CHAPTER 3

LIFE, NEGENTROPY, AND BIOLOGICAL FEEDBACK

3.1 Earth before life appeared

Earth may have originated as a molten mass accumulated (over millions of years) from materials left over from the formation of the sun. In its early stages of cooling, if so, it would have radiated far more thermal energy outward than incoming solar radiation could account for. The trade-off between high-grade solar energy coming in and low-grade heat energy going out would have been tipped strongly in the latter direction.

At some stage along the way, however, the cooling process tapered off, a solid crust formed on the surface, and the surface temperature reached an approximate equilibrium. For this to happen, the amount of energy reaching the surface (internally by continued cooling and externally by solar radiation) would have to match the amount leaving the surface as low-grade heat. Once its temperature had reached a stage of approximate equilibrium, the earth's surface was ready for the appearance of life.

Other conditions had to be right, of course, for life to make an initial appearance. Once its surface had reached thermal equilibrium, the globe had to be spinning at a rate and angle maintaining periodic temperature variations within tolerable limits. Its magnetic field had to be aligned to deflect high frequency solar radiation that would have been fatal to primitive organisms. And its gravitational pull had to be weak enough to allow the formation of a gaseous atmosphere, but strong enough to keep molecules on which life depends (e.g., O_2, CO_2, H_2O) from drifting off into space. These are only a few of such conditions that might be mentioned.

Our concern in this chapter, however, is limited to energy flows on and about the earth's surface. As we shall see, not only has the life process become a major factor determining the character of these flows, it is now interacting with these flows in a manner that might prove self-destructive.

3.2 The nature of life

In one way or another, the question of the nature of life engages the interests of most reflective people. One does not have to be a philosopher to ask whether life has meaning, or a theologian to wonder about its ultimate source. Such concerns do not preclude viewing life as fundamentally a biological process. For reasons that should by now be obvious, this latter view will prevail through most of the present study.

Scientists commenting on the nature of life seem to agree on its highly improbable character. For example, Carl Sagan (astrophysicist) has remarked that the "improbability of contemporary organisms…is so great that these organisms could not possibly have arisen by purely random processes…." Konrad Lorenz (ethologist) speaks of life as "a steady state of enormous general improbability;" and R. A. Fisher (statistician) has described biological evolution as "a mechanism for generating an exceedingly high degree of improbability."[1] Given the close association of improbability (lack of randomness) with order and usable energy (Chapter 2), this suggests that life is essentially characterized by its orderliness and its use of energy.

There is less agreement among scientists regarding the nature of this phenomenon they find so improbable. Some think of life in terms of its physiological functions (reproducing, growing, responding to stimuli), while others focus on its biochemical features (being based on proteins, metabolizing under the control of enzymes). Yet others stress genetic and evolutionary characteristics (genetic instructions passed from parent to offspring, species shaped through natural selection). While some of these features may be *necessary* and others *sufficient*, it remains debatable whether any are *both* necessary and sufficient for life as we know it.

There are enterprises for which a precise definition of life in terms of necessary and sufficient conditions is important. One such enterprise is inquiry into the moral status of certain medical procedures. If genetic duplication of cells in a fertilized ovum is sufficient for life, then a life is snuffed out by an early-term abortion. Again, if metabolic self-sufficiency is necessary for life, then removing a brain-dead person from life-support is not letting a person die.

Another enterprise requiring a precise definition is our ongoing search for life on other planets. Is oxygen necessary for the metabolism of living organisms, or could life be present in an atmosphere (like that of Mars) consisting mostly of carbon dioxide? Again, are organic compounds like nucleic acids sufficient for life's occurrence wherever they are found, or would the discovery of such compounds on other planets leave open the question of whether life itself is also present?

Important as these enterprises may be in their own right, however, our present inquiry does not require a precise definition of life. As already noted, what our inquiry requires is an account of life that makes clear its relation to its surrounding environment. What we need in particular is an account of how a living organism exchanges energy with its environment, and of how the environment is affected by this exchange. The present chapter is intended to provide an account of this sort.

3.3 Schroedinger's characterization

In his now-classic description of metabolism, the physicist Erwin Schroedinger remarked that "the device by which an organism maintains itself stationary at a fairly high level of orderliness (= fairly low level of entropy) really consists in continually sucking orderliness from its environment."[2] To "suck up" orderliness is tantamount to receiving usable energy, which is equivalent in turn to acquiring negentropy (Chapter 2). Another remark of Schroedinger, in terms of the latter, is:

> What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive.[3]

However one puts it, the point is simple: as a result of the interaction between organism and environment, the organism gains order and the environment gains entropy.

Not only is a living organism able to "suck up orderliness from its environment;" it is able typically to acquire order (or energy) from components of its environment that exist at lower levels of order (or energy) than itself. For example, acorns and carrots are structurally less complex, and contain less energy for useful work, than the squirrels and rabbits they serve as food. A rabbit eating a carrot is roughly equivalent thermodynamically to a piece of warm toast receiving warmth from cold butter laid upon it (making the butter yet colder).

