4 *Cybernetics*

The American mathematician Norbert Wiener first gave common use to the word 'cybernetics' (from the Greek word for 'steersman', 'kubernetes'), to describe that branch of study which is concerned with self-regulating systems of communication and control in living organisms and machines. The derivation seems apt, since the primary function of many cybernetic systems is to steer an optimum course through changing conditions towards a predetermined goal.

We know from long experience that stable objects are those with broad bases and with most of their mass centred low, yet we seldom marvel at our own remarkable ability to stand upright, supported only by our jointed legs and narrow feet. To stay erect even when pushed, or when the surface beneath us moves, as on a ship or a bus; to be able to walk or run over rough ground without falling; to keep cool when it is hot or vice versa, are examples of cybernetic processes and of properties exclusive to living things and to highly automated machines.

We stand upright—after a little practice—on a ship that rolls because we possess an array of sensory nerve cells buried in our muscles, skin, and joints. The function of these sensors is to provide a constant flow of information to the brain about the movements and location in space of the various parts of our bodies, as well as the environmental forces currently acting on them. We also have a pair of balance organs associated with our ears which work like spirit-levels, each having a bubble moving in a fluid medium to record any change in the position of the head; and we have our eyes to scan the horizon and tell, us how we stand in relation to it. All this flow of information is processed by the brain, usually at an unconscious level, and is immediately compared with our consciously intended stance at the time. If we have decided to stand level in spite of the ship's motion, perhaps to look at the receding harbour through binoculars, this chosen posture is the reference point used by the brain to compare with departures from it caused by the rolling of the vessel. Thus our sense organs continually inform the brain about our stance, and counter-instructions pass constantly from the brain down the motor nerves to the muscles. As we tip from the vertical, the push-and-pull of these muscles changes, so as continuously to maintain the upright position.

This process of comparing wish with actuality, of sensing error and then correcting it by the precise application of an opposing force enables us to stand erect. Walking or balancing on one leg is more difficult and takes longer to learn; riding a bicycle is even trickier, but this also can become second nature through the same active control process which keeps us upright.

It is worth emphasizing the subtle mechanisms involved in simply standing in one place. If, for instance, when the deck beneath us tilts slightly, the correcting force applied by our muscles is too great, we shall be driven too far the other way; over-anxious compensation might then swing us suddenly in the original direction of the tilt, setting up an oscillation which could topple us or at the least frustrate our wish to stay upright. Such instabilities or oscillations in cybernetic systems are all too common. There is a pathological condition known as 'intention tremor'. With this the unfortunate sufferer who tries to pickup a pencil overreaches his target, over-compensates and swings too far the other way, oscillating back and forth in the frustrating failure to achieve a simple aim. It is not enough merely to oppose a force which is pushing us away from our goal; we must, smoothly, precisely, and continuously, match the power of the opposition if we are to keep to our purpose.

What, you may be wondering, has all this to do with Gaia? Possibly a great deal. One of the most characteristic properties of all living organisms, from the smallest to the largest, is their capacity to develop, operate, and maintain systems which set a goal and then strive to achieve it through the cybernetic process of trial and error. The discovery of such a system, operating on a global scale and having as its goal the establishment and maintenance of optimum physical and chemical conditions for life, would surely provide us with convincing evidence of Gaia's existence.

