THE Living Brain

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Contents

CHAPTER 5

Totems, Toys and Tools

Am Ende hängen wir doch ab
Von Creaturen die wir machten.
Goethe

THE MAKING of images may have a variety of purposes, and the intention of the maker is not always clear to those who look on them. This chapter will be about mimicry of life, so it may be well to explain at the outset why a scientist resorts to methods which might seem more appropriate to the entertainer, the artist or the priest. The suspicion that the scientist is not quite sincere in professing that his purpose is purely mechanical and illustrative goes a long way back. The notion of magic is deep-rooted. A term fairly applicable to our subject, for instance, "Electro-biology," is found in Roget's Thesaurus (authorised copyright edition, 1946) listed under "Acts of Religion," in the sub-section, "Sorcery."

It all goes back to the totems of primitive man, to the images we used to make of game or enemy on the walls of the cave, to the images of their rivals into which village boys and girls still hopefully stick pins. Then the totem is set up for worship, developing perhaps into forms and images of great beauty and unchallengeable piety and found in greater or less profusion as iconoclast alternates with iconolater. There are images in the canon of all faiths, excepting that of the Semites, who discovered the unrepresentable behind their graven images and abolished them, and that of the Quakers and Christian Scientists, who never had any. We are daily reminded how readily living and even divine properties are projected into inanimate things by hopeful but bewildered men and women; and the scientist cannot escape the suspicion that his projections may be psychologically the substitutes and manifestations of his own hope and bewilderment.

There is, however, a well-defined difference between the magical and the scientific imitation of life. The former copies external appearances; the latter is concerned with performance and behaviour. Until the scientific era, what seemed most alive to people was what most *looked* like a living being. The vitality accorded to an object was a function primarily of its form. Even ships, most wilful and exacting of all contrivances, were not fully alive until they had been given a figurehead and were formally christened and blessed, the figurehead being an embodiment of the ship's soul.

Moreover, any performance by a sacred image must be magical—a Virgin with an ingenious mechanical smile would get no worship. Again, an image may be only a toy. The technical genius of the Swiss watchmakers was really wasted on their delicate clockwork automata; they arouse only a passing interest because they are neither sacred nor, like life, unpredictable, their performance being limited to a planned series of motions, be it a boy actually writing a letter or a girl playing a real keyboard instrument.

With the coming of steam, and later electricity, a new sort of automatic device became necessary, not as totem or toy but as tool, something to enable a machine to control its own effective use of the power it generates. The first steam engine, left to itself, was unstable—pressure went down when power was used and boiler blew up when it was not used. Watt introduced the safety valve and automatic governor which stabilise by themselves both boiler pressure and engine speed. These two important devices were taken rather as a matter of course by engineers, but the great Clerk Maxwell devoted a paper to the analysis of Watt's governor. Maxwell was perhaps the first to realise the significance of this key process of feedback. Later, physiologists pointed out that Watt had incidentally constructed in principle the first working model of a reflex circuit similar to what they describe in the organisation of sense organs, nerves and muscles. Self-regulating devices, so common today that their existence is taken as a matter of course by the millions who use them, are the gas oven and refrigerator thermostats and the automatic volume-control in your radio which maintains the volume of sound within certain limits.

But until the invention of the thermionic tube, any ambition to construct a true imitation of a reflex circuit, let alone follow in the footsteps of Mary Shelley and her Frankenstein, would have been a scientific vanity. Consider for a moment what a "monster" indeed would be a working model of the brain, even with the miniature tubes and other components available today.

First, some model living cells—what would be the smallest size theoretically possible? They would have to generate, accumulate, discharge and regenerate their own minute voltages. If the necessary chemical contents of one cell, with insulation, capacitance and trigger mechanism, could be crowded into a quarter of a cubic inch, it would be a miracle of construction, though still gross compared with the original. To put aside the standard number of these cells, 10,000 million, for one brain, while considering the wiring problem, warehousing space of about one and a half million cubic feet would be required.