It is evident that the relation between rabbit and carrot is quite different from that between warm toast and cold butter. In the latter case, heat energy flows from a higher level in the toast to a lower level in the butter. In the interchange between rabbit and carrot, however, energy is transferred from a lower level in the (cooler and structurally less complex) carrot to a higher level in the (warmer and more complex) rabbit. The same apparently "reverse" movement of energy occurs when a squirrel eats an acorn or when a hawk eats a squirrel. This raises questions about the relevance of the Second Law of Thermodynamics (Chapter 1) to processes involving the metabolic activity of living organisms.

3.4 An apparent conflict with the Second Law

At first glance, the metabolic process as Schroedinger described it appears contrary to the Second Law of Thermodynamics. According to this law, transformations of energy always tend to result in greater degrees of disorder and greater amounts of entropy. Yet in the energy transactions between organism and environment, the organism gains order and casts off entropy.

As commentators often note, however, the appearance of conflict with the Second Law arises only when we focus too narrowly upon the organism itself. When the consequences for both organism and environment are taken into account, any hint of conflict disappears. The order gained by the organism is lost by the environment, which is what Schroedinger meant by the organism's "sucking orderliness from its environment." Another way of putting it is that the entropy lost by the organism is gained by the environment, which is tantamount to the organism's "freeing itself from all the entropy it cannot help producing while alive."

Far from conflicting with the Second Law, the metabolic activity of living organisms provides an instructive illustration. The amount of entropy passed off to its environment by a living organism invariably is greater than the amount of order it gains from its environment initially. The environmental cost of he organism's enhanced order is always a comparatively greater amount of disorder within the environment itself. When both organism and environment are considered together, accordingly, the upshot is that any interchange in which the organism gains structure or energy will result in an overall increase in entropy.

In effect, the life-process serves as a "catalyst" speeding up the production of entropy in its surrounding environment. As a consequence of playing host to the organisms living within it, a given sector of the environment becomes disordered more quickly than it would if no life were present. This is what the Second Law leads us to expect in stating that entropy tends to increase as a result of any (irreversible[4]) natural process.

Another aspect of this interaction is that an environment tends to gain entropy more quickly as the organisms it supports increase in complexity. The reason is that increased complexity goes hand in hand with increased amounts of energy needed to support the metabolisms of the organisms in question. Since human beings have greater energy needs than squirrels and rabbits, for example, humanity inflicts more disorder than these other creatures upon its supporting environment. The fact that humanity at large discharges more entropy per capita into the biosphere than any other species figures prominently in the following discussion.

3.5 Feedback connections between organism and environment

For an organism to gain energy from its surrounding environment, it must be appropriately coupled with specific energy sources. For example, a carrot can serve a rabbit as a sources of energy only if the rabbit is near the carrot, can perceive it as such, and is capable of chewing and digesting it once the pieces are swallowed. Generally speaking, a given organism must be properly connected to its surroundings before its can gain the energy it needs for growth and sustenance. Conjoining the organism with its environment in the requisite fashion is the role of what biologists (following engineers) call *feedback*.

Feedback occurs when the activity of an operating system[5] is influenced in turn by the effect this activity has upon its operating environment. While feedback occurs in many forms, all can be classified either as *negative* or *positive*.

Contrary to their common connotations, the term 'positive' here does not indicate something particularly desirable (as with a "positive response" from a theater audience), and 'negative' does not indicate something undesirable (as with a "negative review" by a music critic). In this context, both terms take on meaning with respect to derivation from a standard state—for example, a specific room temperature. Positive feedback increases deviation from the norm, as when heat from uncontrolled burning makes a fire burn yet hotter. Negative feedback, on the other hand, decreases ("negates") deviating activity, as when an air-conditioner returns room temperature to a preset level.

Positive feedback is a source of instability which, if unchecked, can lead to destruction of the operating system. The spread of fire through a burning building is a striking example. Another is a pothole in a heavily traveled road-surface, which breaks up more rapidly as the hole gets bigger. Yet another is the explosion of a keg of gunpowder, in which the rate of oxidation (burning) increases proportionately to the heat produced by the oxidation underway. The same dynamic is at work in a so-called "population explosion" (in which a population increases more rapidly the bigger its gets), save that the social process might continue through many generations whereas gunpowder explodes within a matter of milliseconds. What happens in each of these cases is an increasingly rapid deviation from a standard condition (nonincindiary temperature, steady population level), exacerbated by changes introduced into the system by the ongoing process.

Standard examples of negative feedback are thermostatically-controlled heating and cooling systems, which operate to maintain living spaces at stable temperatures. A familiar biological example is the process by which level of illumination is regulated on the retina. When light striking the retina exceeds an optimal level of intensity, the pupil of the eye contracts to reduce incoming light energy; and when illumination decreases below optimal level, the pupil dilates to let more light enter.

Negative feedback is a process of stability and control, and as such is essential to the life process itself. In the following section we look at various kinds of negative feedback operating within individual organisms. Then we consider negative feedback in the interactions among different organisms, which leads directly to the topic of ecosystems.

