold device connected to a sensor for red light. When it is activated by the red light, it activates another threshold device which in turn is connected back to the first device. Once a red light is sighted, the two devices will activate one another forever. Take a wire from the output of one of the two threshold devices and connect it to a bell: the ringing of the bell then signals the fact that at some time in the past this particular vehicle sailed in the vicinity of a source of red light.

This is an elementary sort of MEMORY. It is not difficult to understand how out of such elementary memory stores (consisting of reciprocally connected threshold devices) complex memories can be synthesized, with the possibility of storing extremely complex events. But there is a limit to the quantity of facts the vehicle can store this way. For instance, when storing numbers, if the vehicle has a bank of ten elementary memory devices, it cannot fit any number that has more than ten digits (in binary notation), since each elementary device can at most remember one digit by being active or inactive ("one bit of information").

There is a trick that can be used by our brand 5 vehicles to overcome the intrinsic limitation of their storage capacity. Imagine a vehicle involved in a calculation in which numbers occur that are much larger than the number of parts in the vehicle's own interior. You might think that such a task would be forever beyond the comprehension of that particular vehicle. Not so if we employ the following strategy. Let's transfer our vehicle to a large, sandy beach. The vehicle can crawl on the beach, leaving marks in the sand indicating the succession of digits in the large numbers that emerge from its calculations. Then it can crawl back, following

its own track, to read off the digits and put them back into the calculation.

The vehicle is never able to comprehend these large numbers at any one moment. But using itself as an instrument in a larger scheme involving the environment, and partly directed by it, it ends up with the correct result. (Of course, to be on the safe side, we must suppose that the sandy surface has no limits.) If you want a concrete example, think of the vehicle calculating the difference (small enough for it to comprehend) between two large numbers, which it can produce but not comprehend. It will produce one number by leaving marks on its way along the beach. It will produce the other number on its way back. And then it will measure the difference by counting the number of marks that are in default or in excess of the first number.

Later on, we will learn how to incorporate into a vehicle something quite analogous to the sand outside, and almost as boundless in its capacity.

Vehicle 6

Selection, the Impersonal Engineer

In this chapter things get slightly out of hand. You may regret this, but you will soon notice that it is a good idea to give chance a chance in the further creation of new brands of vehicles. This will make available a source of intelligence that is much more powerful than any engineering mind.

Out of the collection of vehicles that we have produced for the purposes of our experimentation, we will choose some of the more complicated specimens and put them onto a large table. Of course there will also be some sources of light, sound, smell, and so forth on the table, some of them fixed and some of them moving. And there will be various shapes or landmarks, including the cliff that signals the end of the table top.

Now you and I will gather a plentiful supply of materials (tin, plastic, threshold devices, wheels, motors, sensors, wires, screws and bolts) and proceed to build vehicles, taking as our models vehicles that we pick from the ones circulating on the table. Each time we copy a vehicle, we will put both the model and its copy back on the table, pick up another vehicle, copy it, and so on. Of

course we will not pick up vehicles that have fallen on the floor because they have proved their own inability to cope with the environment. We will be careful to produce vehicles at a pace that roughly matches the rate at which vehicles fall off the table, to prevent the race from dying out, on one hand, and to prevent the table from becoming unduly crowded, on the other.

Note that while we are playing this game, we won't have time to test the behavior or to study the wiring, let alone to understand the logic of the vehicles that we pick up as models for copying. Nor should we. All we are asked to do is to slavishly connect the parts according to the pattern in the model.

Note also that when we do this in a hurry, we are bound to make occasional mistakes. It may be our fault when our copy of a perfectly well-tested vehicle falls off the table as soon as we put it down. But it is also possible that we will unwittingly introduce a particularly shrewd variation into the pattern of connections, so that our copy will survive forever while the original may turn out to be unfit for survival after all.

It does seem surprising that errors arising in the sloppy execution of a task should act as germs for improvement. What is less astonishing is the creative power of a special sort of error consisting of new combinations of partial mechanisms, each of which is not disrupted in its own well-tested structure. This can easily happen when we pick up one vehicle as a model for one part of the brain and then by mistake pick up another vehicle as a model for another part of the brain. Such errors have a much greater chance of transcending the intelligence of the original plan.

This is an important point. If the lucky accidents live on forever, they will also have a multitude of descendants, for they will stay on the table all the time while the less lucky ones come and go. Therefore, they have a much greater chance of being picked up by the copyists as models for the next generation. Thus very good ideas unwittingly introduced into the wiring, though improbable, do become quite widespread in the long run.

This story is quite old and goes by the name of Darwinian evolution. Many people don't like the idea that everything beautiful and marvelous in organic nature should be due to the simple cooperation of reproduction, errors, and selection. This is no problem for us. We have convinced ourselves that beautiful, marvelous, and shrewd machines can be made out of inorganic matter by this simple trick. Moreover, we already know that analysis is much more difficult than synthesis. Where there has been no conscious engineering at all, as in the case of our type 6 vehicles, analysis will necessarily produce the feeling of a *mysterious* supernatural hand guiding the creation. We can imagine that in most cases our analysis of brains in type 6 vehicles would fail altogether: the wiring that produces their behavior may be so complicated and involved that we will never be able to isolate a simple scheme. And yet it works.

Vehicle 7

Concepts

We have already used the word knowledge, even if in a somewhat facetious way, when we discussed the properties of Vehicle 3. And we have just observed how a process akin to Darwinian evolution may incorporate knowledge into machines in a mysterious way, though it is not immediately obvious through what channel the knowledge (about the dangers connected with a cliff) entered the "brain" or in what form it is contained there. In both cases we are referring to fixed, inborn knowledge that, whether right or wrong, belongs to the individual vehicle for better or for worse. This is fine for a set environment but may be catastrophic when the conditions change. Therefore, in a precious vehicle that we love, we should build in mechanisms of adaptation to make it more flexible. Not only will our vehicle then be prepared to meet catastrophic events but it will also be ready to cope with a greater variety of situations and thus be less confined to a particular environment.

We proceed as follows. First, we buy a roll of a special wire, called Mnemotrix, which has the following interesting property: its resistance is at first very high and stays high unless the two components that it connects are at the same time traversed by an electric current. When this happens, the resistance of Mnemotrix decreases and remains low for a while, little by little returning to its initial value.* Now let's put a piece of Mnemotrix between any two threshold devices of a fairly complicated vehicle of type 5. This is a lot of wiring, but the effect is not great at first, due to the high resistance of Mnemotrix. Very little current will spread from an active component to all the other components to which it is connected.

As the vehicle (which is now type 7) moves around and experiences various situations in its environment, some of its Mnemotrix connections will change their strength. Suppose aggressive vehicles in that particular environment are often painted red. Then the sensor for red in our type 7 vehicle will often be activated together with the threshold device that responds to aggressive behavior, and the Mnemotrix wire connecting the two will have its resistance decreased so often that it will not have time to return to its initial value. The consequence is obvious: every time the vehicle senses red, the whole set of movements with which it normally responds to aggressive behavior will be activated. So our vehicle will turn away from its dangerous fellow. The enhanced connection between the components represents what philosophers call ASSOCIATION, the association of the color red with aggression. More generally, we may say a new CONCEPT has arisen in the vehicle: whenever an aggressive vehicle is around, even if it is blue or green, our type 7 vehicle will "see red." As far as we are concerned, this can mean

* I don't care if the electricians shudder. They know very well that even if Mnemotrix is not available commercially as a wire, it can be simulated by a simple circuit. And they also know that such things exist in animals' brains. If you want a fairly realistic explanation of Mnemotrix wire, think of a material that changes its conductance as a function of temperature: the current heats the two components connected by Mnemotrix, and the temperature change at the two ends of the connection induces the change in resistance.

only: the vehicle does some of the things it did previously only when it was confronted with the color red.

This process of translating things that happen together in the environment into "complexes" of activity within the vehicles is of such great importance that we ought to familiarize ourselves with it some more. One consequence, we have already seen, is concept formation. When it happens between different categories of things (such as red color and aggression), we prefer to call it association. But it may happen within a single category, say smell, when a number of chemicals dissolved in the air are frequently perceived together, such as burned plastic, lubricating fluid, and battery acid, which are set free when a vehicle is wrecked. So it is justified for surviving vehicles to store the "smell of death" in order to be able, later on, to identify dangerous regions of their environment. This is done by the formation of a new olfactory concept.

Visual concepts may be formed in a similar manner. The straightness of a line in different parts of the visual field, for example, may come to signify the dangerous cliff at the side of the table. And the movement of many objects in different directions may come to represent the concept "region crowded with vehicles." But visual concepts can be treated more efficiently later on when we provide our vehicles with the a priori category of space. For now, we should explore some of the philosophical implications of the process of concept formation.

Let philosophers watch a breed of type 7 vehicles and let them speculate about the vehicles' behavior. One philosopher says: This is all very well, but learning to recognize situations that are of some importance is a fairly trivial performance, especially if it is done the hard way, by reward and punishment. It would be a different matter altogether if these vehicles could form their own concepts in quiet meditation, without an external tutor telling them what is important. But they never will, because abstraction is one of the powers that is unique to the human mind.

But look, says another philosopher, I just watched an ABSTRACTION being made by one of these creatures. It was moving around in a crowd of peaceful, unpainted gray vehicles when it met a vehicle painted red that proved to be aggressive; then it met a green vehicle that also proved to be aggressive. When my vehicle met another painted fellow, this one painted blue, it immediately thought that this one was aggressive too. And it turned away in a hurry. This is a true abstraction, the concept of color replacing the individual colors red and green of the original experience. Or if you wish, we can say that a GENERALIZATION has taken place from particular colors indicating danger to the general danger signal "color."

Sure enough, says the third philosopher, but that is not difficult to explain either. It has something to do with the way colors are represented by the activity of the electronic parts in the gadget. Undoubtedly in all the mess of wires there will be one wire that signifies "gray" as the even mixture of all colors. Then there might well be one that signifies "not gray," and that one was active when the red vehicle appeared. So the "not gray" wire had the strongest correlation with aggressiveness, and this was learned. No wonder this "not gray" wire functioned as a danger signal when the blue aggressor arrived.

All right, says the fourth philosopher, but nobody in his right mind ever suspected anything more mysterious behind the "faculty of generalization."

Fine, says I, as long as you admit it.

Vehicle 8

Space, Things, and Movements

We take the next step in the improvement of our vehicles primarily as a favor to ourselves, to keep things tidy and to make the wiring less cumbersome. But we will find that the introduction of internal maps of the environment is of inestimable value for the vehicles too, making it much easier for them to discover the truth about their environment.

What I mean by a map is this: take a set of photocells, say one hundred of them, but instead of distributing them messily over the surface of the whole vehicle, arrange them in a neat square of ten by ten photocells on the front surface of the casing (figure 11). Now fit a lens on top of the array, making it into a camera. You know that if everything is set correctly, the inverted image of things in front of the vehicle will be projected onto the array. Of course, you cannot pick up a perfect TV picture with just one hundred photocells, but you will get a picture. It will not be scrambled information about the outside world; it will be a representation of the order of things, of their neighborhood relations and, roughly, of the distances between them.

It is easy to make good use of this orderliness. We may build networks of threshold devices that can distinguish among random

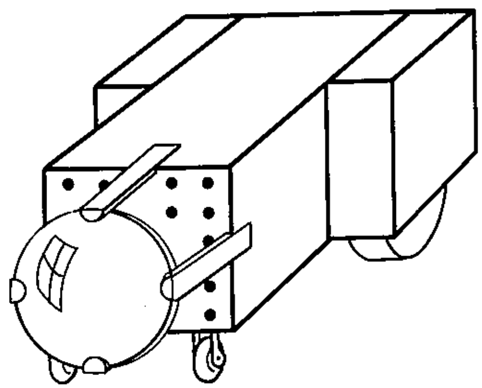


Figure 11
Vehicle 8 with a lens eye.

environments and environments that contain lumps of matter, things that move and ordered structures.

Build yourself an array of threshold devices, each connected to a group of neighboring photocells, say four of them arranged in a square (figure 12). Now as long as the vehicle is surrounded by little insignificant objects or by objects quite far away, all of the photocells might see just a few of these things, all in more or less the same numbers. Consequently, the photocells will all become active roughly to the same degree. Even if some photocell accidentally sees a few more things than its neighbors and consequently gives a little more output, the effect will probably be averaged out by the threshold devices, which always add the output of four neighboring photocells. But when a larger object appears in the neighborhood of our vehicle, it will be seen by one or more groups of photocells that are all connected to the same threshold device. This device will be activated much more strongly than the others and thus will function as an *object detector,* of inestimable value for the vehicle.