The kind of circuit necessary to imitate the behaviour of a nerve fibre was a laboratory problem of no mean order and was only recently solved. Just consider the specification for a model nerve. It must conduct an impulse in both directions, wherever the impulse is applied; it must convey what is known as an all-or-nothing impulse, followed by a refractory period—when no impulse is carried; moreover, the travelling impulse must be self-propagating and non-decremental—that is, it must travel any distance without decreasing its volume or voltage. The difficulties of design and construction were overcome only after many experiments; a diagram of the circuit will be found in Appendix A. Supposing a sufficient number of these simplest of imitation nerves were constructed, more millions of cubic feet of warehousing would be required.

At this point we might have to consider cost. A cell with one fibre might conceivably be made for about a dime,—in all, say, $1,000,000,000. Wiring connections, 10^{20} of them, at about two cents each, say $2,000,000,000,000,000,000. Power required would be at least a million kilowatts, even if the transistor crystal were used instead of the prodigal thermionic tube; the human brain runs on 25 watts. The cost would be incalculable. And the comparable cost of producing a first-class living brain? Twenty thousand dollars?

No, nobody is going to make an artificial brain on those lines, even with the smallest and cheapest conceivable midget parts. An entirely different approach seemed necessary to make it a practical problem, if we were to learn about life by imitation as well as observation of living things.

One other possible approach to the baffling complexities of the nervous system there did seem to be. What we have just reduced to absurdity is any prospect of reproducing all its elaboration of units in a working model. If the secret of the brain's elaborate performance lies there, in the number of its units, that would be indeed the only road, and that road would be closed. But since our enquiry is above all things a question of performance, it seemed reasonable to try an approach in which the first consideration would be the principles and character of the whole apparatus in operation.

This raised a new question in brain physiology. It meant asking whether the elaboration of cerebral functions may possibly derive not so much from the number of its units, as from *the richness of their interconnection.*

As a hypothesis, this speculation had the great advantage that its validity could be tested experimentally. An imitation of two or three interconnected elements, including reflex circuits to demonstrate their behaviour, should be a simple matter for a laboratory that had produced the EEG analyser and the toposcope.

But how many elements would be needed to demonstrate this? How many elements could be managed? Here we ran into an unforeseen difficulty—that of reckoning how many ways of behaviour are possible with a given number of elements. Neither mathematicians nor communications engineers were acquainted with precisely the problem this raised.

Reduced to its simplest form the question is, How many ways of behaviour would be possible for a creature with a brain having only two cells? Behaviour would depend on the activity of one or both of these cells—call them A and B. If (1) neither is active, there would be no action to be observed; if (2) A is active, behaviour of type *a* would be observed; if (3) B is active, behaviour of type *b;* if (4) A and B are both active, but independently, there would be behaviour of both types *a* and *b,* mixed together; if (5) A is "driving" B, type *b* would be observed but subordinate to A; if (6) B is "driving" A, type *a* would be subordinate to B; if (7) A and B are "driving" each other, behaviour will alternate between type *a* and type *b.* The internal states of such a system in these seven modes may be represented symbolically as:

$$\mathrm{O, A, B, A + B, A \rightarrow B, A \leftarrow B, A \leftrightarrows B}$$

with behaviour types:

$$\mathrm{o}, a, b, a + b, b(\mathrm{fA}), a(\mathrm{fB}), ababab \ldots$$

From the above it will be seen that the first four ways of behaviour would be identifiable by simple observation, without interfering with the system, whereas the last three could only be identified by operating on the system—by, as it were, dissecting out the arrows.

Thus, with only two elements interconnecting, there are seven modes of existence. With six units there would be enough modes to provide a new experience every tenth of a second throughout a long lifetime. If there are *n* elements, the number of modes is given approximately by $M = 2^{(n^2 - n)}$ for six or more elements. So an extremely varied behaviour is possible when a modest collection of elements is capable of intricate interaction. If the reader would like to calculate how many possible modes there might be in the brain, with its ten thousand million elements, take the number 2 and double it a hundred million million million times—which is making a fantastic "monster" of the brain itself.

How many functional units, then, we may ask, must a brain contain in order to account for its behaviour, assuming the interconnection may be as complete and varied as it is usually supposed to be? As a start, we may suggest that the number of active elements may be of the order of 1,000 ensembles of homologous neurones. If these are capable of dynamic combinations and permutations according to the above equation, then the number of behaviour patterns possible would be of the order of $10^{300,000}$—that is, if written out at length, a figure so long that it would fill more than a hundred pages of this book. Even were many millions of permutations excluded as being lethal or ineffective, the number is still large enough to satisfy the requirements of individuality and plasticity.