Cybernetic systems employ a circular logic which may be unfamiliar and alien to those of us who have been accustomed to think in terms of the traditional linear logic of cause and effect. So let us start by considering some simple engineering systems which employ cybernetics to maintain a chosen state. Take temperature control, for example. Most homes now possess a cooking oven, an electric iron, and a heating system for the house. In each of these devices the goal is to maintain the desired and appropriate temperature. The iron must be hot enough to smooth without scorching; the oven to cook rather than burn or undercook; and the heating system is required to keep the house comfortably warm and neither too hot nor too cold. Let us examine the oven more closely. It consists of a box, designed to conserve heat without losing it too fast to the kitchen, a control panel, and heating elements which convert the electrical power supply into heat within the oven. Inside the oven there is a special kind of thermometer called a thermostat. This device does not need to show the temperature visually, like an ordinary room thermometer. It is arranged instead to operate a switch when the desired temperature is reached. This chosen temperature is set and indicated by a dial on the control panel, which is linked directly with the thermostat. An essential and perhaps surprising feature of a well-designed oven is that it must be capable of reaching temperatures far higher than will ever be needed in cooking: otherwise, the time taken to reach the desired level of heat would be far too long. If, for example, the dial is set at 300 degrees and the oven is turned on, the elements will be supplied with full power and will often glow red-hot, rapidly flooding the box interior with heat. The temperature rises fast until the thermostat recognizes that the set level of 300 degrees has been reached. The power supply is then switched off, but the inside temperature continues to rise for a short while, as heat flows from the red-hot elements. As they cool, the temperature drops, and when the thermostat senses that it has fallen below 300 degrees the power is switched on again. There is a brief period of further cooling while the heaters warm and then the cycle recommences. The oven temperature thus swings a few degrees above and below the desired level. This small margin of error in temperature control is a characteristic feature of cybernetic systems. Like living things, they seek or approach perfection but never quite make it.

Now what is so special about this arrangement? Grandmother was surely able to cook magnificient meals without using a newfangled oven equipped with a thermostat. But was she? True, in grandmother's day the oven was heated by burning wood or coal and so arranged that if all went well just enough heat from the fire reached the oven to keep it at the right temperature. Yet on its own such an oven could never cook properly; it would either burn the cakes or leave them sad and stodgy. Its efficiency depended entirely on grandmother herself functioning as the thermostat. She learned to read the oven's signs and recognize when the desired temperature was reached; she knew that it was then time to damp down the fire. At intervals she would check that the food was cooking satisfactorily, judging by sound and smell as well as sight and feel. Today, an engineer could design an oven just as good with a robot grandmother to sit in the kitchen and watch it, sensing its temperature and remotely controlling the electricity supply.

Anyone who tries to cook by an oven lacking either human or mechanical supervision soon finds that the results are far from satisfactory. To maintain the required temperature for, say, an hour, it is essential that the input of heat compensates exactly for any heat losses from the oven. A cold draught from outside, a change in the electricity supply voltage or gas pressure, the size of the meal to be cooked, and whether or not other parts of the stove are in use, are all factors which could frustrate our desire to attain the right working temperature for the right length of time.

The attainment of any skill, whether it be in cooking, painting, writing, talking, or playing tennis, is all a matter of cybernetics. We aim at doing our best and making as few mistakes as possible; we compare our efforts with this goal and learn by experience; and we polish and refine our performance by constant endeavour until we are satisfied that we are as near to optimum achievement as we can ever reach. This process is well called learning by trial and error.

It is interesting to recall that well into the nineteen-thirties men and women were using cybernetic techniques throughout their lives without conscious recognition. Engineers and scientists were applying them to the design of intricate instruments and mechanical devices. Yet nearly all these activities were performed without a formal understanding or logical definition of what was involved. It was rather like Monsieur Jourdain, Moliere's would-be gentleman, who had never realized that what he spoke was prose. The over-long delay in the understanding of cybernetics is perhaps another unhappy consequence of our inheritance of classical thought processes. In cybernetics, cause and effect no longer apply; it is impossible to tell which comes first, and indeed the question has no relevance. The Greek philosophers abhorred a circular argument as firmly as they believed that nature abhorred a vacuum. Their rejection of circular arguments, the key to understanding cybernetics, was as erroneous as their assumption that the universe was filled with the air we breathe.