It might be even more useful to construct a set of *movement detectors* connected with the array of photocells (figure 13). Put the output of each photocell into a *delay,* a device that gives off a signal a little while after it has received one. Nothing's easier than that. A sluggish threshold device will do. Now make a new array of threshold devices. Each is connected with one photocell via a delay device, and with another neighboring photocell located to the right directly, without a delay device. These threshold devices become active only when they receive a signal from both channels. Every time a bright object moves by from left to right, it will elicit a signal in one photocell, which will be stored for a short while in the delay. By the time the object elicits a signal in the neighboring photocell, the delay will give off its signal as well so the two signals will hit the movement detector–threshold device at the same time, making it active. Obviously, a spot moving in the opposite direction will not have the same effect because it will hit the fast threshold device first

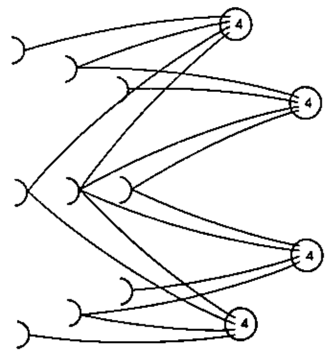


Figure 12
An object detector. Each of the threshold devices on the right responds only when four neighboring sensors arranged in a square are active together.

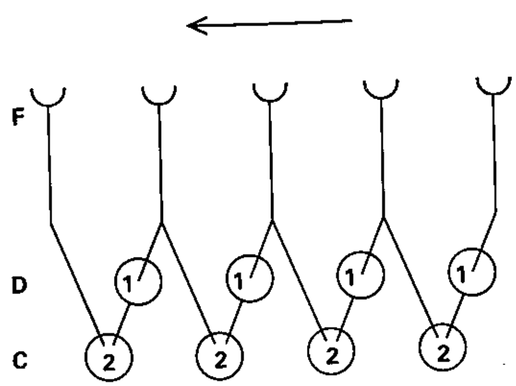


Figure 13
A set of movement detectors (C) for movement from right to left. The threshold devices C become active when they receive input directly from the sensor F to the left, and at the same time receive input indirectly, via a delay element D, from the neighboring sensor to the right.

and the sluggish one afterward—so their output will not coincide at the next level. Thus our movement detectors are directional.

We can of course make different sets of movement detectors for different directions so that no movement will escape the attention of our vehicle. We can also make them for various velocities, or even for objects of various sizes. In order to do this, we first make an array of object detectors, as in figure 12, and connect their outputs in pairs to the movement detectors. Only movement of objects of a certain size, defined by the wiring of the individual object detectors, will elicit activity in the movement detector. We may also proceed the other way around. First we make an array of movement detectors, all tuned to movement of the same velocity in the same direction. Then we take the output of sets of neighboring movement detectors and connect each set to a threshold device, which then acts as an object detector. But this object detector sees an object only as a set of points, all moving in the same direction. This, by the way, is how we humans see certain objects too—such as a cuttlefish moving on the sandy ocean floor, no matter how good the mimicry of the beast.

Another well-known way to make good use of an array of photocells is what is often called *lateral inhibition* (figure 14). Make an array of threshold devices behind the array of photocells. Connect them one-to-one to the photocells, so that each will be activated by light in the corresponding position. Now introduce lateral inhibition: let each active threshold device put a brake on the activity of its neighbors, so that the more it is activated, the more its neighbors are inhibited. You can easily see that there will be an uneven match between neighboring threshold devices receiving different amounts of excitation: the one more strongly excited will put the other one completely out of business. Thus, instead of getting a continuous distribution of activity reflecting all the shades of the environment seen by the photocells, you will get a representation of isolated bright spots. Only in the case of an entirely uniform illumination

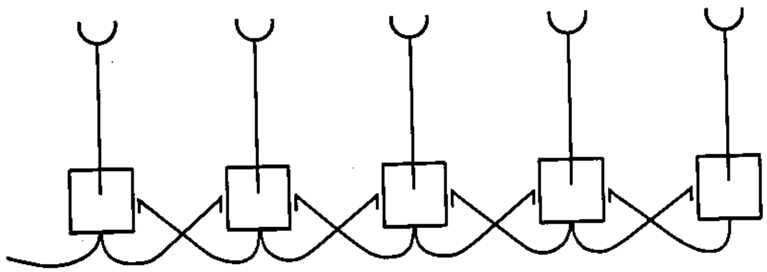


Figure 14
Five threshold devices, excited by that many sensors, each connected to its neighbors by inhibitory connections. Uniform excitation of the whole set will be subdued by the inhibitory interactions, while isolated spots of excitation will stand out.

will all the threshold devices stay at the same level (although there are difficulties at the borders of the array). But in the case of uniform illumination, the threshold devices will also inhibit each other by the same amount. Thus uniformity will be weakly represented, which is all right, for uniformity is uninteresting.

It is quite clear that these tricks, and a number of other tricks that you might invent, are only possible when there is an orderly representation of the "sensory space" somewhere in the body of the vehicle. This need not be 2-dimensional visual space, as in the examples just discussed. It may be 3-dimensional tactile space; we can represent internally, in a 3-dimensional array, all the points that the vehicle touches by means of a jointed arm carrying a tactile sensor. We can also represent 3-dimensional visual space, if we pass the signals from two eyes through a device that performs the sort of computation known as "stereoscopic vision" in human psychology.

We can invent all sorts of bizarre internal spaces which we might use to file in a convenient way the information reaching the vehicle. Two-dimensional visual space combined with one temporal dimension may lead to a representation of all the images, past and pres-

ent, in a 3-dimensional spatial array within the vehicle. Inspired by some of the things that are known about animal brains, we could also invent a 3-dimensional array for the filing of acoustic information, with one dimension representing the frequency, the second the intensity, and the third the phase of the acoustic signals.

Curiously, when we construct internal spaces for vehicles, we are not even confined by the 3-dimensionality of familiar space that seems to limit our immediate intuitive understanding. It is difficult to imagine solids of more than 3 dimensions, say a 4-dimensional cube or a 5-dimensional sphere. In fact, when we think of an ordinary 3-dimensional cube, we tend to imagine something like a box with 6 square sides. If we want to imagine a 4-dimensional cube, we notice that the sides would have to intersect. But we cannot picture this, so we give up.

On the other hand, it is quite easy to imagine or to draw networks of more than 3 dimensions (figure 15). The drawing shows spheres connected by wires. The network is truly 4-dimensional, since in order to specify the coordinates of one of the balls (or the path that leads from one ball to a certain other ball), you have to indicate how many steps to move in directions x, y, z, and w. If you disregard distance and angles on the drawing (you can't keep them equal on a projection even in the case of a 3-dimensional net), and if you imagine the net continued ad infinitum in all 4 directions, the network will look the same no matter which ball you sit on or in which of the 4 directions you look. Now, you could even build the network, or a piece of it, out of spheres and wires: you would be able to hold in your hands a structure that is intrinsically 4-dimensional, though of course collapsed ("projected") into the 3 dimensions of space in which your hands move. (An architect similarly collapses his buildings into the 2-dimensional space of his drawing board.) You could even sit on your network and squash it into a 2-dimensional felt. It would not matter. A louse finding its way along the wires would still notice the

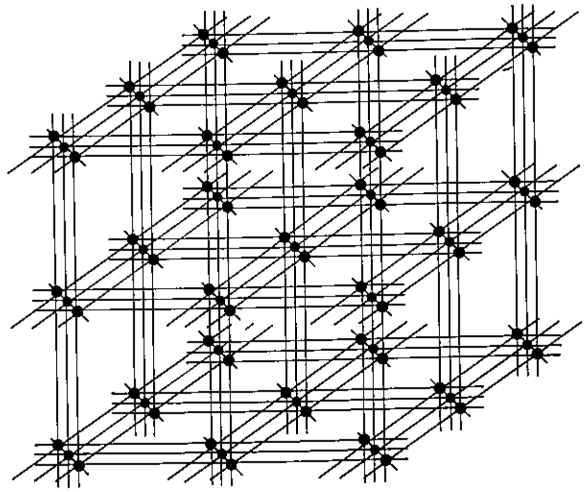


Figure 15
A four-dimensional cube. Each edge is marked by three black dots on a line, connected by a wire.

4-dimensional connectivity, provided it had the necessary mathematical acumen.

The point I want to make is the special virtue of networks as opposed to solids. Once you have decided to represent space by discontinuous, discrete points within the vehicle, you can represent "neighborhood" by means of lines connecting the points. This gives you the freedom to mimic all sorts of spaces, including spaces that a human mind cannot imagine. Can the vehicle imagine such spaces?

We must turn to the philosophers again. Let us ask a philosopher whether Vehicle 8 is endowed with the a priori concept of space, for this is a familiar question to him. Only, in this case the philosopher cannot just close his eyes and look inside himself for an answer. He will have to invent experimental situations in which the vehicle could demonstrate its proper use of an internal representation of space. A simple test: move the vehicle from its present position a

certain distance in a certain direction, and then again in another direction. If the place where the vehicle was before had some favorable connotations, it might want to go back. Will it move back exactly the way it came, or will it choose the diagonal, which is the quickest way to get there? If it has an internal representation of 2-dimensional euclidean geometry (that is, if it has 2-dimensional space built in a priori), it will head directly toward the goal.

Now this internal representation of space is something that we could very easily wire into the network within the vehicle. Just imagine a 2-dimensional sheet made of a material which has everywhere the same conductance value for electric currents. This is defined as the current (in amperes) divided by the voltage applied (in volts) for a wire of a certain thickness and a certain length. Now if we apply a voltage difference between two points on the sheet, the current that flows through the material is strongest (the current density, current per cross-sectional area, is highest) along a straight line connecting the two points. If we let one of the two points represent the place where the vehicle is and the other point the place where it wants to go, we can easily construct a device that will determine the best course for the vehicle by way of a simple measurement of current density in different directions on the sheet.

So we would conclude that Vehicle 8 does have the a priori concept of 2-dimensional space. Could Vehicle 8 embody that of 3- and 4-dimensional space as well? To wire an internal representation of 3 dimensions into the vehicle, we could use a block of the same material out of which we made the 2-dimensional sheet, with many electrodes embedded in it to produce voltage differences and measure currents. But for 4 dimensions we already know that we have to resort to 4-dimensional networks, since we are not able to make (or even imagine) 4-dimensional blocks. In principle, this does not make much of a difference. We could still measure shortest distances by the method of current density analysis. We could also use the 4-dimensional network in more complicated ways to let the vehicle show off its built-in a priori concept of higher dimensional space. If the vehicle could talk, we would ask it to rotate in its mind a 4-dimensional cube, let us say 90 degrees, around one of the axes. There are such exercises in human IQ tests, using 2-dimensional pictures of 3-dimensional dice with three sides showing. The three sides are decorated in different ways. The questions are of this sort: is cube A just another view of cube B, C, D, or E? Some humans have trouble with 3-dimensional dice, all with 4-dimensional ones. But a vehicle endowed with a network like the one in figure 15 might very well pass the IQ test for 4-dimensional cubes if the question was posed in a language it could understand.

I can hear myself talking to the philosophers again. The point I am making is that orderly representation of space in a vehicle is more than just convenience of construction. It provides for easy tests of reality. We have seen how easy it is to knit networks that will react to images moving at certain speeds. If these can be taken as images of objects in the world outside, the velocity of the movement of the images will stay between certain reasonable bounds, dictated by the physical laws governing the movement of the objects. In particular, there won't be any movement of infinite velocity; there won't be any sudden displacement. Continuity of movement, no matter at what velocity, is a primary criterion for the physical reality of an object. Also, the continuity and certain regularities of the change of shape of a shadow indicate that the shadow is cast by a solid object. This, too, could be fairly easily detected by a network with 2-dimensional connectivity. And of course identity of shape irrespective of movement (a strong clue for objects keeping a certain geometrical relation with a given vehicle) can also be detected by such networks. We will take up this point again from a different point of view in the next chapter. Here it was sufficient to show that in our vehicle, just as in the physics of relativity, the recognition, or even the existence, of objects is related to the dimensionality of space, internal and external.

Vehicle 9

Shapes

We will improve on our vehicles some more, along the lines outlined in the construction of the preceding brand 8, but with a different intention this time. We will try to furnish our vehicles with a convenient set of ideas referring to the shapes of things, especially to shapes as we see them with our eyes (and as a vehicle sees them if it is equipped with a good camera-type eye).

First of all, if we want to consider shape independently of color and other irrelevant details, we must produce an outline drawing of things in the visual field of the vehicle, as a draftsman would with a pencil. (Webster's dictionary defines shape as "the quality of a thing that depends on the relative position of all points composing its outline or external surface.") This is not very difficult if things stand out clearly against their backgrounds—for instance if these things are birds in the sky or vehicles on a white sheet. We can then use the trick of lateral inhibition, which we have already learned (figure 14). Only sharp boundaries will be passed on to the next level, thereby producing a pure line drawing. If the interior of the figure represented is quite homogeneous, say all black, there will be only the outline or shape.

Let us construct detectors for elementary properties of shape.