The outlook for an experimental model brightened at once with the problem reduced to the behaviour of two or three elements. Instead of dreaming about an impossible "monster," some elementary experience of the actual working of two or three brain units might be gained by constructing a working model in those very limited but attainable proportions.

But if the performance of a model is to be demonstrably a fair imitation of cerebral activity, the conditions of stimulation and behaviour must equally be comparable with those of the brain. Not in looks, but in action, the model must resemble an animal. Therefore it must have these or some measure of these attributes: exploration, curiosity, free-will in the sense of unpredictability, goal-seeking, self-regulation, avoidance of dilemmas, foresight, memory, learning, forgetting, association of ideas, form recognition, and the elements of social accommodation. Such is life.

This rules out the charming creations of the Swiss watchmakers; in spite of the intention of the artificers, evident in the name of "automates," they are not automata in the sense of being endued with spontaneous motion, and in no sense of the word have they any claim to autonomy or self-regulation. Their performance is prescribed or, as we say today, programmed from beginning to end of the starting impulse.

Nor can variety of programming endow a machine with the autonomous qualities of a true mimicry of life. The computing machine is a model of Nineteenth Century predestination; it was devised more than a hundred years ago without a thought of imitating the living brain. The works of two mathematicians of the day, Boole and Babbage, taken together, provide all the basic theoretical and mechanical knowledge necessary for a blueprint of one of the giant machines, lacking only the thermionic tube to give it the speed of an electron instead of a piston. A third famous Victorian mathematician immortalised their manner of operation for all children, young and old: "Can you do addition?" the White Queen asked. "What's one and one and one and one and one and one and one and one and one and one?" "I don't know," said Alice. "I lost count." The algebra of Boole is the algebra of yes and no. Computers are essentially machines that do sums in that fashion but don't lose count. Babbage made one in 1822; a few years later when he was constructing a much more elaborate one for the Government he discovered a new mechanical arrangement which he called "the engine eating its own tail." The discovery no doubt made it very tedious to go on with the machine already begun, on which he had spent £6,000 of his own and £17,000 government money; in any case official support was withdrawn in 1842, and the completed fragment—"a beautiful machine which does its work with unerring accuracy but is useless," as described not long after Babbage died in 1871—ended in the South Kensington Museum. His analytical engine was never constructed. It is recorded that "in his later years he was chiefly known by his fierce hostility to organ-grinders"—envious perhaps of the persistent demonstration of their "engines" while his remained on paper, 400 detailed drawings and many volumes of notes. It was, in the modern style, to be programmed by punched cards, with special cards for particular functions; it was to calculate the numerical values of any formula or function of which the mathematician could indicate the method of solution, relieving him "of all the drudgery of computing," and was of course to print its answer. Among the wonders of constructional anticipation it is comparable with those of Hero of Alexander and Leonardo da Vinci.

The first attempt to make a machine that would imitate a living creature in performance, as distinguished from appearance, seems to have been suggested by the familiar test of animal intelligence in finding the way out of a maze. Thomas Ross in 1938 made a machine in America which successfully imitated this experiment. By trial and error it could "learn" to find its way to a correct goal on a system of toy train tracks. Another tram-like creature of the same species, *Machina labyrinthca,* to give it a mock-biological name, was also built by an American, R. A. Wallace, in 1952, "to demonstrate that a relatively small and simple digital computing machine can solve a class of conceptual problems other than numerical calculations." It also runs on minute rails, with automatic switches, or "choice points," of which it can cope with 63 and get home without programming as to the order of exploration or any assistance in summating its experience. Once it has found its way home, its choices are pre-set—it has programmed its own route and, restarted from the same point, will go direct home without error. Claude Shannon has also devised a maze-learning creature, less rail-bound, a sort of electro-mechanical mouse that fidgets its way out of confinement.