Think again about our temperature-controlled oven. Is it the supply of power that keeps it at the right temperature? Is it the thermostat, or the switch that the thermostat controls? Or is it the goal we established when we turned the dial to the required cooking temperature? Even with this very primitive control system, little or no insight into its mode of action or performance can come from analysis, by separating its component parts and considering each in turn, which is the essence of thinking logically in terms of cause and effect. The key to understanding cybernetic systems is that, like life itself, they are always more than the mere assembly of constituent parts. They can only be considered and understood as operating systems. A switched off or dismantled oven reveals no more of its potential performance than does a corpse of the person it once was.

The Earth spins before an uncontrolled radiant heater, the sun, whose output is by no means constant. Yet right from the beginning of life, around three and a half aeons ago, the Earth's mean surface temperature has never varied by more than a few degrees from its current levels. It has never been too hot or too cold for life to survive on our planet, in spite of drastic changes in the composition of the early atmosphere and variations in the sun's output of energy.

In chapter 2 I discussed the possibility that the Earth's surface temperature is actively maintained comfortable for the complex entity which is Gaia, and has been so maintained for most of her existence. What parts of herself, I wonder, does she use as the thermostat? It is unlikely that a single simple control mechanism for planetary temperature would be subtle enough to serve her purpose. Moreover, three and a half aeons of experience and of research and development have no doubt given time and opportunity for the evolution of a highly sophisticated and comprehensive control system. We shall have some notion of the subtleties we need to look for and may expect to find during the disentanglement of Gaia's mechanism for temperature regulation if we consider how the temperature of our own bodies is regulated for us.

The clinical thermometer still provides the physician with evidence for or against a suspected invasion by foreign microorganisms, and the pattern of variations in the rise and fall of the patient's temperature which it reveals gives him useful information as to the identity of the invaders. In fact, it has been so invaluable as a diagnostic aid that some diseases, such as undulant fever, are named after their characteristic temperature patterns. Yet to nearly all physicians, even today, the processes by which the body controls its temperature are as mysterious as they are to their patients. It is only in recent years that some physiologists, showing great courage and mental stamina, have given up their work in medicine to retrain as systems engineers. From this new beginning has come partial understanding of the wonderfully co-ordinated process of body temperature regulation.

Our temperature in health is not maintained at a constant value, that mythical normal level of 98.4° F (37°C); it varies according to the needs of the moment. If we are obliged to run or exercise continuously, it will rise by several degrees, well into the fever area. In the early hours or when we starve it may fall as far below 'normal'. Moreover, this relatively constant value of 98.4° F only applies to our core region, which covers the trunk and the head, wherein lie most of the important administrative systems of the body. Our skin, hands, and feet have to endure a greater range of temperature, and are designed to function even when near to freezing with no more than a shiver of complaint.

T. H. Benzinger and his colleagues extended the horizon with their discovery that body temperature is adjusted by a consensus

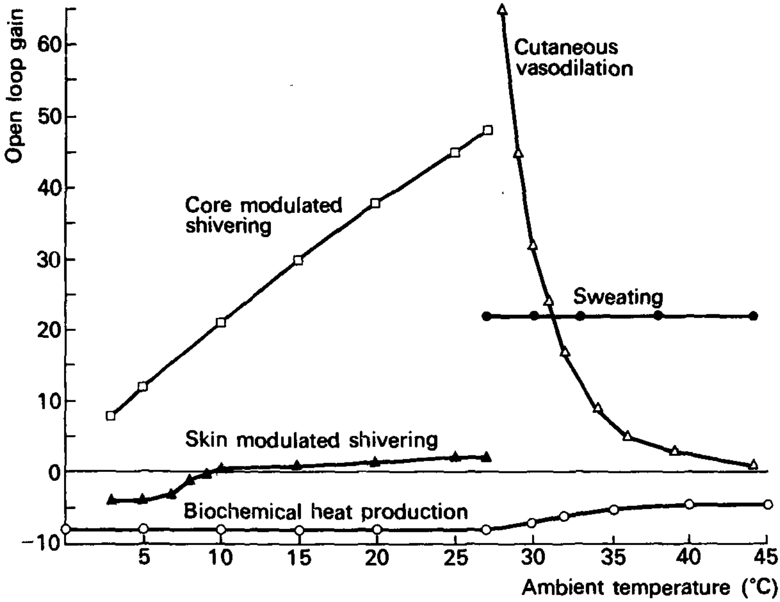

Fig. 3. An engineer's diagram illustrating the power of the five processes of human temperature regulation to function when a naked man is exposed to different environmental temperatures.