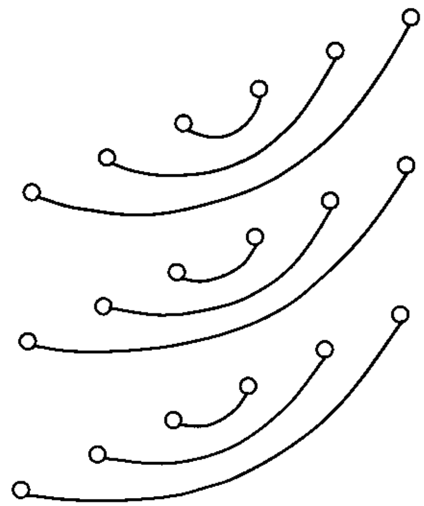


Figure 16
A detector for bilateral symmetry. There is an array of elements onto which an image is projected. Elements symmetrically spaced with respect to the midline enhance each other. There will be a strong activation of the array for bilaterally symmetrical images.

The first property that comes to mind is bilateral symmetry. Its detector is easy to construct and enormously valuable (figure 16). Again we make an array of threshold devices onto which a picture of the external world is projected by means of a suitable camera system (we can filter the picture first through a network with "lateral inhibition" to enhance relevant detail). One half of it receives a picture of the right half of the visual environment, everything to the right of the vehicle; the other half receives a picture of the left half of the world. Now we connect by a wire each pair of threshold devices occupying symmetrical positions on the right and left sides. Through the wire the threshold devices influence one another in such a way that when they both receive input, they become much

more active than when only one of them is activated. It is clear now that when the vehicle faces a symmetrical shape (with a vertical axis of symmetry, such as an upright human figure seen from the front or from behind), there will be much more activity in this array of threshold devices than there will be in any other case. For every element excited on one side of the vehicle, its symmetrical element on the other side will also be excited, with the consequent reciprocal enhancement.

Let's not talk about an upright human figure; that introduces an unintended aesthetic aspect. Think only of a world populated by vehicles of the various kinds that we have been building. Up to now we have not talked much about the exterior appearance of our vehicles, although we have implicitly assumed that the vehicles are made of two halves, mirror images of one another: two motors, one on each side, two nostrils, a symmetrical casing like an automobile. Of course such vehicles, seen from the side, are not symmetrical: their sense organs are in front, their motors are in the back, and their prevalent movement is always in the same "forward" direction. Nor are the vehicles symmetrical in the up-down direction if they move around on surfaces, as our vehicles mostly do; for reasons connected with gravitation, there will be wheels (or other instruments of locomotion) on the side of the vehicles facing the ground, the so-called underside.

But there are good reasons for the vehicle to be symmetrical in the direction perpendicular to both the "front-back" and the "up-down" directions—along the axis defined by the pair of concepts "right" and "left." We have seen this early on in the cases of Vehicles 2, 3, and 4, which showed surprisingly lifelike behavior on the basis of paired, very simple, symmetrical connections between two sense organs and two motors. The kind of behavior associated with two symmetrical reins governing the motors is one in which an object is isolated from the environment as a partner in behavior. The vehicle's movements are directed by feedback, either turning the vehicle toward the object or turning the vehicle away from the object.

Consider the first case: feedback that makes the vehicle turn toward the object. An observer might say that our vehicle has that object on its mind or our vehicle pays attention to that object. Well, what if the object is another vehicle? What would the situation look like to that vehicle, and how should it react? Obviously the situation in which a vehicle sees another heading directly toward it, whether in an inquisitive, a friendly, or an aggressive mood, is a special case and well worth special attention. The detector for bilaterally symmetrical shapes, which we have just described, proves helpful here: we may connect it to the output in such a way as to trigger the mechanisms that govern the appropriate reactions to "another vehicle facing me" or "another vehicle having me in mind." (Perhaps one should reactivate the beautiful term "confrontation": fronts coming together, facing each other.) In fact, it is clear that bilaterally symmetrical configurations in a natural world containing only vehicles (and no other man-made objects, such as churches or monuments) would mostly signify just that: a partner in interaction with the observer.

There is a relation between bilateral symmetry in sensory (especially visual) space and the concept of "thou," the pronoun of the second person singular. This has been used by the builders of temples and churches who, by a pointedly symmetrical architecture, evoke the presence of an abstract thou, a partner in conversation always facing the observer. The same principle can be observed in biology: certain flowers, such as orchids, adopt bilaterally symmetrical shapes in order to be accepted as "partners" by insects with detectors keyed to this type of symmetry.

I want you to note that something new and very important has crept into our discussion of a detector with bilateral symmetry. We decided to give our type 9 vehicles a system of connections between corresponding points on their right and left sides. In order to explain how useful such a system would be, we had to invoke not only the external appearance of other vehicles (which our vehicle might meet) but their behavior as well. Things are getting complicated: we are no longer working on individuals taken by themselves but on the members of a community in which there are complicated interactions between vehicles of the same or of different kinds.

Every improvement that we invent for the latest breed of vehicles put in circulation will either force others out of business by a process of Darwinian selection (see Vehicle 6) or make others change their behavior through learning (see Vehicle 7). Of course, this makes it difficult to foresee what will actually work out as an "improvement." Sometimes the net effect will be contrary to what we expect, due to unforeseen reactions of the environment. But certain great inventions will survive all vicissitudes and will be immune to all shrewd defenses. I suspect that the detector of bilateral symmetry, which provides information about "being in someone's focus of attention," belongs to this category. Even in biology with all its complicated interactions between species, the symmetry detector has remained of primary importance. An insect in search of a sexual mate does not really care if it gets occasionally sidetracked by an orchid as long as its symmetry detector serves the right purpose in the majority of cases.

Other insects fall for different kinds of flowers, for those with radial symmetry, like daisies. We can also construct radial symmetry detectors for our type 9 vehicles: these detectors might indicate singularities in the world, sources from which something emanates in all directions. A radial symmetry detector could also be based on the fact that no movement is perceived on approaching a pattern like that of figure 17. The picture remains identical to itself.

A fundamental category of form is periodicity. A repetitive pattern may signify many important situations. It may signify a collection of identical individuals. Then again, a periodic pattern left on the ground may be the track of a vehicle moving by some sort of

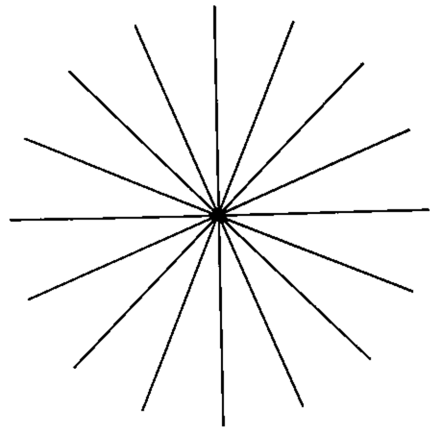


Figure 17

A pattern that is invariant to changes of scale. A vehicle approaching the center of the figure has a constant visual input (provided we make the figure large enough and the lines infinitely thin). The absence of perceived movement may be used as diagnostic for figures with radial symmetry.

periodic stepping mechanism. Or the pattern may be generated by some oscillatory movement in the form of a standing wave—an indication of stored energy. For all these reasons periodic patterns are happenings of great importance in this world; they are just as fundamental as bilaterally symmetrical or radially symmetrical figures. So we should equip our vehicles with detectors for periodicity.

This can be done in various simple ways. For instance, we can give them periodic templates with different spacing and let them match the picture of the environment with the templates by the mathematical process of *cross-correlation*. This is the principle of Fourier analysis. Its technical realization does not require too much ingenuity. Another interesting detector of spatially periodic input is implicitly contained in the network described in the previous chap-

ter as lateral inhibition. We have seen that such an array of threshold devices neglects continuous excitation and enhances contrasts. It gives maximal output for patches of excitation spaced sufficiently far apart so that they won't disturb each other by inhibition. For a periodic pattern, the spacing is determined by the length and strength of the inhibitory connections. If we test the lateral inhibition device with striped patterns, we will notice that it gives the same output no matter how the stripes are oriented if the inhibition works in all directions.

Taken together, vehicles of types 8 and 9 have provided much new evidence for our law of uphill analysis and downhill synthesis. A problem that taxes the minds of psychologists when they deal with real animals or humans, that of inborn concepts, found many solutions when we attacked it from the downhill, synthetic direction. We built very simple homogeneous networks and then discovered that they contain implicit definitions of such concepts as 3-dimensional space, continuous movement, reality of objects, multitude of objects, and personal relation. More and more we are losing our fear of philosophical concepts.

The exercises in synthetic psychology contained in this chapter deal mostly with visual input. It is of course easy to imagine a priori concepts in other categories of input, such as the tactile or olfactory inputs. It is quite elementary to provide the vehicle with detectors of aural periodicity. They would detect various frequencies in the purely time-dependent (nonspatial) input derived from one of the vehicle's ears (microphones). The a prioris of frequency, the so-called resonators, have been basic to human auditory theory for a long time.

Vehicle 10

Getting Ideas

The time has come to sit back and consider the strange variety of vehicles that populate our laboratory. They all go about their business according to certain rules, some of which we understand, because we invented them ourselves, and some we don't, because they emerged from a sort of Darwinian evolutionary process. The objects of their interest are defined by simple properties such as smell and color, or by more abstract properties, such as the periodicity of their coloring or the symmetry of their outline. Formal properties may stand for even more abstract definitions, as we have seen in the case of bilateral symmetry signifying the situation of "somebody having me in mind."

Some of our vehicles seem to move around smoothly, as if attracted and repelled by the sources of various fields of force superimposed on one another. Others appear to make sudden decisions, rousing themselves from a rather phlegmatic condition to take off on isolated ventures, after which they resume their state of rest. The vehicles seem to know their environment rather well, so much so that they are able to reach some objects with closed eyes, so to speak, apparently on the basis of some internalized map on which the object's location is recorded. On the whole, these vehicles

are surprisingly smart, especially considering the limited amount of intelligence that we, their creators, have invested in them.

But do they think? I must frankly admit that if anybody suggested that they think, I would object. My main argument would be the following: No matter how long I watched them, I never saw one of them produce a solution to a problem that struck me as new, which I would gladly incorporate in my own mental instrumentation. And when they came up with solutions I already knew, theirs never reminded me of thinking that I myself had done in the past. I require some originality in thinking. If it is lacking, I call the performance at best reasonable behavior. Even if I do observe a vehicle displaying a solution to a problem that would not have occurred to me, I do not conclude that the vehicle is thinking; I would rather suppose that a smart co-creator of vehicles had built the trick into the vehicle. I would have to see the vehicle's smartness arising out of nothing, or rather, out of not-so-smart premises, before I concluded that the vehicle had done some thinking.

But this does not mean that we cannot create vehicles that would satisfy this condition. We shall do this gradually, starting with the problem of *having ideas*. Let us take one of the vehicles of type 7, the ones with the Mnemotrix connections that introduce the effects of experience into the brain. This vehicle has been around for some time and has absorbed a great deal of knowledge about the world. This knowledge takes the form of statistical correlations between elementary events in the vehicle's sensory spaces or statistical correlations between more complex events represented in some threshold devices of its interior (or between elementary events and complex events).

Suppose the vehicle has learned that certain objects, A, B, C, D, are situated near the rim of the table top on which it lives: a broken-down vehicle, a light, a battery, a hill, a supply of screws. It has learned to associate these objects with the concepts "margin of the universe" and "dangerous cliff." On its occasional excursions toward the margin of the universe, it will also have noticed the neighborhood relations among pairs of these objects: the screws are next to the hill, the light next to the battery, and so forth. One day, after enough excursions, the vehicle will suddenly realize that all these paired associations (A next to B, B next to C . . . , Z next to A) make sense if the whole situation is seen as a closed chain. The vehicle now has the idea of a finite bounded universe, with objects A to Z marking the marginal closed line. Once this "image" or "idea" is generated out of individual items of knowledge, it is there to stay. It may, in fact, be immediately recorded on the maps, whose use we have discussed. If so, we will observe that forever after the vehicle moves around much more expertly.

We must be careful, however, not to let the process of acquiring new ideas interfere with the detailed knowledge that our vehicle has assiduously collected and carefully stored in many associative connections during its lifetime. We know that this may happen in humans who are overly dedicated to the development of ideas. They tend to connect many individual cases into general categories and then use the categories as if they were things, losing the potential for categorizing in other ways by remembering each instance.

In the example of the discovery of the margin of the universe, I can see this danger. The idea of a closed chain of objects may be so strong that it keeps the images of these objects permanently active in the vehicle's brain. The consequence is that associations will develop between every object on the margin—and every other object on the margin. The serial order that led to the original idea will thereby be lost or at least submerged in a system of much stronger, massive associations. The way out in our case would be to let the excitation circulate in the closed chain associations. This would strengthen the associations representing the serial order of the objects and would not allow cross-association to develop.

Here are some more examples of ideas that may arise in vehicles. There are coins lying around on the floor in the universe of the

vehicles. Some of the coins are decorated with a picture of a human head and others are decorated with a number. One of our vehicles has already learned to recognize and to distinguish the two types of coins. That is, there are distinct patterns of activity, say two different threshold devices becoming active when one or the other kind of coin is seen by the eye of the vehicle. Now one of the coins showing a human head is flipped around by the vehicle—and suddenly it shows the number. This happens again and again until, by the learning process that we have already incorporated in our vehicles, an association is formed: "head, flipping, number." Of course, the association also works the other way around. Once the association is acquired, the vehicle knows that, after adding the action of flipping to the sighting of "number," the picture of the head will be seen. It may also be reinforced by the contrary experience, when the flipping of coins showing the number reveals the head.

