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Vehicles

Experiments in Synthetic Psychology

Valentino Braitenberg

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Cambridge, Massachusetts
London, England

Foreword

Valentino Braitenberg is a cybernetician, a neuroanatomist, and a musician. He seeks to understand how the beautiful structures of the brain constitute a machine that can enable us to exhibit such skilled behavior as that involved in playing music. Since the early 1960s, I have turned to Valentino for detailed neuroanatomy and for lively essays that cut away the technical details to illuminate the key issues of what we may call cybernetics or artificial intelligence or cognitive science.

One of the most exciting of these essays had the most formidable of titles: "Taxis, Kinesis and Decussation," published in 1965. *Taxis* is the reflex-oriented movement of a freely moving organism in relation to a source of stimulation; *kinesis*, by contrast, is movement that lacks orientation but depends on the intensity of stimulation; and a *decussation* is a band of nerve fibers that connects one half of the body to the opposite half of the brain. The title was forbidding, the essay was delightful. By designing little vehicles that moved around in response to smell and vision, Braitenberg gave his readers vivid insights into how the brain might have evolved so that olfactory input goes to the same side of the brain while vision, touch, and hearing send their input to the opposite side of the brain.

Having shared this paper with friends and students over the years, I was delighted to hear from Valentino, at a workshop in 1983, that it had provided the nucleus for this book. *Vehicles: Experiments in Synthetic Psychology* is fun to read, and this fun is heightened by the incredible illustrations of Maciek Albrecht. But it is serious fun and will help many people, specialist and layman alike, gain broad insights into the ways in which intelligence evolved to guide interaction with a complex world.

Michael A. Arbib
Amherst, Massachusetts

Vehicles

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

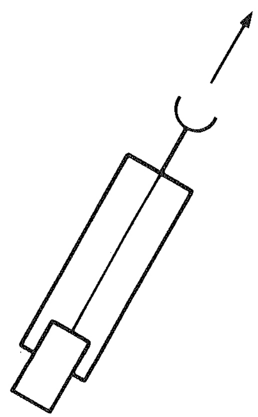

Figure 1

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

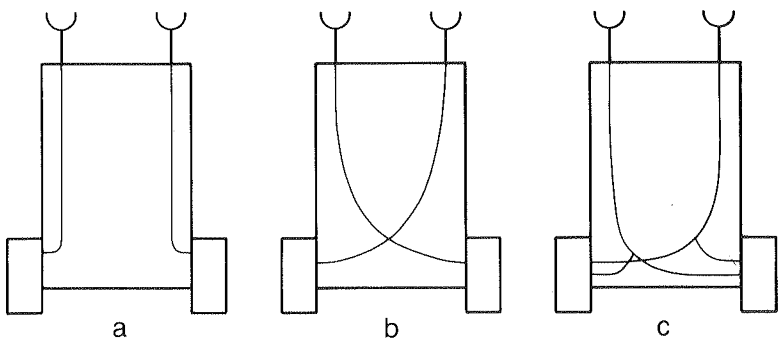

Figure 2
Vehicle 2, with two motors and two sensors; otherwise like Vehicle 1. The connections differ in a, b, and c.