decision arrived at by the brain in consultation with other parts of the body as to the most suitable temperature for the occasion. The reference is not so much to temperature scale, but to the efficiency range of the different organs of the body in relation to body temperature. What is sought and agreed is right for the occasion rather than optimum temperature *per se.*

It has long been suspected that shivering indicates more than just the misery of exposure to cold. It is in fact a means of generating heat by increasing the rate of muscular activity and so burning more body fuel. Similarly sweating is a means of cooling the body, since the evaporation of even a small amount of water disperses with it a considerable amount of heat. The remarkable discovery, hiding its light under a bushel of commonplace scientific observations on sweating, shivering, and related processes, was that a quantitative assessment of these activities provided a complete and convincing explanation of body temperature regulation. Our ability to sweat or shiver, to burn food or fat, and to control the rate of blood flow to our skin and limbs is all part of a co-operative system for the regulation of our core temperature over an environmental range from freezing to 105° F (40.5°C).

Different animals use each of these regulating processes to a different extent. The dog uses its tongue as the main area for evaporative cooling, as anyone who has seen the winner of a greyhound derby in closeup on television immediately after the event will readily confirm. In addition, human and other animals intentionally seek a warmer or cooler environment, as the case may be, in their ceaseless

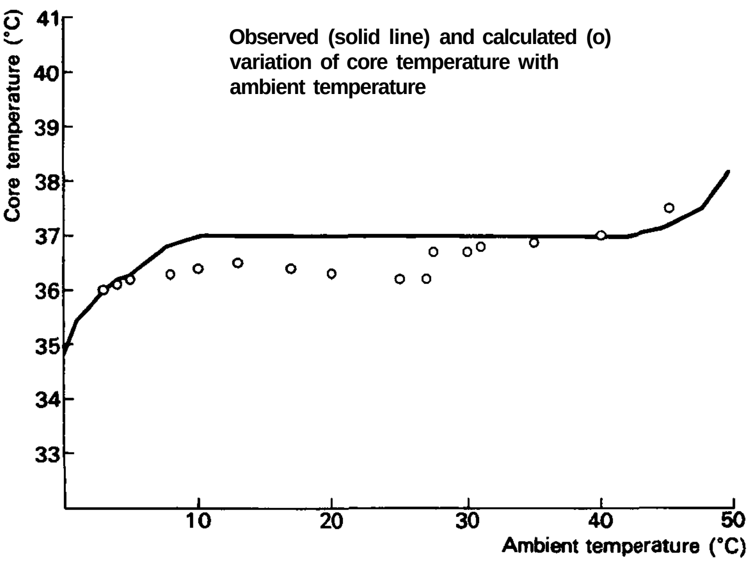

Fig. 4. A comparison between the temperature sustained in the core of a real man (shown as the solid line) with the temperature calculated from the information in Figure 3 (shown as dots). We see that it is possible accurately to account for human temperature regulation by a consensus among the responses of the five separate systems.

pursuit of the goal of maximum comfort. If necessary, the local environment is modified to reduce exposure to bearable limits. We wear clothes and build houses; other animals grow fur or seek and make burrows. These activities constitute an additional mechanism of temperature control, which is vital when conditions pass beyond the capacity of internal regulation.