We may call the whole complex of head-flipping-number and number-flipping-head the idea of a coin with two faces. It arises in the vehicle although the two faces of a single coin are never seen together. The idea of a coin with two faces can arise even if there are some coins around with human heads on both sides, as long as these coins escape the vehicle during the phase of "getting the idea."

Here's another example. Moving through a garden, a vehicle finds out that flower number one of a row is a source of food, flowers 2 to 7 are not (they are poisonous), flower number 8 is again a source of food and so are flowers 15, 22, and so forth. After a while it may happen that in the brain of the vehicle only one of 7 threshold devices (connected in a circular fashion) always becomes active in temporal coincidence with the finding of a source of food in a flower. This is again "getting the idea": that particular threshold device will be associated with the food finding system—with the consequent advantage of being able to predict sources of food without having to invest much energy in the process of sniffing around. We must suppose, of course, that the time it takes for one threshold device to become active after another has been activated is exactly the same as the time it takes to get from one flower to the next or, better still, that the advancement of activity by one step in the ring of threshold devices is triggered by each flower.

All of this is not complicated in principle but boring to carry out in detail. We rely on the process of Darwinian selection that, starting with the vehicles of type 6, has introduced a great variety of different patterns of connections into the vehicles without our even noticing it (although we do recognize the vehicles' greatly increased complexity of behavior). We can well imagine that the vehicle could get the idea "edible flower" even if the only flowers that were edible were those whose ordinal numbers were square or whose ordinal numbers were prime. There is, however, a complication in the cases of squares and of prime numbers. If these numbers get too large, the vehicle has to perform a long and intricate dance between one flower and the next in order to find out whether the flower's number is square or prime, leaving marks on the earth and retracing them according to complicated rules. We have seen this before, at the end of the chapter on Vehicle 5, which also had its limitations. No such difficulty arises if the vehicle has to find out whether a number is even or odd, or whether a number is a multiple of six or of eleven, as long as the vehicle can count to eleven.

In this chapter we were only interested in the general idea of "getting ideas." Readers who want to know exactly what kind of network of threshold devices is necessary to calculate numbers that are square, or prime or whatever, must read the textbooks of automata theory.

Vehicle 11

Rules and Regularities

Most of you will not yet be convinced that the process of getting ideas as it was described in the previous chapter has anything to do with thinking. It is not surprising, you will say, that occasionally something clicks in the workings of a fairly complicated brain and from then on that brain is able to perform a trick (an algorithm, as some people say) that can be used to generate complicated sequences of numbers or of other images. It is also not surprising that these may occasionally match sequences of events or things in the world of the vehicle.

I will show you that this is just one step in the direction of creating behavior akin to thinking. In the following chapters we will introduce more elements of the thought process, making new vehicles to show new tricks, new types of performance. In the end our vehicles will surprise us by doing some real thinking.

We want to equip Vehicle 11 with a brain about which it can be said—in a more radical way than it could be said about previous editions—that it is a model of the world. We already introduced partial aspects of this model idea, when we talked about the usefulness of internal maps representing external spaces (Vehicle 8), and when we described a learning process (Vehicle 7) that discovers things in the environment and establishes their internal models (called concepts). But this is not enough. These things move around, bang against each other, associate and dissociate, grow and break. We have altogether missed these dynamic aspects up to now.

We will introduce these dynamics by improving on the system of Mnemotrix connections already introduced in the type 7 vehicle. You will remember that these connections between elements in the vehicle's brain were of different strengths and could be made more effective when the elements they connected were often activated together. This turned out to be very convenient, because so many of the facts about the world that are interesting and important to us (and to the vehicles) may be expressed as things or events that tend to occur together. For this reason it is unlikely that we will give up the trick of associative learning in any further development of more refined vehicles.

But we soon discover that there are important pieces of knowledge about the world expressed in a different form: events that do not present themselves at the same time but in succession—pairs of events, of which one is always the first and the other the second, like lightning and thunder, swinging a hammer and hitting the nail, or, in the world of vehicles, meeting a source of food and tasting the food. When we discover a pair of such events, we tend to think that one is the cause of the other, whatever that means. But this may lead to wrong interpretations, for instance when both events are produced by a third hidden event, only with different delays. Most of the time, however, when two events regularly occur in succession, it is no accident. And it certainly is useful for a vehicle to know what to expect when events occur that have important, possibly dangerous, consequences.

We could use our old supply of Mnemotrix wire together with a little electronics to incorporate into the vehicles' brains all those delayed coincidences of events we have been describing. What we want to achieve is a connection between the two internal representatives of an event A and an event B such that, when the representative A is activated by the input, the representative B is activated by the connection, but not vice versa. The connection would then represent the fact that "B often follows A" or, if you wish, the causal tie between A and B. This would force us to do a rather complicated wiring for every such connection. In order not to burden our constructive imagination too much, we prefer to buy a different sort of wire, called Ergotrix, which conducts in one direction only and has an increased conductance when it is interposed between elements that are active in succession within a brief time. We must be careful, of course, to install the wire in the right direction, conducting from the element that tends to be active first to the one that tends to be active second.

Once again we will see to it that all of this happens automatically. Plenty of Ergotrix wire will be installed between as many elements as possible so that whatever sequences occur can be recorded in the system. Of course there will be no lack of opportunity for learning. With all the movement in the world around the vehicle, with all the natural laws operating, and with all the other vehicles displaying fairly regular behavior on the basis of all the tricks that we (or the processes of evolution) have built into them, many sequences of events will repeat themselves and they will be worth learning.

You may ask why we did not use Ergotrix wire in the first place (Vehicle 7) when we first gave our vehicles the capacity to learn, starting with those complexes of properties that frequently occur together because they belong to one "thing." We used the Mnemotrix wire, which is ideal for associations, because it couples elements in a symmetrical fashion; once coupled, each of the properties can recall the other in quite the same way. For each Mnemotrix connection we could have used two Ergotrix wires (one for each direction) to obtain almost the same result. But there are two reasons to leave things as they are.

First of all, we don't want to go back in evolution and change things that have already proved to be convenient, since we might lose some advantage that we have not even realized. (Remember the law of uphill analysis and downhill synthesis: we run the risk of not understanding any longer what we previously put together.) Second, it is probably a good idea to keep the two processes conceptually separated—the associations of elementary properties into things or concepts on one hand and the sequencing of concepts on the other hand, one controlled by the Mnemotrix, the other by the Ergotrix system. The two kinds of learning produce two different kinds of knowledge, like geography and history, or systematic zoology and animal behavior, referring to what kinds of things exist and to how they develop and interact.

If we let our imaginations go and try to work out in detail what kinds of things the Mnemotrix system will discover in a real world, and what kinds of dynamic laws will be incorporated in the Ergotrix system, we soon discover that the two kinds of knowledge are perhaps related more than we had assumed initially for reasons of conceptual convenience. First of all, it would seem that the process of abstracting things from the environment—concept formation at the most elementary level—must occur prior to the process of discovering the dynamic properties of these things. For the laws of successions of events refer to the development and to the combination of things rather than their elementary properties. This is familiar from our own human experience: listening to a new language we want to learn, we must first discover individual words, or roots of words (something like the morphemes in linguistic terminology), before we can even hope to discover the rules that govern their use. Also, in the development of a science it is often apparent how the discovery and denomination of phenomena precedes the definition of the laws of their transformation. Chemistry had to go through a descriptive phase before the physics underlying the variety of substances could be understood. Zoology had to be taxonomic before it was organized by the theory of evolution.

On the other hand, purely descriptive classification is not only boring, it is also potentially misleading. It may lead to the wrong categories when it is not guided by at least the intuition of a theory of the underlying processes. A century of microscopic anatomy has filled the libraries with thousands of beautifully illustrated volumes that are now very rarely consulted because the descriptive categories of the old histology have been largely superseded by the new concepts of biochemical cytology. The example from linguistics that we have just mentioned may well serve to prove the contrary point, with word roots–morphemes–words as the segments of speech that must be learned. While it is true that these chunks of meaning in some languages (largely in English) coincide with acoustically well-defined episodes (the syllables, which the naive listener can recognize), it is certainly true that a better, more general definition of morphemes or words is derived from grammar. Words (I use this term loosely) are the segments of speech that we discover as the ultimate particles of grammar. If we had no idea or no experience of grammar, we might never discover that these are the pieces that are shuffled around to form sentences. We might propose a different, incorrect segmentation of speech, for example, a segmentation into syllables in a language with polysyllabic words. Words become meaningful insofar as they are used in a grammatical system.

In other words, abstracting meaningful chunks from the environment (things, events) and discovering the rules of their behavior are two processes that condition each other and are necessarily interlaced, like the learning of the vocabulary and the learning of grammar in a language course.

Coming back to Vehicle 11, it seems like a good idea to let the discoveries of the Ergotrix system influence the learning process in the Mnemotrix system, on whose initial abstractions it in turn depends. I don't want to work this out in detail, but something like the following scheme would clearly be possible. We have already described the conditions for the strengthening of an Ergotrix wire. These conditions are fulfilled when an element, say a threshold device, at one end of the wire becomes active shortly before another element becomes active at the other end. We have also seen that it is mostly groups of such elements, strongly interconnected and representing "things," that become active in succession. Now let's introduce the rule that whenever the Ergotrix wires become strengthened, the Mnemotrix wires within each of these groups will also become strengthened.

Thus concepts are established in the vehicle especially when they appear in regular sequences. How would this look to us? We would notice, observing the apparently erratic behavior of a vehicle in its world, that the vehicle displays particularly well defined reactions to events that are known to have consequences. Take, for example, a vehicle approaching an obstacle at high speed. We would not be surprised to see the vehicle promptly react to its perception of the danger of a collision. Similarly, Vehicle 11 will quickly remember which of its own behavior patterns regularly and quickly elicit a reaction from other vehicles. We observe that after an initial learning period Vehicle 11 will either produce these behavior patterns frequently or pointedly avoid them. It will use them as signals. It will also learn those signals that regularly precede certain behavior patterns of other vehicles. After a while Vehicle 11 will react to these premonitory signals just as it reacted, before the learning, to the behavior that regularly followed the signals.

But it would take prolonged observation to notice this particular aspect of learning in the vehicles. As a matter of fact, we might not have suspected it if we had not introduced a piece of our own philosophy into the construction of these vehicles. As our brain children become more efficient, we notice that the "law of uphill analysis and downhill synthesis" becomes more and more compelling. For the time being, take the message in this form: since you were not satisfied with the first meager showing of intelligence in

our vehicles, we started adding a few more tricks, hoping that they would convince you a little more. The first trick we tried was the coding of the environment in those terms that yield a maximum of correlations and logical structure, in other words, in the most meaningful terms.

Vehicle 12

Trains of Thought

At this stage, if you want to be critical, it is easy for you to maintain that up to now you have not discovered anything in our vehicles that goes beyond ordinary learning. True, these creatures seemed to become more and more able to deal with the adversities of their environment, not only by a process of Darwinian selection but also by active assimilation of information from the world. But thinking is different. It is a process that can go on for a long time, as everyone who has done some conscious thinking knows. Thinking can be observed in other people as well, when we get verbal or nonverbal evidence for a succession of mental states that are guided by some criterion of plausibility or logic—mental states that reflect the exploration of various blind alleys and eventual arrival at a result. Sometimes we seem to notice such mental operation even in a monkey or in a dog. But not yet in a vehicle.

The possibility of sustaining long successions of distinct brain states for the purpose of exploring knowledge already incorporated in the brain is what we will introduce in a new brand of vehicle, which we will call Vehicle 12.

First a remark on pathology. All the later vehicles, beginning with type 7, are in constant danger of running into a condition

quite analogous to epilepsy (which is also one of the most common forms of derangement of animal brains). The strengthening of the connections between the elements of the brain, which is at the basis of associative learning, embodies the danger of reciprocal activation beyond control. In a population of elements in which excitatory connections abound, if the number of active elements reaches a certain critical level, chances are the remaining ones will also become activated. These elements, in turn, keep the first set active. A maximal condition of activity is then established and maintained until the supply of energy is exhausted. This maximal activation makes no sense in terms of the information ordinarily handled by the brain, which is keyed to patterns of partial activation of the elements. Necessarily the result is disorderly, ineffective behavior. There are various ways of dealing with this danger, and I propose the following for our vehicles.