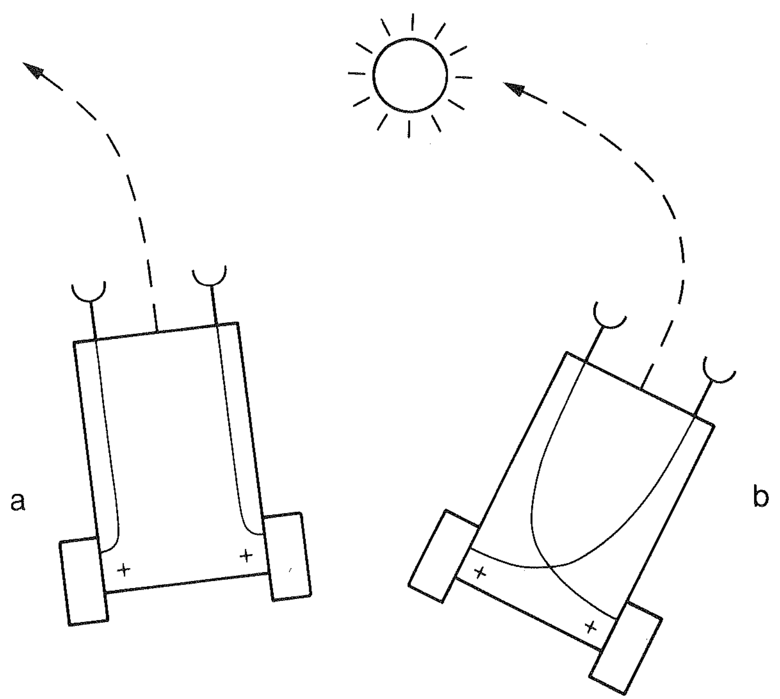

Figure 3
Vehicles 2a and 2b in the vicinity of a source (circle with rays emanating from it). Vehicle 2b orients toward the source, 2a away from it.

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

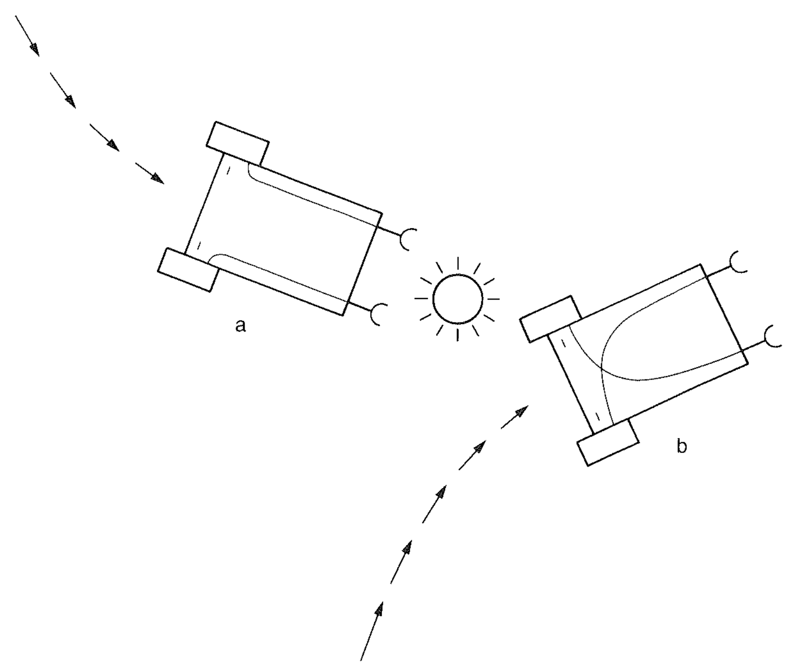

Figure 4
Vehicle 3, with inhibitory influence of the sensors on the motors.

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

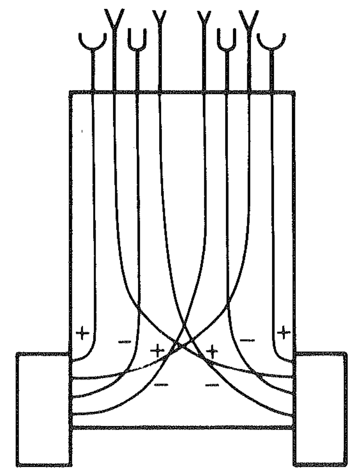

Figure 5
A multisensorial vehicle of brand 3c.

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

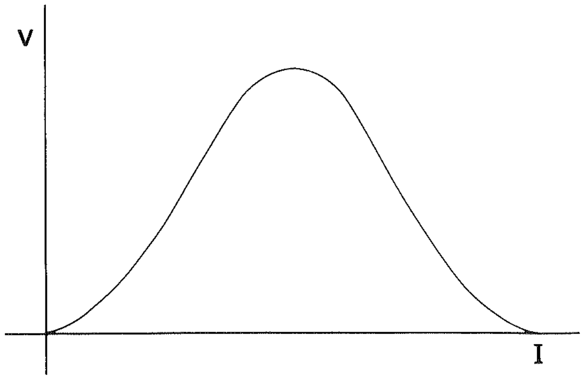

Figure 6
A nonlinear dependence of the speed of the motor V on the intensity of stimulation I, with a maximum for a certain intensity.