Let us turn for a moment to the philosophical aspect of the subject and consider the problem of pain and discomfort. Some of us are so conditioned to regard unendurable heat, cold, or pain of any kind as in some measure a punishment or visitation from on high for sins of omission or commission that we are inclined to forget that these sensations are all essential components of our survival kit. If shivering and cold were not unpleasant we would not be discussing them, since our remote ancestors would have died of hypothermia. If it seems that such a comment is trite, it is worth considering that C. S. Lewis found it sufficiently serious to be the subject of his book *The Problem of Pain.* It is usual to regard pain as a punishment rather than as a normal physiological phenomenon.

The distinguished American physiologist Walter B. Cannon has said: 'The co-ordinated physiological processes which maintain most of the steady states in the organism are so complex and so peculiar to living things, involving, as they may, the brain and the nerves, the heart, lungs, kidneys and spleen, all working together co-operatively, that I have suggested a special designation for these states, homeostasis.' We shall do well to bear these words in mind when seeking to discover whether there is indeed a process for regulating the planetary temperature, and to look for the exploitation by Gaia of a set of temperature control mechanisms, rather than some simple single means of regulation.

Biological systems are inherently complex, but it is now possible to understand and interpret them in terms of present-day engineering cybernetics, which has advanced far beyond the theory behind the still primitive engineering contrivances used for domestic temperature regulation. Perhaps, in response to our need to conserve energy, we shall eventually devise engineering systems as subtle and flexible as their biological counterparts. The home heat controller may learn to restrict its output to that section of the house where people happen to be, switching parts of itself on and off without human intervention.

To come back to Gaia, how do we recognize an automatic control system when we encounter one? Do we look for the power supply, the regulatory device, or for some complex set of contrivances? As already pointed out, analysis of its parts is usually of little help in showing how a cybernetic system works; unless we know what to look for, recognition of automatic systems by using analytical methods is likely to be just as unsuccessful, whether the system is on a domestic or global scale.

Even though we may find evidence for a Gaian system of temperature regulation, the disentangling of its constituent loops is unlikely to be easy if they are entwined as deeply as in the bodily regulation of temperature. Just as important for Gaia and for all living systems is the regulation of chemical composition. Salinity control, for example, may be a key Gaian regulatory function. If its details are as intricate and complex as those of that amazing organ the kidney, then our quest will be a long one. We now know that the kidney, like the brain, is an information processing organ. To achieve its aim of regulating the salinity of our blood, it purposefully segregates individual atoms. In every second it recognizes and selects or rejects countless billions of atomic ions. This recent new knowledge was not easily found and it may be even more difficult to unravel a system for the global regulation of salinity and chemostasis.

Even a simple control system such as an oven can achieve its purpose in a variety of ways. Imagine an intelligent alien with absolutely no experience of our technology during its last two hundred years of development. He would soon learn to use and recognize a gas oven, but what would he make of one in which food was heated by microwaves?

There is a general approach used by cyberneticians for the recognition of control systems. It is called the black box method, and derives from the teaching of electrical engineering. A student is asked to describe the function of a black box, from which a few wires protrude, without opening the box. He is allowed only to connect instruments or power supplies to the wires and he must then deduce from his observations just what the box is all about.

In cybernetics the black box, or its equivalent, is assumed to be functioning normally. If it is like an oven, it is switched on and cooking. If a living creature, it is alive and conscious. We then test it by changing some property of the environment which we suspect can be controlled by the system we are looking at. If, for example, we are studying human systems and have a co-operative subject, we can take the floor through various angles and at varying rates of speed to discover how well he can stand upright when this fundamental part of his environment is undergoing change. From a simple experiment of this kind we could learn a great deal about the subject's capacity to control his balance. Similarly, with the oven, we could try varying the environmental temperature by using it first in a cold store and then in a hot chamber. We could then observe the limits of external variation consistent with the oven's ability to hold its internal temperature constant. We might also observe the change in power requirements during these environmental transpositions.