Thus, within its limits, with a predestined end and a predictable course, *M. labyrinthea* is goal-seeking and self-regulating. Like other machines, it is said to have a kind of memory. But the use of the word at this juncture is unfortunate, seeming to claim a likeness to the flesh that cannot be upheld in detail. Storage of information there certainly is, but it is as unequivocal as the information stored in a book and, being metallic, less perishable. Human memory is subtle, variable, reinforceable in strange roundabout ways, and fallible. The engineer does not imitate it and does not wish to. "Memory" in this connection had better be forgotten with "giant brains."

Another machine with a predestined end, but quite unpredictable behaviour in reaching it, is Ashby's Homeostat. This creature, *Machina sopora,* it might be called, is like a fireside cat or dog which only stirs when disturbed, and then methodically finds a comfortable position and goes to sleep again. There are a number of electronic circuits similar to the reflex arcs in the spinal cord of an animal. They are so combined with a number of thermionic tubes and relays that out of 360,000 possible connections the machine will automatically find one that leads to a condition of dynamic internal stability. That is, after several trials and errors, the instrument, without any prompting or programming, establishes connections which tend to neutralise any change that the experimenter tries to impose from outside. So far as it goes, the homeostat is a perfect example of self-regulation by negative feedback—in fact, it is all negative feedback, like a steam engine that works nothing but the safety valve and governor. A very curious and impressive fact about it, however, is that, although the machine is man-made, the experimenter cannot tell at any moment exactly what the machine's circuit is without "killing" it and dissecting out the "nervous system"—that is, switching off the current and tracing out the wires to the relays.

What we find in this fireside companion is not only the virtue of self-control and the blessing of homeostasis, not only an exemplification of placidity, but also of plasticity, one of the basic principles that seem to govern animal engineering. This means roughly that every part of the mechanism is reversible, interchangeable and expendable—but not replaceable. As a description of a system of interconnections, this is really only half true about the brain, or only true about half the substance of the brain. Overlooking this important point of internal resemblance to an animal nervous system, and judging *M. sopora* entirely by its behaviour, the naturalist would classify it as a plant. More recently Ashby has made and studied a simple machine, functionally related to *M. labyrinthea*, which adjusts its internal connections when presented with two successive stimuli. He has also begotten an heir to Homeostat—with 25 times as many elements.

We now come to an electro-mechanical creature which behaves so much like an animal that it has been known to drive a not usually timid lady upstairs to lock herself in her bedroom, an interesting blend of magic and science.

The first notion of constructing a free goal-seeking mechanism goes back to a wartime talk with the psychologist, Kenneth Craik, whose untimely death was one of the greatest losses Cambridge has suffered in years. When he was engaged on a war job for the Government, he came to get the help of our automatic analyser with some very complicated curves he had obtained, curves relating to the aiming errors of air gunners. Goal-seeking missiles were literally much in the air in those days; so, in our minds, were scanning mechanisms. Long before the home study was turned into a workshop, the two ideas, goal-seeking and scanning, had combined as the essential mechanical conception of a working model that would behave like a very simple animal. At the same time, this conception held promise of demonstrating, or at least testing the validity of, the theory that multiplicity of units is not so much responsible for the elaboration of cerebral functions, as the richness of their interconnection. With the minimum two elements there should be seven modes of existence. And there was another good reason, apart from the avoidance of unnecessary mechanical complications, for the utmost economy of design in *Machina speculatrix*, inevitable name of the species for the discerning, though "tortoise" to the profane; it would demonstrate the first of several principles exemplified in the mechanisms of most living creatures. A few notes on these principles will illustrate the behaviour of *M. speculatrix*, from the observation of which indeed much has been learned about them.

1. *Parsimony.* The Nineteenth Century raised its poetic

eyebrows at "Nature's prodigality"; the Twentieth Century is no less surprised by the economy of structure and function discovered in the mechanics of life. There are very few redundant organs in present-day animals, and many parts of the body were originally something quite different. "Mend-and-make-do" is a popular slogan in the struggle for existence. In *M. speculatrix* the number of units corresponding to nerve cells is limited to two; there are two miniature tubes, two relays, two condensers, two small electric motors, two batteries. These two "sense reflexes" operate from two "receptors" —one a photo-electric cell, which gives the organism sensitivity to light, the other an electrical contact serving as a touch receptor, which gives it responsiveness to material obstacles. The variations of behaviour patterns exhibited even with such economy of structure are complex and unpredictable.