Let every threshold device in the vehicle's brain be touched by a special wire through which we can control its threshold. If we set the thresholds high, the threshold devices will become active only when they are very strongly activated by the input they receive from other threshold devices or from the sensors. For a lower threshold, less input will suffice. So if we watch the operation of the brain—and in particular the total amount of activity in it—we can always prevent an attack of epilepsy by raising all the thresholds. If there is not much activity, we can lower all the thresholds and thereby encourage the circulation of activity through the brain. It is of course quite easy to let this happen automatically. All we need (figure 18) is a box that receives as its input the number of active brain elements at that moment and calculates appropriate thresholds, which it then sets for the whole brain. In real life, the input for this threshold control device might be the rate of change of the number of active elements, in order to give it an opportunity to foresee the catastrophic explosion of activity before it happens. But

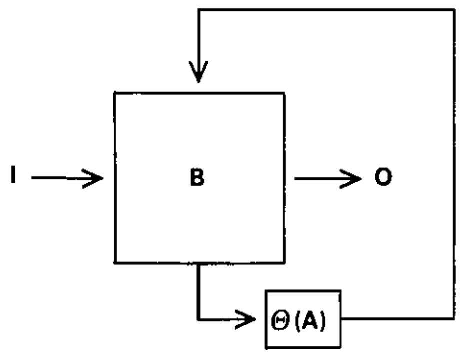


Figure 18
B is the brain, which receives input I and elaborates an output O. At the same time it signals the level of activity A in its interior to a special box that calculates appropriate thresholds Θ for the elements in B.

for purposes of illustration it will suffice if the threshold control device works just on the amount of activity in the brain.

The effect of this global negative feedback on the activity of a vehicle's brain is illustrated in figure 19, which shows the number of active elements as a function of the number of active elements a moment earlier. When the activity is low, it will again be low at the next moment. (For very low excitation, there may even be a tendency for the activity to die out, since a minimum density of active elements in the brain is required to activate the next set of elements, but this is not shown in figure 19.) For very high levels of excitation—that is, for a very large number of active elements—we may imagine that the thresholds are immediately set so high that the activity will drop to a very low level at the next moment. Intermediate levels of activity will lead to maximum activity at the next moment (see the middle part of the curve in figure 19). Later on we will come back to this curve, which has interesting philosophical implications. First let us watch the operation of a brain that con-

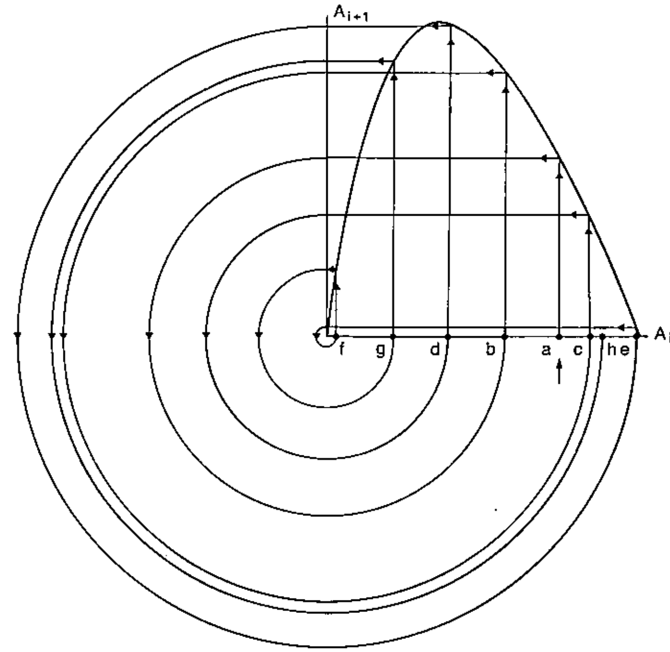


Figure 19
The function describing the next number of active elements A_{i+1} given the present number of active elements A_i. It can be seen by iteration (follow the lines starting from the arrow near a) that the states of a brain controlled by such a rule are quite unpredictable.

tains many learned associative connections while it is being controlled by the feedback of a threshold control device.

We have already noticed that the vehicle's brain has a tendency to explode into fits of activity because of the abundance of reciprocal activation between its elements, a situation reminiscent of the chain reaction in a block of uranium. But most of these explosions, if everything works out the way we have planned, should take place within limited groups of elements that are tied together by particularly strong associative connections. Such sets of elements arise as "concepts" representing things or events that have often presented themselves in the environment.

Let one such thing appear in the sensory space of Vehicle 12. The explosion of activity will happen in the corresponding set of threshold devices responsible for that concept. This implies an increase of the number of active elements in the brain, and the threshold control device will immediately react to it by raising all the thresholds. A moment later many elements that were previously active will be silent. But the elements pertaining to the concept in question are likely to stay active. This is because the strong reciprocal connections within the set, once activated, guarantee a very high level of excitation for each element of the set. This level is so high that the activity of the elements may survive the raising of the thresholds. Thus the first interesting effect of our recent innovation is the focusing of individual concepts—of patterns that have their own internal consistency—at the expense of background activity. We greatly appreciate this effect in a well-functioning human brain, where it is often called the FOCUSING OF ATTENTION.

But there is more. You remember that we have installed not only Mnemotrix wire for concept formation but also Ergotrix wire, which represents within the brain the relation of temporal succession, of consequence or causality. Thus the elements now active in the lone surviving concept after the automatic raising of the thresholds also have some Ergotrix wires attached to them. These Ergotrix wires lead to the elements that have often been activated after the concept in question, the consequences of the active concept, so to speak. Obviously, there will be more than one possible next step for all but the most determined situations.

So we must ask ourselves how the vehicle's brain finds the concept that follows the one it presently holds. The choice, it turns out, is quite automatic. Among all the elements activated by the present concept through the Ergotrix wires, there will be some groups

strongly connected by Mnemotrix wires because they again form concepts. These groups will of course ignite with particular alacrity because the internal connections within each group will provide an explosive kick to the activation from external sources, that is, from the active concept. Now you can see what will happen. The threshold control, alarmed by all this growth of activity, will quickly raise the thresholds, smothering most of the activity and leaving only the most resistant group of elements activated. As we have already seen, this will be the group with the strongest reciprocal connections. In terms of concepts we may put it this way: the next concept, among all the concepts that are possible consequences of the present one, will be the most consistent or familiar one—the one most strongly established by experience.

Note that with all these budding and growing explosions the thresholds have been raised above the level at which they were set for the previous concept. It is therefore very likely that the previous concept will be extinguished. So the system will not swing back into its former condition but will end up with a different concept. This new concept will have its own consequences embodied in Ergotrix wires. And these will again materialize in a new concept by way of the sequence of events that we have just described. The process will continue as long as you wish or as long as the chain of concepts does not lead back to the concept from which it started.

The upshot is something very much akin to thinking, to that process so familiar to our introspection, where images appear in succession according to rules reflecting the relations between the things they stand for. This process goes on in our minds when we try to figure out the best way to get from one point to another in a familiar city by letting our imagination produce successions of street corners (or other landmarks) whose relations of geographical proximity we have experienced. It is also one of the tricks we use to determine the consequences of possible moves in a game of chess, or the consequences of some statement in a discussion. This chain-ing of internal states is exactly what we planned to introduce into the brain of Vehicle 12 to make its meditations look more lifelike, more like our own, not only in the time they take but also in the unforeseen routes they can follow.

There is an important property that the brain of Vehicle 12 shares with the brains of our fellow men. Consider again the curve of figure 19, which shows the number of active elements as a function of the number of active elements a moment earlier. The exact shape of the curve is not very important, as long as it has a maximum and cuts the diagonal ($A_i = A_{i+1}$). Start with a certain value *a* on the abscissa and find the ordinate of the next value *b* on the curve. Put that value *b* again on the abscissa and find *c*, and so on. You will be surprised to find that the succession of values *a, b, c* . . . does not seem to follow any rules and is in general quite unpredictable. Now you will remember that figure 18 describes the effect of threshold control on the activity of the brain of Vehicle 12. We may take *a, b, c* . . . as the number of active elements in the brain in successive moments of time. If there are very few elements, the succession will by necessity become repetitious after a short while. But for a fairly large brain the succession will be truly unpredictable to an observer, for any practicable stretch of time.

I hope you realize what this means. If you could observe the inner workings of the vehicle's brain, say, by watching light bulbs connected to the threshold devices, and these light bulbs lit up every time the corresponding element became active, you could not even predict how many lights would light up in the next moment, let alone what kind of pattern they would form. (For any given number there are of course many constellations with that number of active elements!) At this point we should again invite our philosophers to comment.

I would claim that this is proof of FREE WILL in Vehicle 12. For I know of only one way of denying the power of decision to a creature—and that is to predict at any moment what it will do in the

future. A fully determined brain should be predictable when we are informed about its mechanism. In the case of Vehicle 12, we know the mechanism, but all we can prove is that we will not be able to foresee its behavior. Thus it is not determined, at least to a human observer.

I know what the philosophers will reply. They will say that although this may look like free will, in fact it is not. What they have in mind when they use that term is the real power of decision, a force outside any mechanical explanation, an agent that is actually destroyed by the very attempt to put it into a physical frame.

To which I answer: whoever made animals and men may have been satisfied, like myself, a creator of vehicles, with something that for all intents and purposes looks like free will to anyone who deals with his creatures. This at least rules out the possibility of petty exploitation of individuals by means of observation and prediction of their behavior. Furthermore, the individuals will themselves be unable to predict quite what will happen in their brains in the next moment. No doubt this will add to their pride, and they will derive from this the feeling that their actions are without causal determination.

Vehicle 13

Foresight

And indeed—following up the last sentence of the previous chapter—it may be said that the internal rumblings of Vehicle 12 are at least aimless, if not random, constrained as they are only by the rules of plausibility stored in the vehicle's memories (Mnemotrix and Ergotrix) but not determined by them.

I am sure that most of you will not believe that "aimless succession of images" is an accurate description of what goes on in your minds most of the time. You will not be impressed by our vehicles as long as there is no evidence of some purpose guiding their behavior and some direction in their thinking. These are virtues we are pleased to see in our children. Why shouldn't we try to modify our brain children, the vehicles, in this direction? It won't be difficult in principle, and it means a lot to those philosophers who like to think that goal-directed behavior is the one property that gives living beings their very special status within the physical universe.

There are two aspects of goal-directed behavior we must consider. First, the goal lies in the future. For instance, the eating of the mouse is the goal determining the movements of the cat now. We have the special case of an event defined for a later time having earlier effects, quite contrary to the effects that we are used to

considering in physics. Second, the goal is desirable by its very definition. We cannot talk about goals without first getting straight the concepts of good and bad.

Let us take the first problem first, that of acting toward the future or in accordance with an event in future time. This is obviously nonsense if we take it to mean an action that is now a consequence of something that will happen only in the future. However, it is an entirely different matter—and it does make sense—if we take it to mean an action that is a consequence of something we expect to happen in the future, since that expectation may well be available before the action is planned. There is no violation of the law of causality in this. All we need is a mechanism to predict future events fast enough so that they will be known before they actually happen.

There are of course safe predictions—and others that are not so safe. We have no problem predicting the future of a rolling stone once it is on its way down the slope of a hill. But it is not so certain whether a dog will leave its comfortable pillow when it is shown a piece of cake. Other motions are practically unpredictable, like that of a child playing in the middle of the street. Yet the principle of the prediction is very similar in these cases. We have seen enough rolling stones and hungry dogs that the perception of one situation immediately brings to mind its consequences. Stored sequences of events are all we need for prediction, together with a mechanism forcing them to speed up in the reproduction when necessary, for example, in dangerous situations. Complications may arise when several different predictions are approximately equally likely. In a good prediction there must be the possibility of predicting various outcomes, given a certain situation, and of keeping the various outcomes in mind in parallel. This is what we do when we drive through a street where children are at play.

Now we want to incorporate prediction into the vehicles of type 13. Clearly, the prerequisites are all there in previous types of vehicles. We were careful to reproduce inside the vehicles' brains many rules and regularities that govern the world. This way we could speak of the vehicles' brains as models of the world, as miniature editions of external, public space. Their brains were populated with patterns of activity that mimicked the activities of real objects in their environment. We noticed that these brains (as models of the environment) really came to life only when the dynamic aspects of the world were also represented, so that a given functional state of the elements of the brain would evolve into the next state according to the same rules that make the world evolve from one moment to the next. We did this by using Ergotrix wire, which activates the elements of the brain in the same order as the sequence of events to which they correspond. And we implicitly assumed that the Ergotrix wires would be trained to reproduce sequences of activation at the same pace as the original occurrence of the sequences of events. But this is a somewhat gratuitous assumption: the Ergotrix wires could work faster, or slower, than the sequences that are impressed upon them. Let them reproduce the sequences at a more rapid pace and you will have a brain that works as a predictor (figure 20).

We want to take a closer look at what goes on in a vehicle equipped with such a predictor. Remember that the threshold devices in the brain are under the influence of two kinds of input: first, directly or indirectly (via interposed filters) from the senses and, second, from one another. Only the latter kind of influence is mediated by Mnemotrix or Ergotrix wires. Consider a certain state: the vehicle in quiet contemplation of the world, the threshold control at rest, and the thresholds set high enough so that only a few ideas stand out over the background. (These ideas are of course represented by groups of active threshold devices with their Mnemotrix cross-connections.)