This approach to an understanding of control systems, by perturbations of the properties which they are believed to be able to control, is obviously a general one. It can and should always be a gentle one, which if properly conducted in no way impairs the performance or capacity of the system being investigated. The development of this perturbation approach has been somewhat like the evolution of our approach to the study of other living creatures. Not long ago we would kill and dissect them *in situ*. Later, it was recognized that it was better to bring them back alive and look at them in zoos. Nowadays we prefer to watch and observe them in their natural habitats. This more enlightened approach is, alas, not yet general. It may be used in environmental research but in agriculture all too frequently we may leave the animals alone but destroy their habitats, not as a planned perturbation but simply to satisfy our own real or imaginary needs. Many are revolted by the bloody consequences of the hunter's gun or the foxhound's teeth; yet these otherwise sensitive and compassionate people often show little or no concern over the piecemeal death and dispossession wrought by the bulldozer, the plough, and the flame-thrower, in destroying the habitats of our partners in Gaia.

So normal among us all is the acceptance of genocide whilst rejecting murder, the straining at gnats while swallowing camels, that we may well ask ourselves whether this double standard of behaviour is, as altruism is said to be, paradoxically an evolved characteristic favouring the survival of our own kind.

Thus far we have considered cybernetics and control theory only in very general terms. It is beyond the scope of this book to express the cybernetic concepts in the true language of science, mathematics, from which alone can come a complete and quantitative understanding; but we can and must go a little more deeply into this branch of science, which most effectively describes the complex activity of all living things.

Engineers might well be called applied cyberneticians. They use mathematical notation to convey their ideas, together with a few key words and phrases which serve to label the more important concepts of control theory. These descriptive terms are down-to-earth and succinct, and since there is as yet no better way of conveying their meaning in words, we shall now attempt to define them. So let us re-examine our electric oven from an engineer's viewpoint, since the working description provides a convenient and natural context for explaining such cybernetic terms as 'negative feedback'. We have a box made of steel and glass and surrounded by a packing of glass wool or similar material, which serves as a blanket to prevent heat escaping too rapidly and also ensures that the outer surface of the oven is not too hot to touch. Inside, lining the oven walls, are electric heaters. The oven also contains a suitably sited thermostatic device. In the simple oven described earlier, this was a crude affair, no more than a switch designedto turn off the electricity as soon as the desired temperature was reached. The oven we are now studying is a better model, designed for laboratory rather than kitchen use. Instead of an off-and-on switch to control temperature, it has a temperature sensor. This device produces a signal which is proportional to the oven temperature. The signal is in fact an electric current strong enough to activate a temperature gauge, but far too weak to have any heating effect on the oven. In essence it is a device which conveys information rather than power.

The weak signal from this temperature sensor is led to a device which amplifies in much the same way as the amplifier of a radio or television receiver, until it is an electric current powerful enough to heat the oven. The amplifier does not generate electricity; it merely draws on the supply and subtracts a fractional amount from the total requirement to cover its own running costs. Since the signal from the temperature sensor increases in direct proportion to the oven temperature, it cannot be connected directly to the amplifier. If it were, we would have assembled not a temperature-controlled oven but the elements of a cybernetic disaster, and an example of what engineers call 'positive feedback'. As the temperature of the oven rose, the power supplied to the heating elements would increase all the more. A vicious circle would be established and the oven temperature would rise ever more swiftly until the interior became a miniature inferno, or until some cut-out device such as the fuse in the electricity supply broke the circuit.

The correct way in which to join the temperature sensor to the amplifier or, as the engineers would say, 'close the loop', is so that the greater the signal from the temperature sensor, the less the power from the amplifier. This form of connection or loop-closing is called 'negative feedback'. In the oven which we are considering, positive and negative feedback are determined by no more than the order of the two wires from the temperature sensor.

The rapid build-up to disaster in positive feedback, or the precision of temperature control in negative feedback, depends on a property of the amplifier called 'gain'. This is the number of times the weak signal from the sensor is multiplied so as either to enhance or oppose the energy flowing to the heater. Where several loops coexist, each has its own amplifier whose capacity is called the 'loop gain'. In many complicated systems like our own bodies, positive and negative feedback loops coexist. It is obviously helpful to use positive feedback at times, perhaps to restore normal temperature rapidly after a sudden chilling, before negative feedback resumes control.