2. *Speculation.* A typical animal propensity is to explore the environment rather than to wait passively for something to happen. This faculty gives the device its name and distinguishes it from other machines. The most elaborate computing machine does not look round for problems to solve; nor do *M. labyrinthea* and *sopora.* But *M. speculatrix* is never still except when "feeding"—that is, when the batteries are being recharged. Like the restless creatures in a drop of pond water, it bustles around in a series of swooping curves, so that in an hour it will investigate several hundred square feet of ground. In its exploration of any ordinary room it inevitably encounters many obstacles; but, apart from stairs and fur rugs, there are few situations from which it cannot extricate itself.

3. *Positive tropism.* Sensory susceptibility to the attrac-

tions of the environment. The one positive tropism of *M. speculatrix* is exhibited by its movement towards lights of moderate intensity. The photo-cell, amplifier and motors are connected in such a way that, when an adequate light signal is received, the exploratory behaviour is checked and the organism orientates itself towards the light and approaches it. Until it "sees" a light, the photo-receptor is in continuous rotation, scanning the horizon for light signals. This scanning process is linked with the steering mechanism in such a way that the "eye" is always looking in the direction of movement; thus, when a signal is received, from any direction, the machine is in a position to respond without too much manoeuvring.

4. *Negative tropism.* Certain perceptible variables, such as very bright lights, material obstacles and steep gradients, are repellent to *M. speculatrix;* in other words, it shows negative tropism towards these stimuli. Observing the principle of parsimony, this is accomplished without introduction of additional components, by making any slight displacement of the organism's shell close a contact which converts the photo amplifier into an oscillator; this causes alternating movements of butting and withdrawal; so that the robot pushes small obstacles out of the way, goes round heavy ones, and avoids slopes. This device automatically introduces the next important principle.

5. *Discernment.* Distinction between effective and ineffective behaviour. When the machine is moving towards an attractive light and meets an obstacle, or finds the way too steep, the induction of internal oscillation does not merely provide a means of escape—it also eliminates the attractiveness of the light, which has no interest for the machine until

after the obstacle has been dealt with. There is a brief "memory" of the obstacle, so that the search for lights, and attraction to them when found, is not resumed for a second or so after a material conflict.

6. *Optima.* A tendency to seek conditions with moderate and most favourable properties, rather than maxima. The circuit of *M. speculatrix* (shown in Appendix B) is so adjusted that exploration is undertaken in darkness and moderate lights are attractive, whereas bright lights are repulsive. Thus the machine can avoid the fate of the moth in the candle. Also, with the scanning device, it can avoid the dilemma of Dante's free man, *intra due cibi,* or of Buridan's ass, which starved to death, as some animals acting tropistically in fact do, because two exactly equal piles of hay were precisely the same distance away. If placed equidistant from two equal lights, *M. speculatrix* will not aim itself half-way between them, but will visit first one and then the other.

7. *Self-recognition.* The machines are fitted with a small flash-lamp bulb in the head which is turned off automatically whenever the photo-cell receives an adequate light signal. When a mirror or white surface is encountered the reflected light from the head-lamp is sufficient to operate the circuit controlling the robot's response to light, so that the machine makes for its own reflection; but as it does so, the light is extinguished, which means that the stimulus is cut off—but removal of the stimulus restores the light, which is again seen as a stimulus, and so on. The creature therefore lingers before a mirror, flickering, twittering and jigging like a clumsy Narcissus. The behaviour of a creature thus engaged with it own reflection is quite specific, and on a purely empirical basis, if it were observed in an animal, might be accepted as evidence