The evolution of the vehicle's mental state may be affected in three ways. First, meditation. Even if the brain is at equilibrium, with the thresholds fixed, it cannot be entirely at equilibrium be-

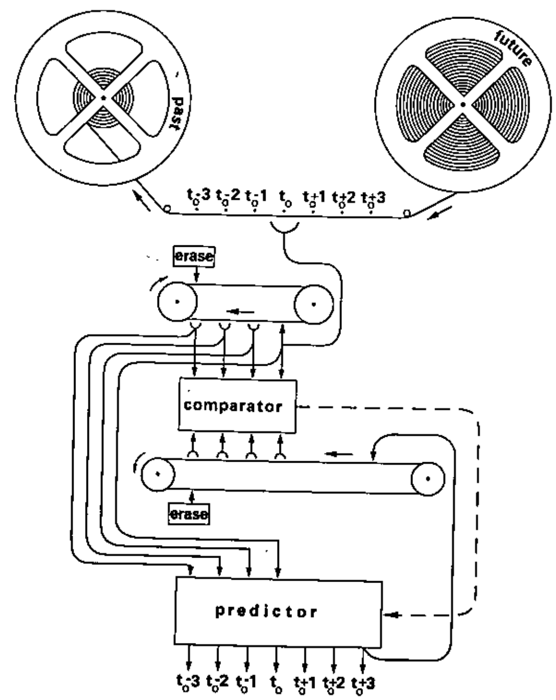


Figure 20

A predictor with some auxiliary equipment. The flow of life is represented by the film (or tape) being unwound from the reel marked *future* and ending up on the reel marked *past*. Only one moment of time, t_o, is available as input to the machine. The input is stored, however, for three units of time on the endless tape of a short-term memory. From there both the present input and the content of the short-term memory are relayed to the predictor which computes the future three units of time ahead. The predictor contains statistical information about the past embodied in the Ergotrix wires in its interior. The prediction for $t_o + 3$ is stored on another short-term memory until it is ready to be compared, by a special comparator, to the real input *t* and to the input three units of time back. (This depth in time of the comparator is desirable in order to assess the dynamic properties of the predictor.) The comparator in turn emits signals that may modify the predictor or switch it off (broken arrow).

cause the Mnemotrix connections between the active elements will slowly grow in power, the longer the idea is on. But this may not be apparent for a while, unless new elements are recruited to make the idea more ponderous, thereby upsetting the equilibrium and making the brain go on a thinking tour, as we have already seen (Vehicle 12).

Second, things may happen in the environment. The vehicle's mental state will change according to new input from its sensors. The transition from one state to the next will be aided by the Ergotrix wires in the case of a sequence of events that has occurred before, but the Ergotrix connections are too weak by themselves to effect the transition without the help of the sensors' input.

Third, the sensors may signal a condition of the environment that has always evolved in a certain way in the past. The Ergotrix connections in this case will be very strong. And the next state of the vehicle's brain will be entirely determined by them. As a result the vehicle will be blind to the real input that follows. Most of the time this will not hurt the vehicle because the sequence of events will be the same as it has been in the past.

But occasionally the rare event happens and the input clashes with the internal prediction. This will result in a garbled condition that cannot develop further in any coherent way. We want to avoid this, especially in view of the fact that discrepancies between reality and expectations are interesting and should be analyzed in detail. Eventually we would like to provide the vehicle with a device that is turned on by just these discrepancies and amends the system of rules used for the prediction, so that the vehicle will know better the next time it meets the same situation.

First, we provide the vehicles with two separate representations of the environment, one in the predictor, the other in an equally large ensemble of elements that receive only the fresh input from the sensors and do not elaborate on it. These two half brains are connected point to point to each other, so that the discrepancies between their states of activity can be detected as easily as the differences between two drawings if you hold them one on top of the other against the light. The technical realization is easy. Say the two half brains are connected by inhibitory connections between corresponding points. There won't be much activity if the two patterns of activation are exactly equal, because of the reciprocal inhibition. But if one of the two representations contains some activity not present in the other, this will stand out strongly.

We want our vehicles to be imaginative, but mainly realistic. That's why in the case of conflicting information we want to take the information from the realistic half brain more seriously than that from the predictor. We may incorporate a rule: when in doubt, believe the sensors. And we do this by introducing a mechanism that simply turns off the predictor in cases of conflict. But we want to go one step farther; we want to educate the predictor to make it more realistic. This is not as easy as it may sound. Remember that the event in the environment that caused the predictor to make the wrong prediction belongs to the past by the time the clash between the two half brains reveals the mistake.

Thus we want something like short-term memory (figures 20, 21), a third representation of the environment lagging behind the other two, so that, if necessary, the past is available at any time a few steps back. Such a mental echo is not difficult to incorporate in the vehicle's brain. Just connect every element of the sensory half brain with another element that becomes active one unit of time after the first, and with yet another set of elements that becomes active two units of time later, and you have an efficient short-term memory.

Now with a few additional pieces of equipment, we can greatly improve the predictor by making it more flexible and open to new experiences. We do not worry about occasional wrong predictions, especially if the mistakes are not fatal ones. Knowledge is incorporated all the time in the Mnemotrix and Ergotrix connections, and

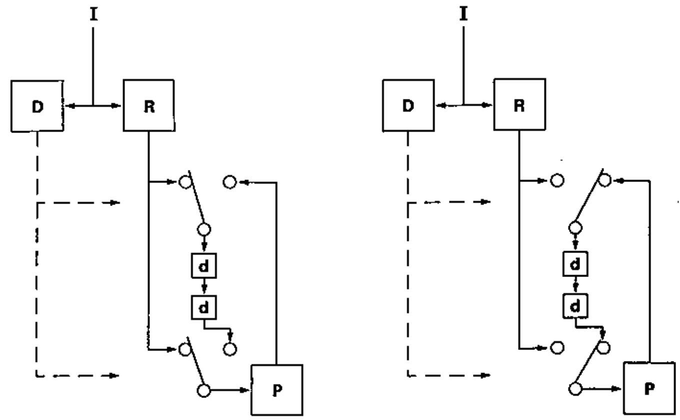


Figure 21

Learning by internal repetition of one-time events. I is the input. D is the Darwinian brain which emits judgments on the desirability of the input and sets two switches accordingly (through the broken arrows). On the left: normal operation, with the Darwinian brain quiescent. The realistic brain R feeds the predictor P and also an open chain of two delay elements d. On the right: the Darwinian brain D signals emotional input. The two switches are thrown to the right, the predictor is no longer fed by the realistic brain but receives the contents of the two delay elements d to which in turn it gives output. The information preceding the emotion reverberates through the predictor and the delay elements until the Darwinian brain calms down again and sets the switches to the normal position.

the statistical knowledge about the world they represent is never complete (by its very statistical nature!). But this piecemeal learning may not be sufficient when the one occasional deviation from the statistics is a very important one (in the good or in the bad sense). Say, for example, that most of the time green vehicles display peaceful behavior, but there is an occasional green vehicle whose aggressiveness is particularly vicious. It would be wrong to associate the

property "99% peaceful" with the color green and to react indifferently to the sight of green, since sooner or later an encounter with the green maverick is bound to take place and the victim must be on the defensive. It is better then to give special weight to the rare but decisive experience and to consider green vehicles as generally bad.*

How is this done? We are talking about "good" and "bad" as if these concepts were easy to define. Of course they are not, but there is a way out of this difficulty. Remember the vehicles of our earlier models. They were fairly simpleminded compared to the ones we are now developing, but they were efficient. The type 6 vehicles, which underwent a process of Darwinian selection, know one thing for certain: the avoidance of danger and the search for advantage. And they know this even though no one (neither the vehicles' builders nor the vehicles themselves) has any idea of a definition of good or bad. The type 6 vehicles simply move forward toward good things and back away from dangerous things. But this is all we need.

Catch one of those Darwinian vehicles of type 6, take away its motors, and you have a detector for good and bad. The wire that went to the forward motor signals "good" and the wire that went to the backward motor signals "bad." So we can incorporate the brain of Vehicle 6 into the brain of Vehicle 13 and thereby provide it with important, ancient, intuitive knowledge.

We can now put the pieces together. Short-term memory, two steps back in time for everything that happened, is already there. The predictor is there. A switch that momentarily turns off the

*I hope you remember that we are only talking about little machines. It would be wrong to cite the usefulness of one-instance learning in vehicles as a justification for prejudice and superstition in human behavior. We do have vastly more complex brains that enable us to make the diagnosis of good and bad independent of superficial markers such as the shape or the color of the casing.

predictor in the case of a conflict between prediction and reality is also there. The Darwinian evaluator is ready to signal particularly sinister or joyous events. The new trick: figure 21.

Whenever the Darwinian evaluator D signals an unpleasant turn in the real course of events, or a very pleasant one, the predicting half brain P is disconnected from the input it normally receives from the realistic (sensory) half brain, R. Instead the predicting half brain receives its input from the short-term memory two steps back. So it will go again through the two instants preceding the important happening. At the same time its output is connected to the input of the short-term memory. So it will receive over and over again via the short-term memory the succession of the two events, a and b, until the Darwinian evaluator D has calmed down and everything is switched back to normal.

The net effect is that successions of events leading to strongly emotional consequences are incorporated firmly in the Mnemotrix-Ergotrix system even if they occur only rarely. The internal reverberation set up by the Darwinian evaluator artificially makes up for their low frequency and turns them into high-frequency events in the inner workings of the brain.

We may relax now and observe Vehicle 13 in action. Its power of prediction is quite apparent when it follows a moving object around, say another vehicle carrying a source of attraction. When the object temporarily disappears behind an obstacle, Vehicle 13 will head toward the place where it is likely to show up again. We also notice more peculiar properties. For no obvious reason, Vehicle 13 seems to avoid certain places and vehicles in its environment, and it seems to have an irrational affection for some other places and vehicles. If we watch it long enough, we may find out that there are indeed reasons for these idiosyncrasies. The vehicle may associate a one-time event with this or that place or vehicle, and act accordingly. Vehicle 13 remembers facts much as we do, individual facts and events of its past experience. This remembering is different from the memory we have considered before, which consisted in the molding of behavior according to the unchanging rules and regularities of the environment, perceived through the statistics of many individual events. The vehicles of type 13 derive their experiences from rare but important happenings. They will be quite different, one from the other, because each vehicle builds up its own character based on the particular experiences of its early life.

Vehicle 14

Egotism and Optimism

As time goes on, we grow affectionate toward the diversified crowd of our vehicles, from the very simple ones to the more complex models displaying interesting social interactions and sometimes quite inscrutable behavior. We can play with them, we may get to know them personally (and they may get to know us), we can tease them, test them, teach them tricks, and let them love or fight each other. We do not feel, however, that they show any personality, not even the most complex ones of type 13. It is difficult to say what we mean by that.

Perhaps we would accept them more readily as partners if they gave more convincing evidence of their own desires and projects. We notice that our fellow men usually seem to be after something, when they go about their business or when we converse with them. Dealing with people is interesting because of the challenge their continuous internal scheming seems to provide. The system of desires we suspect behind their scheming may be part of what we call the personality. It may be the lack of just such projects that we notice in our vehicles. We cannot help feeling that they are driven by necessity rather than drawn by goals—in spite of all the efforts

we put into them, in spite of special mechanisms that are apt to abolish lowly forms of causality, and in spite of the predictor that seems to draw motives from a future state of the world.

Once we have noticed this, we can of course, in a last creative effort, endow a new kind of vehicle, our last, Vehicle 14, with a certain amount of systematic egotism, with a touch of the pleasure principle, in order to make it look more like our fellow humans. We proceed as follows.

Remember that our more sophisticated vehicles already have built into them many components that come in handy for this new project. With the introduction of the Ergotrix wires (Vehicle 10) prediction became one of the vehicles' mental habits. In Vehicle 13 the updating of the predictor was greatly improved by a mechanism giving great weight to rare but important events. This was achieved by incorporating into the brain of Vehicle 13 another, more primitive, Darwinian brain that contributed all the ancient information about good and bad things its ancestors had accumulated through the generations.

Still earlier, we had noticed (Vehicle 12) that the succession of mental states dictated by the Ergotrix connections was essentially random and quite unpredictable (perhaps even unpredictable as a matter of principle because of the peculiar mathematical property we associate with the function of figure 19). The randomness of the decisions made by Vehicle 12 in part reflected the statistical nature of the knowledge incorporated in the Ergotrix connections and the continuous updating of this knowledge by an ongoing learning process. It also depended on the very nature of the process that makes the brain swing from one state of activity to the next during alternate episodes of raising and lowering the thresholds, automatically imposed by the mechanism of threshold control. We will now give this process an optimistic slant so that the pump of thoughts in the brain of the vehicle will produce a succession of more and more pleasurable mental images. We will convince ourselves in the end that such optimism not only leads to nice dreams but also has objectively favorable consequences.

We will assume that most of the time the uncertainty as to the next state, given a certain state of activity, is not only an uncertainty for the observer but an inherent uncertainty in the sense that the predictor points toward (at least) two states that are equally likely as a continuation of the present state of the brain (and therefore of the world). Such a dilemma in previous vehicles might have been decided by a random element built into the brain (for example, by a Geiger counter making its decisions on the basis of whether or not it was hit by a cosmic ray within the last tenth of a second). But from now on we will impose the following rule for Vehicle 14: when choosing among several equally likely next brain states, choose the most pleasing one.