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-

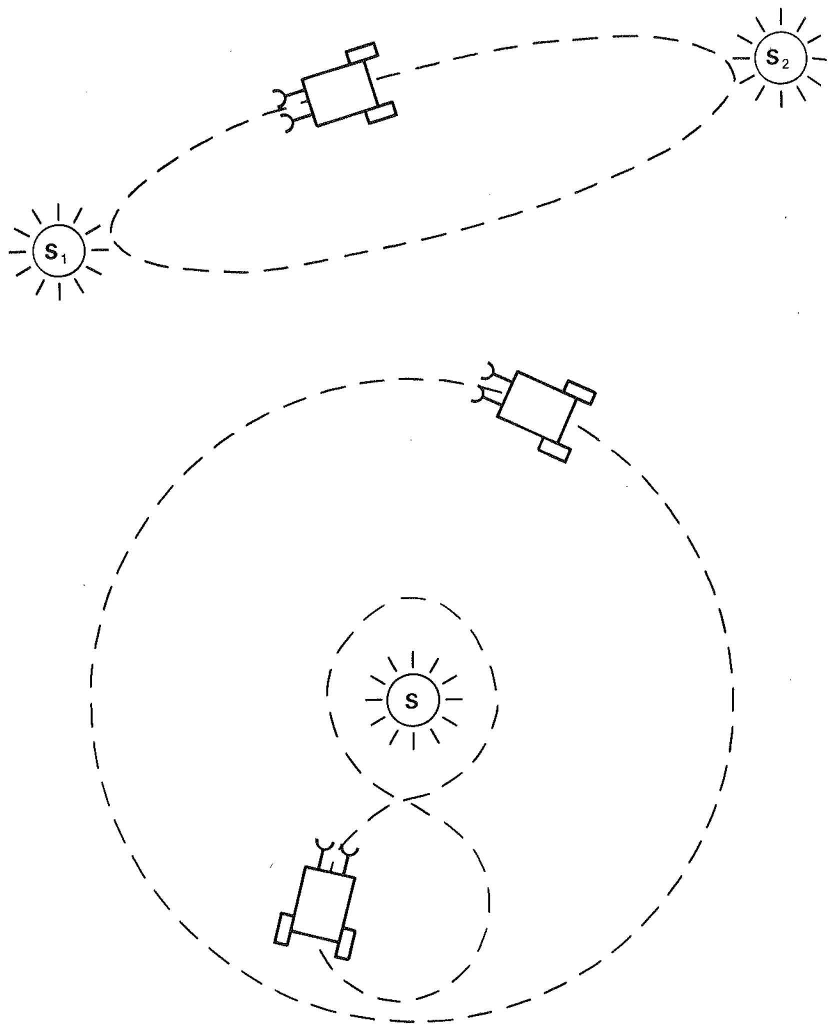

Figure 7
Trajectories of vehicles of brand 4a around or between sources.

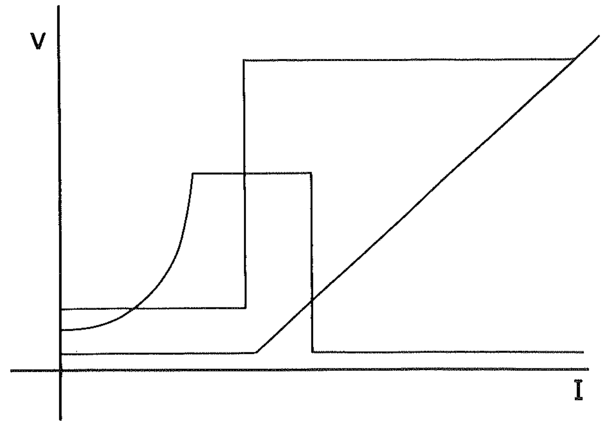

Figure 8
Various bizarre kinds of dependence of the speed of the motor (ordinate) on the intensity of stimulation (abscissa) in Vehicle 4b.