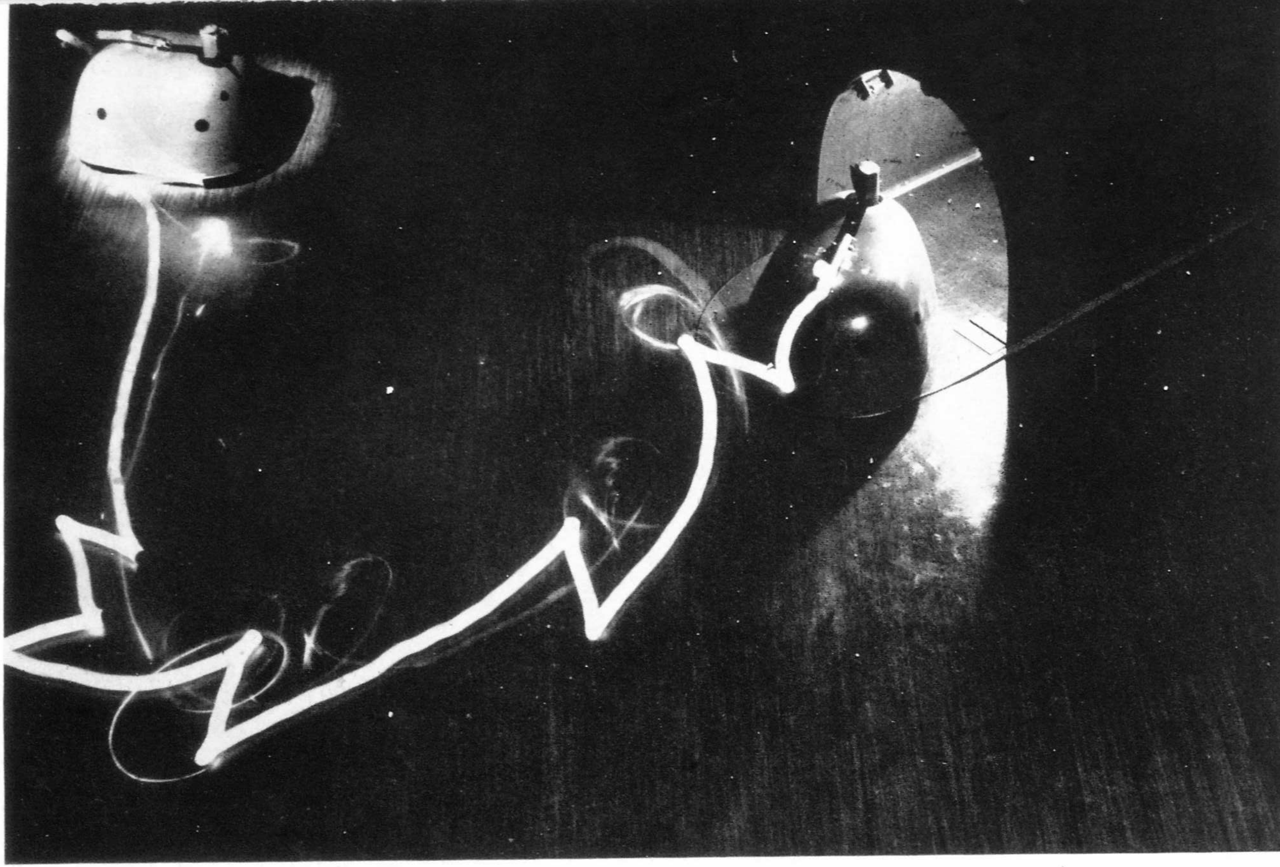

Figure 11. ". . . moderation gives place to appetite." *Speculatrix* finds her way home.

of some degree of self-awareness. In this way the machine is superior to many quite "high" animals who usually treat their reflection as if it were another animal, if they accept it at all. This leads on to:

8. *Mutual recognition.* Two creatures of the same type, attracted by one another's light, both extinguish the source of attraction in themselves in the act of seeking it in others. Therefore, when no other attraction is presented, a number of the machines cannot escape from one another; but nor can they ever consummate their "desire," and when seen from the back or side a fellow creature is merely an obstacle. In a sense, then, a population of machines forms a sort of community, with a special code of behaviour. When an external stimulus is applied to all members of such a community, they will of course see it independently and the community will break up; then, the more individuals there are, the smaller the chance of any one achieving its goal, for each individual finds in the others converging obstacles.