You have already guessed how we want to achieve this. We hold the present state for a short time (no problem, short-term memory is already there) while the predictor is allowed to go quickly through its various predictions. At the same time the built-in Darwinian evaluator is asked to evaluate these predictions for their favorable or unfavorable aspects. It will in general come up with different values for the different predictions. When this is done, the predictor quickly goes once again through its predictions and stops at the prediction with the highest score for pleasurableness. This is then the next state of the brain.

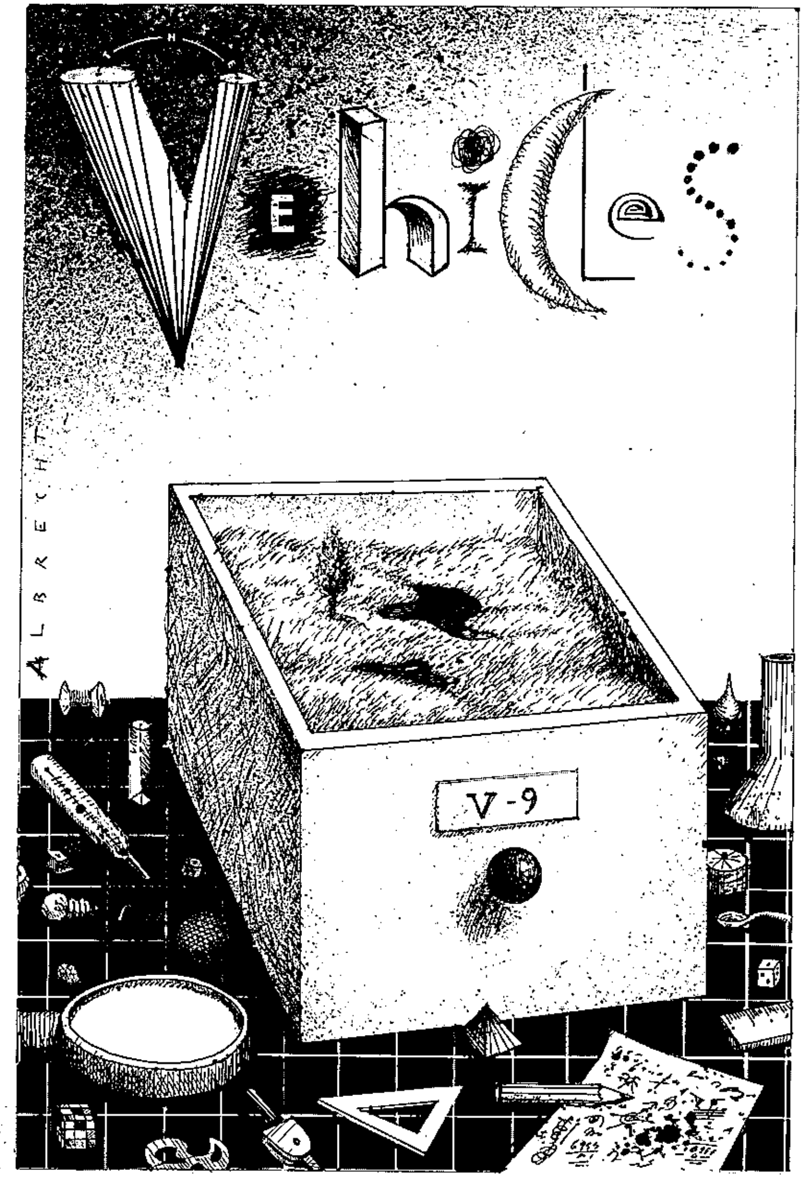
We don't need more than that. We may put the vehicles back on the table and meditate about their behavior. A superficial observer, or an impatient one, will not notice anything special. We, as creators of vehicles and experienced observers of their behavior, do notice subtle changes in our latest perfected brain children. We know their tastes: we have ample opportunity to see which sources of stimuli, which situations and which other vehicles they are attracted by and which they avoid. Their reactions to these things in the past were quite direct and easily observable when the object was

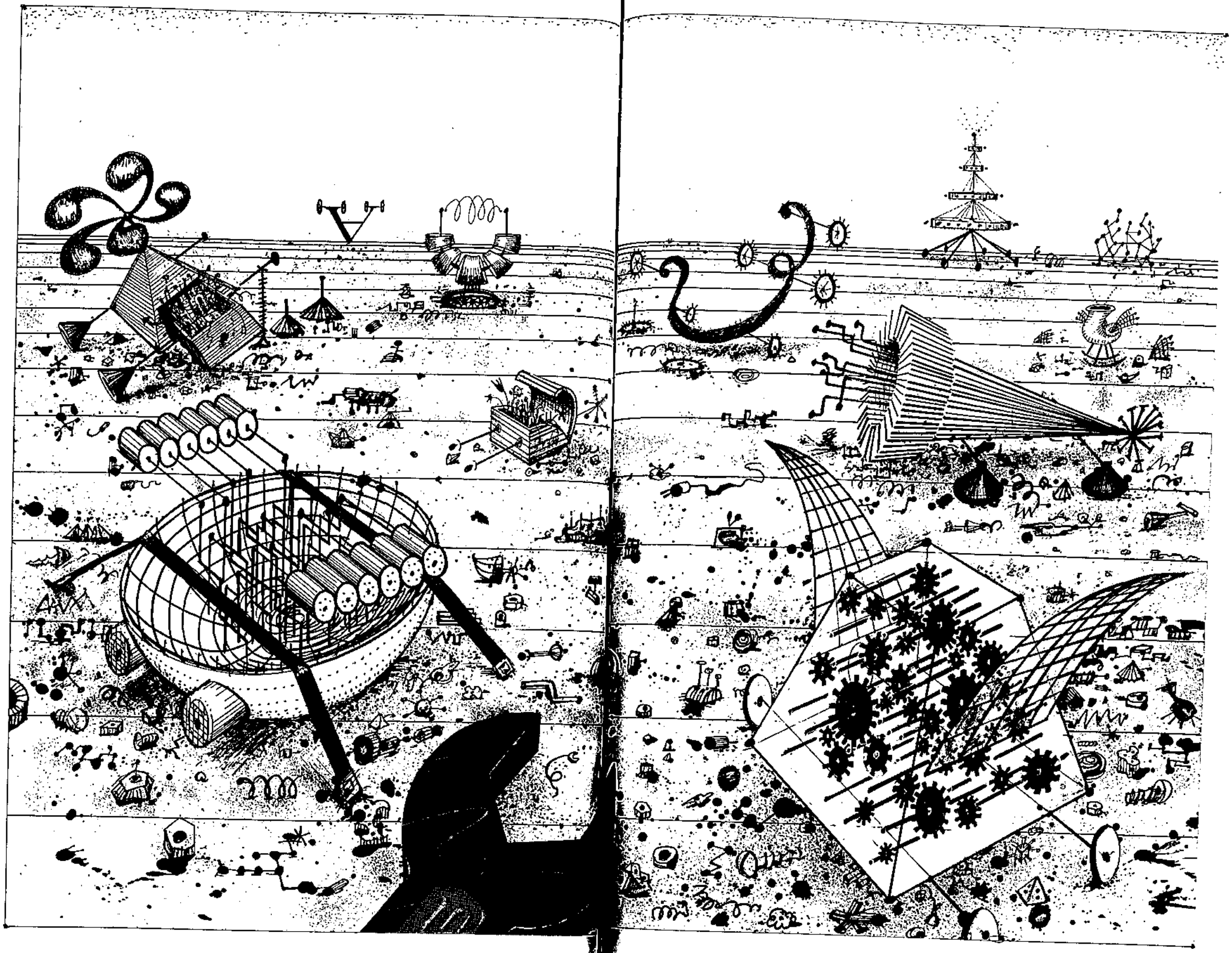
in the vicinity of the vehicle. Distant sources and situations did not seem to affect them much.

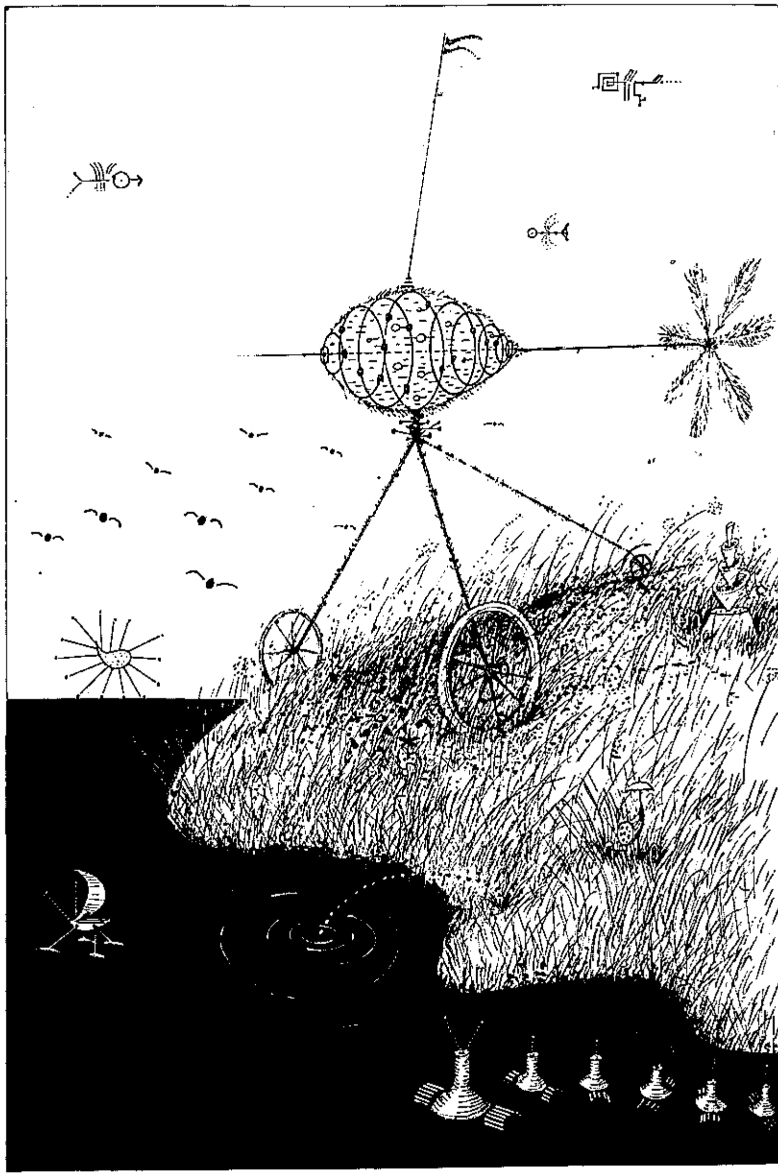
Now it is different with type 14 vehicles. They move through their world with consistent determination, always clearly after something that very often we cannot guess at the outset—something that may not even be there when the vehicle reaches the place it wants to get to. But it seems to be a good strategy, this running after a dream. Most of the time the chain of optimistic predictions that seems to guide the vehicle's behavior proves to be correct, and Vehicle 14 achieves goals that Vehicle 13 and its predecessors "couldn't even dream of." The point is that while the vehicle goes through its optimistic predictions, the succession of internal states implies movements and actions of the vehicle itself. While dreaming and sleepwalking, the vehicle transforms the world (and its own position in the world) in such a way that ultimately the state of the world is a more favorable one.