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

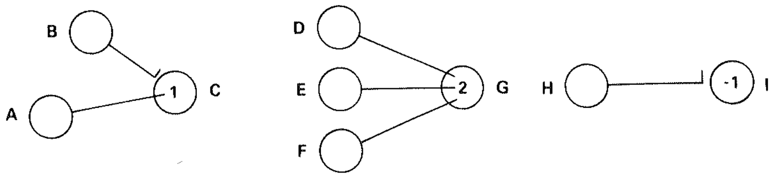

Figure 9
How threshold devices act on each other. Explanation of symbols: The circles stand for threshold devices. The L-shaped fiber between B and C stands for inhibition; the penetrating fiber from A to C means activation. Each active element contributes one unit of activation to the element (threshold 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.

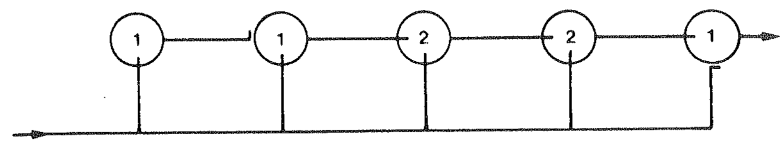

Figure 10a
A network that gives a signal when a burst of 3 pulses presents itself, preceded and followed by a pause.

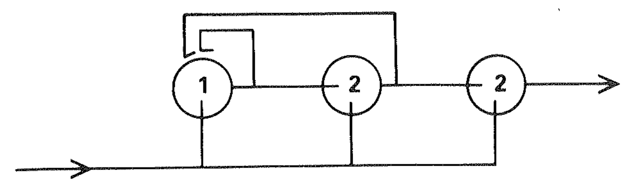

Figure 10b
A network of threshold devices that emits a pulse for every third pulse in a row in the input.

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

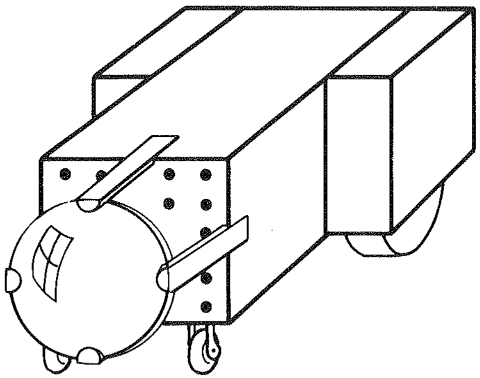

Figure 11
Vehicle 8 with a lens eye.

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

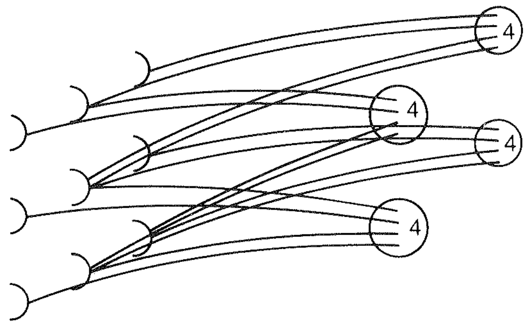

Figure 12
An object detector. Each of the threshold devices on the right responds only when four neighboring sensors arranged in a square are active together.

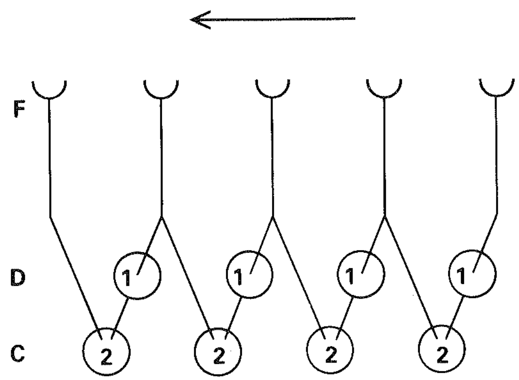

Figure 13
A set of movement detectors (C) for movement from right to left. The threshold devices C become active when they receive input directly from the sensor F to the left, and at the same time receive input indirectly, via a delay element D, from the neighboring sensor to the right.