9. *Internal stability.* One of the advantages of making a moderate light a positive stimulus is that this can be used as a sign or symbol for the energy which the creatures require for their sustenance—electricity. A light is placed in their "hutch" is such a position that they are attracted to it, and therefore tend to enter the hutch of their own accord. However, if their batteries are fully charged, the intensity of the light operates the repelling circuit when over the threshold, and they withdraw for further exploration. When their batteries *require* recharging, on the other hand, moderation gives place to appetite and the light continues to exert an attraction until they are well within their quarters. (See Figure 11.) At this point, contacts on the side of the shell

can engage with others in the hutch, thus closing the battery-charging circuit. Current flowing in this circuit operates a relay which turns off the power to their sensory and motor systems, so that the machine remains motionless until, the battery voltage having risen, the charging current falls and their internal mechanism is once again energised. This arrangement is very far from perfect; there is no doubt that, if left to themselves, a majority of the creatures would perish by the wayside, their supplies of energy exhausted in the search for significant illumination or in conflict with immovable obstacles or insatiable fellow creatures.

Some of these patterns of performance were calculable, though only as types of behaviour, in advance; some were quite unforeseen. The faculties of self-recognition and mutual recognition were obtained accidentally, since the pilot-light was inserted originally simply to indicate when the steering-servo was in operation. It may be objected that they are only "tricks," but the behaviour in these modes is such that, were the models real animals, a biologist could quite legitimately claim it as evidence of true recognition of self and of others as a class. The important feature of the effect is the establishment of a feedback loop in which the environment is a component. This again illustrates an important general principle in the study of animal behaviour—that any psychological or ecological situation in which such a reflexive mechanism exists, may result in behaviour which will seem, at least, to suggest self-consciousness or social consciousness.

The way in which the social behaviour of the models breaks down under the influence of a competitive struggle for a common goal, imitates almost embarrassingly some of the less attractive features of animal and human society. That is the fault of the maker, who could, however, easily endow his creatures, as man is endowed, with a discriminatory recognition circuit that would function in an emergency, a "women-and-children-first" reflex.

Further, it would only be a matter of patience and ingenuity to endow *M. Speculatrix* with other "senses" besides sight and touch, to enable it to respond to audible signals audibly, and so forth; also to provide it with hands—with a different tool for each finger, dream of our electronic childhood! For the time being we have removed, and shall presently be describing as characteristic of a separate species, *M. docilis*, that part of the brain with which it could learn how to use any tools put into those hands. There is no serious difficulty about the elaboration of function, once the principles of mechanical "life" have been demonstrated in a working model. If the principles are preserved, no matter how elaborate the functions of the machine, its mimicry of life will be valid and illuminating. On the other hand, if the principles are abandoned in favour of programming the machine for special purposes, as Wiener foresees, the result may be productive, the machine may entirely supplant human labour in the factory, but it will be of little interest to the physiologist. It will no longer be part of a mirror for the brain.

The character of *M. speculatrix* as the prototype of an electro-mechanical species, however, is not dependent on the possibilities of elaboration, but contrariwise on the impossibility of any simplification of the functional mechanism. Little virtue or interest would lie in achieving lifelike effects with a multiplication of mechanisms greater than life would tolerate. Creatures with superfluous organs do not survive; the true measure of reality is a minimum. Occam's razor is as sharp in the struggle for existence as it is in wordy strife.

This law can be seen at work in the progeny of *M. speculatrix:* the sports and unadaptable mutations fade away, the successful imitations already form more than one sub-species. Most interesting among these is an acknowledged offspring reported last year by a brilliant young American engineer, Edmund C. Berkeley. It is, not inappropriately, a squirrel compared with the British tortoise; "a squirrel gathering nuts" was the specification; meanwhile it is practising on golf balls with its ingenious scoops. It would not in any case live on nuts, even if it could gather them; it subsists on the same fare as its prototype, on the design of which also its essential mechanisms are based. Its creator calls it Squee; in the annals of mock-biology it is likely to be remembered as *M. speculatrix berkeleyi.*

The educated laboratory mascot, *M. docilis,* the "easily taught" machine, will presently be found worthy of separate attention. But the untutored ones are not to be despised. As toys they refresh the spirit of the laboratory children we all are, leading us to familiarity with more and more elaborate mechanisms. As tools they are trustworthy instruments of exploration and frequent unexpected enlightenment. As totems they foster reverence for the life they have so laboriously been made to mime in such very humble fashion—and still would foster it even should they, creatures of "sorcery" peering into the dim "electro-biological" future in search of a *deus ex machina,* look up at us and declare that God is a physiologist.