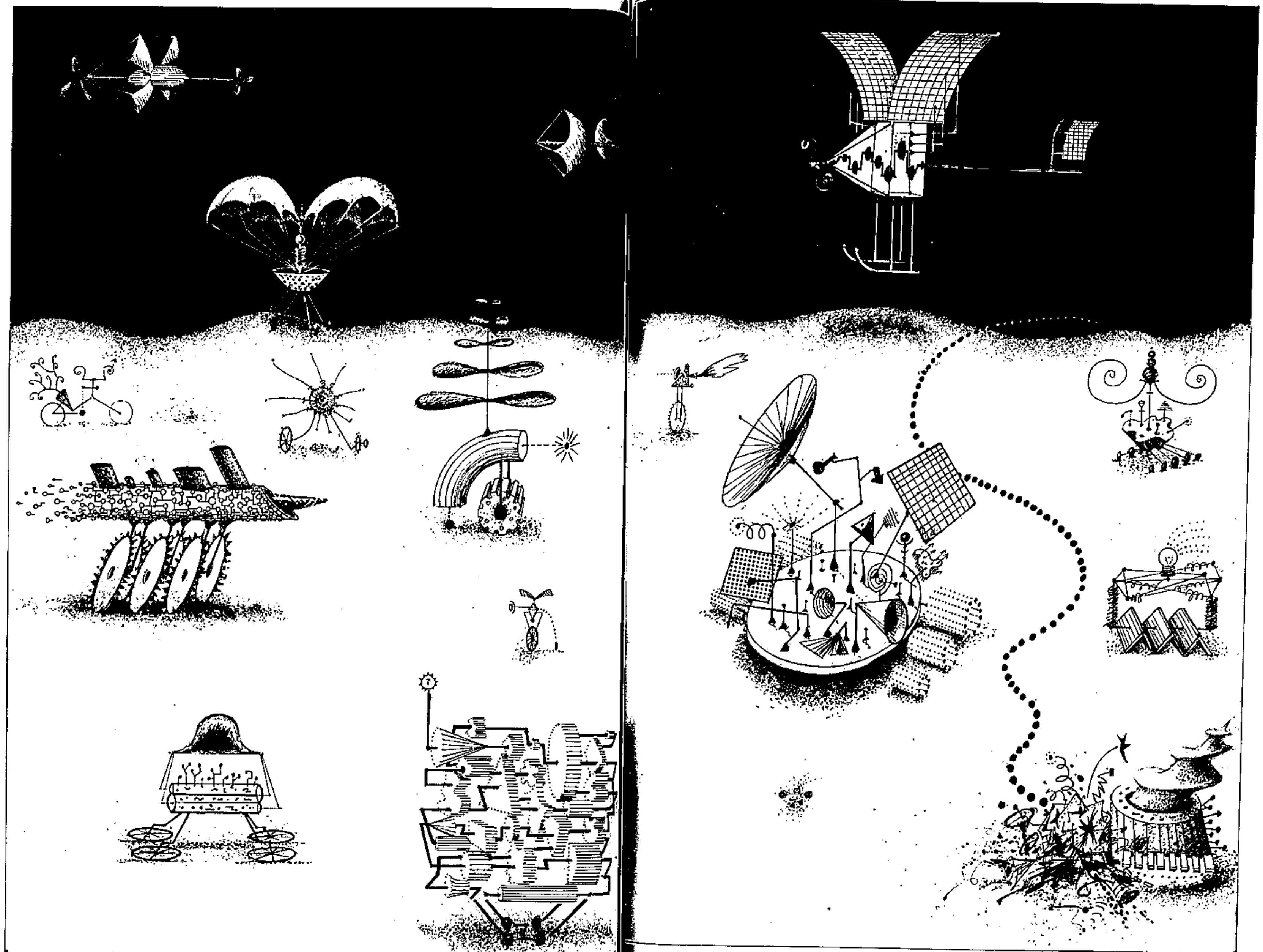
We observe at some stage how one of the vehicles of type 14 is waiting for another vehicle to appear. This other vehicle carries a very appealing source which Vehicle 14 intends to tap. It seems to be waiting impatiently, since every now and then it performs the motions that are associated with the tapping, as if by anticipating its own behavior in the presence of the desired event, it could accelerate the event's occurrence. "This is very human," we say. "Haven't we all felt an urge to run to the door long before the doorbell rings, when waiting impatiently for a beloved friend?" Indeed, it is aberrant behavior dictated by a very subjective law of causality, but it does seem to reflect a basic attitude of humankind, this irrational belief in the effectiveness of one's own actions.

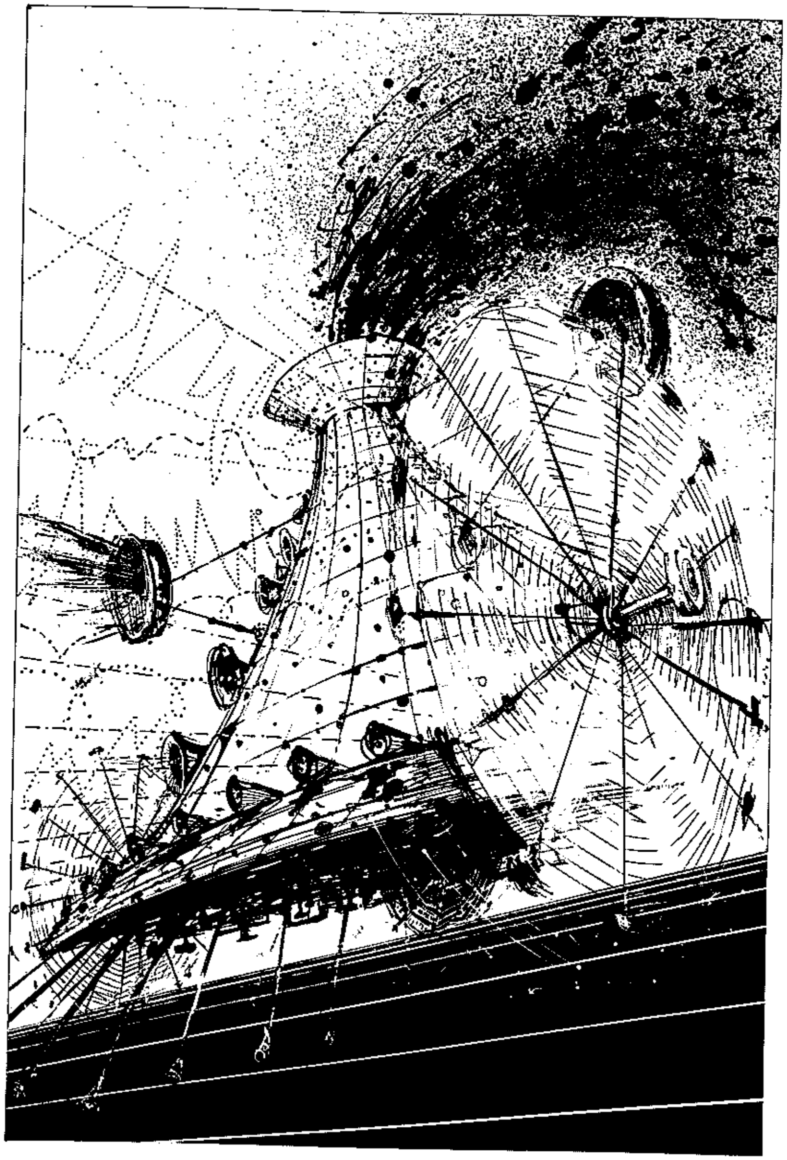
This portfolio of vehicles, some placidly at rest, most madly careening over the landscape of the artist Maciek Albrecht's imagination, illustrates only a few of the many marvelous "creatures" inspired by Valentino Braitenberg's text.

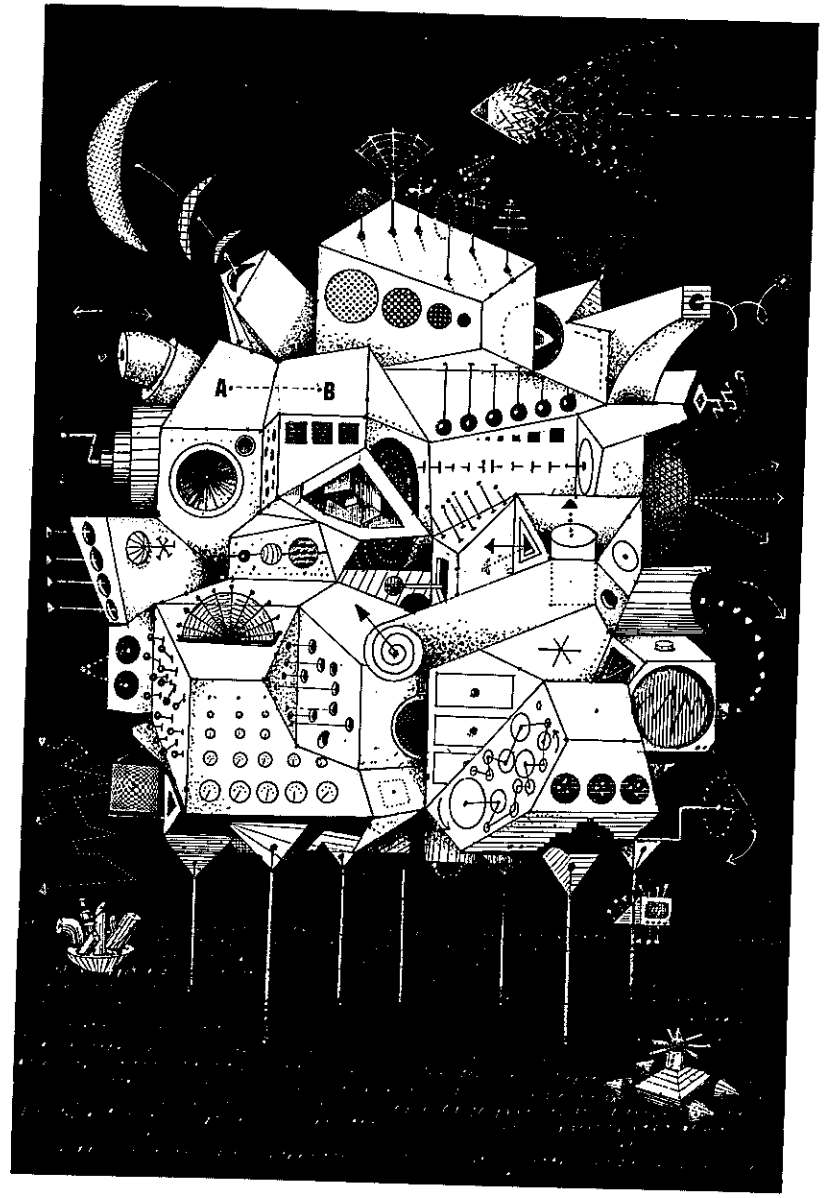








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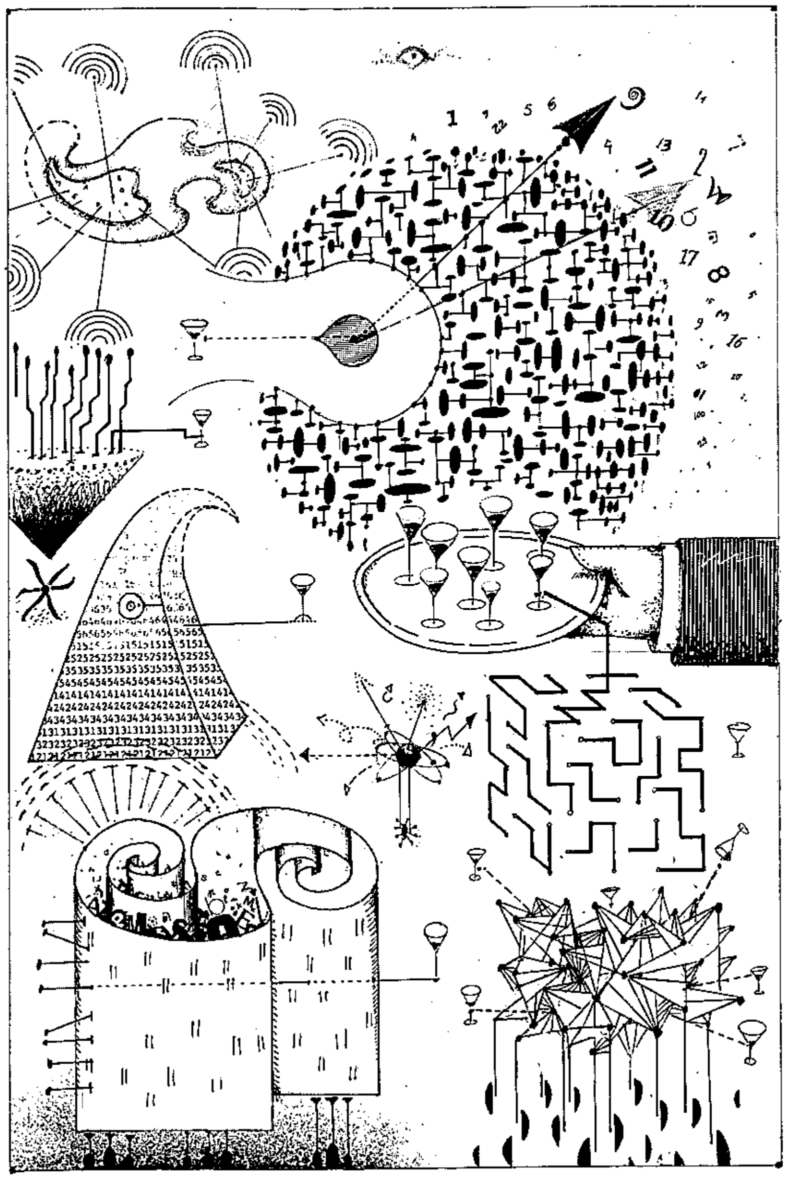

Biological Notes on the Vehicles

The preceding fantasy has roots in science. I will now sketch a few facts about animal brains that have inspired some of the properties of our vehicles, and their behavior will then seem less gratuitous than it may have seemed up to this point. I have been directly or indirectly involved in most of the research I shall mention. These notes should not be taken as a treatise on brain science but as a series of disconnected and quite personal essays.

The virtues of crossed connections (Vehicles 2, 3, and 4)

Vehicles 1 to 4, the early ancestors of the whole breed, spring from an attempt to understand that very curious basic fact of brain science, the crossed representation of the world in the (vertebrate) brain. The general principle is apparent in the projection of visual space onto the brain. A million or so fibers of the two optic nerves carrying signals from both eyes toward the brain cross each other in such a way as to represent in the left brain an image of everything to the right of the animal and vice versa in the right brain. Just how many fibers of the right eye actually see points of