Grandmother's oven, the kitchen range, where no temperature sensor existed when she was out of the kitchen, is called an 'open loop' device. It would be true to say that the greater part of our search for Gaia is concerned with discovering whether a property of the Earth such as its surface temperature is determined by chance in the open loop fashion, or whether Gaia exists to apply negative and positive feedback with a controlling hand.

It is important to recognize that what is fed back by a sensor is information. This may be transmitted by an electric current, as with our oven, which passes information by varying the strength of its signal. It could equally well be any other information channel, such as speech itself. If, when a passenger in a car, you sense that its speed is hazardous for local conditions and call, 'Too fast: slow down', this is negative feedback. (Assuming the driver heeds your warning. If the wires are unfortunately crossed between you, so that the more you shout slow, the faster he feels impelled to drive, we have another example of positive feedback.)

Information is an inherent and essential part of control systems in another sense, that of memory. They must have the capacity to store, recall, and compare information at any time, so that they may correct errors and never lose sight of their goal. Finally, whether we are considering a simple electric oven, a chain of retail shops monitored by a computer, a sleeping cat, an ecosystem, or Gaia herself, so long as we are considering something which is adaptive, capable of harvesting information and of storing experience and knowledge, then its study is a matter of cybernetics and what is studied can be called a 'system'.

There is a very special attraction about the smooth running of a properly functioning control system. The appeal of the ballet owes much to the graceful and seemingly effortless muscular control of the dancers. The exquisite poise and movements of a 'ballerina assoluta' derive from the subtle and precise interaction of force and counter-force, perfectly timed and balanced. A common failing in human systems is the application of the correcting effort, the negative feedback, too late or too soon. Think of the learner-driver swinging the steering wheel and the car from side to side, through failure to sense in time a drift from his intended course; or think of the drunkard's unsteady progression towards the lamp-post that 'comes out and hits him', as alcohol slows his reactions and he is unable to take avoiding action in time.

Where there is a substantial delay in closing the loop of a feedback system, the correction can turn from negative to positive feedback, especially when events happen within a fairly sharply defined interval of time. The device may then fail by oscillating, sometimes violently, between its limits. Such behaviour can be terrifying when it happens to the steering system of a car, but it is also the source of sound in wind, string, and electronic musical instruments, and of an unceasing array of electronic devices which generate periodic signals of all kinds.

It will now be apparent that the control system of the engineer is one of those forms of protolife mentioned earlier in this book which exist whenever there is a sufficient abundance of free energy. The only difference between non-living and living systems is in the scale of their intricacy, a distinction which fades all the time as the complexity and capacity of automated systems continue to evolve. Whether we have artificial intelligence now or must wait a little longer is open to debate. Meantime we must not forget that, like life itself, cybernetic systems can emerge and evolve by the chance association of events. All that is needed is a sufficient flux of free energy to power the system and an abundance of component parts for its assembly. The level of water in many natural lakes is remarkably independent of the rate of flow in the rivers which feed them. Such lakes are natural inorganic control systems. They exist because the profile of the river which drains the lake is such that a small change in depth leads to a large change in flow rate. Consequently there exists a high-gain negative feedback loop controlling the depth of water in the lake. We must not be misled into assuming that abiological systems of this kind, which might operate on a planetary scale, are part of Gaia; nor, on the other hand, should we dismiss the possibility of their adaptation and development to serve a Gaian purpose.

This chapter on the stability of complex systems indicates how Gaia may function physiologically. For the present, while the evidence for her existence is still inconclusive, it will serve as one kind of map or circuit diagram to compare with what we may find in further exploration. If we discover sufficient evidence of planet-sized control systems using the active processes of plants and animals as component parts and with the capacity to regulate the climate, the chemical composition, and the topography of the Earth, we can substantiate our hypothesis and formulate a theory.