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

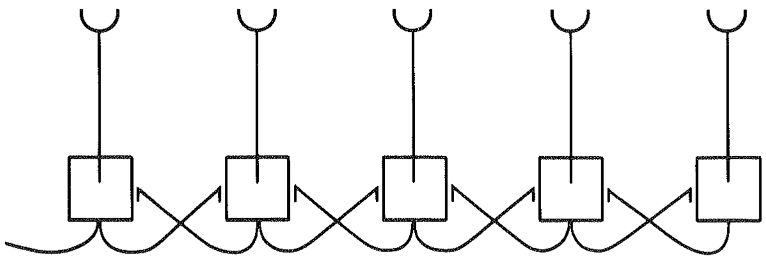

Figure 14
Five threshold devices, excited by that many sensors, each connected to its neighbors by inhibitory connections. Uniform excitation of the whole set will be subdued by the inhibitory interactions, while isolated spots of excitation will stand out.

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 present, 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

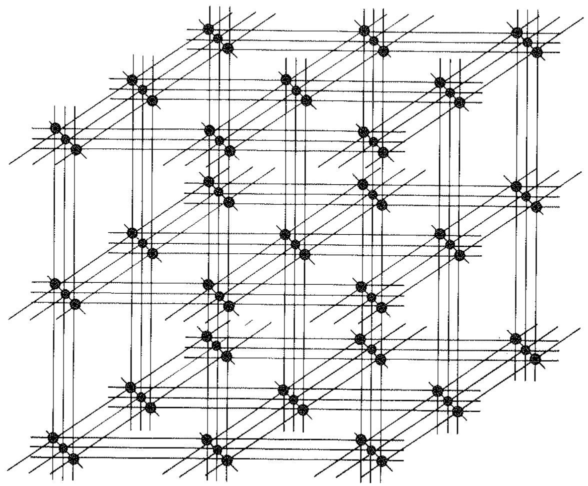

Figure 15

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.

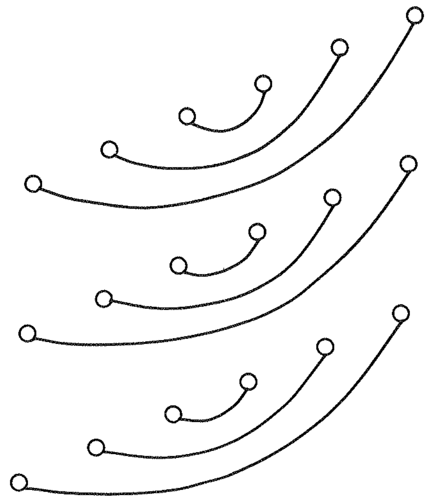

Figure 16

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

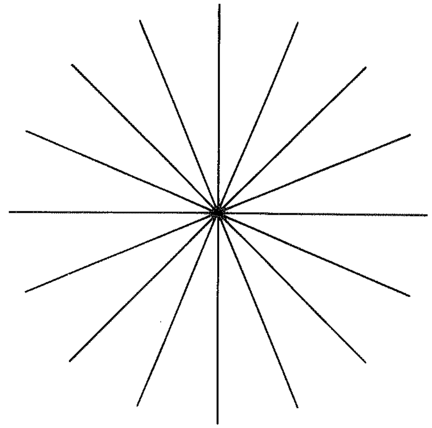

Figure 17
A pattern that is invariant to changes of scale. A vehicle approaching the center of the figure has a constant visual input (provided we make the figure large enough and the lines infinitely thin). The absence of perceived movement may be used as diagnostic for figures with radial symmetry.

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.