3.6 Biological forms of negative feedback

There are two general types of negative feedback a living organism might depend upon in maintaining a viable relation with its surrounding environment. One type works by making adjustments internal to the organism itself. This type might be called *homeostatic*, and is the basis of the biological process known as *homeostasis*. The other works by adjusting the relation between organism and environment. This second type has been referred to as *heterotelic* feedback.

As its name indicates, homeostasis is a process by which a system maintains itself (hence 'homeo-') in a stable ('-stasis') operating condition. Stable operation typically requires holding certain key variables of the system (e.g., temperature in mammals) within a normal range of values. A key variable is protected by homeostatic feedback when its deviation from normality is countered by other changes within the system itself. Even when deviation is brought about by external causes, the system compensates by internal adjustments that return the values of its protected variables to a tolerable range.

This process is illustrated by the way some mammals control excessive body temperature by perspiration. Human body temperature, for example, must be held close of 98.6˚F for normal metabolic activity. When ambient temperature is lower than body temperature, metabolic heat is discharged from the body surface by convection and radiation. But when ambient temperature exceeds body temperature, these same processes tend to transfer heat into the body instead. The body responds to this counterproductive tendency by emitting perspiration, which then cools the body's surface as it evaporates. Rates of perspiring vary both with ambient temperature and with humidity (under tropical conditions, the sweat glands of an adult human can emit over three liters of moisture an hour). Sweating thus is an homeotelic adjustment by which the body counteracts increases in temperature induced from without.

The other general type of negative feedback in biological systems is one in which the organism maintains stability under changing external circumstances by taking action that affects those circumstances directly. This type of called heterotelic in view of its serving to bring about or to maintain an optimal state of the system by adjusting its relation to other ('hetero-') factors. A nonbiological example is a target-seeking missile that responds to changes in its target's position by corresponding changes in its own direction, thus maintaining a state of active pursuit. Biological examples include the daisy that maximizes its input of solar energy by keeping its petals directed toward the sun (heliotropism), and the oak tree that assures itself a ready supply of water by sending its roots deep into the moist underground.

[Technical addendum. The process of perspiration has already been mentioned as an example of homeostatic feedback. If we represent the protected states of a given organism (e.g., body temperature) by 'S', relevant states of its operating environment (e.g., ambient temperature) by 'O', and the effector mechanisms involved (e.g., sweat glands) by 'E', then homeostasis feedback can be represented schematically as follows:

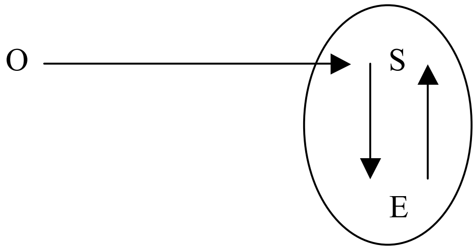


Figure 3.1

The point to be noted here is that the organic system (encircled) responds to external disturbances by engaging effectors that produce compensating changes within the system itself. As indicated by the return arrow from E to S, these effectors are internally directed.

Heterotelic feedback, by contrast, is a process by which the system responds to external provocation by adjusting its relation to the environmental factors involved. Since heterotelic feedback works through its effect on the operating environment, it can be diagrammed in the following manner (reading 'S', 'O', and 'E' the same as above):

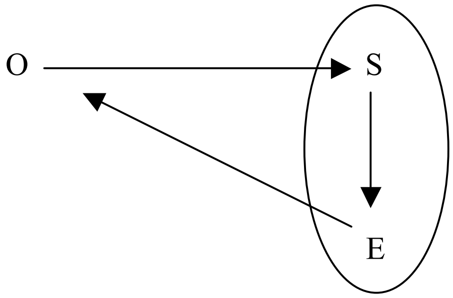


Figure 3.2

Because the activity of E is directed back to O where the feedback interchange began, systems of this sort (O → S → E → O) are called *feedback loops*. As we shall see presently, heterotetic feedback is the basis of more complex forms of feedback typical of organisms at the upper levels of the food chain.]

Of the two forms of negative feedback considered here, the homeotstaic form is the more rudimentary. One reason is that any organism requires active homeostasis for continued operation, whereas it is not uncommon for organisms to remain viable without active heterotelic adjustment. (Sleeping hounds remain healthy when not chasing rabbits.) Another reason concerns the effect upon the organism when environmental perturbation is excessive. If the organism's only means of coping is by internal changes (homeostasis), external stress might produce results the organism cannot tolerate. (A deer cannot survive a forest fire merely by sweating.) But if it is also capable of altering its external circumstances, the organism can avoid effects that might otherwise prove fatal. (A deer capable of running can survive the fire.)

3.7 Extensions of heterotelic feedback

Once heterotelic feedback is in place, it can provide the basis for other forms of feedback that are highly beneficial to the organisms involved. One such is *sentient* feedback, which enables perception at a distance of external objects. Heterotelic feedback by itself enables avoidance behavior; but the states it protects (S in Figure 3.2) must be disturbed for this response to occur. If the effect of the operating environment (O) upon S is particularly severe, the organism might lose its ability to escape further damage. (A rabbit can escape a hawk by taking cover under brambles, but this capacity is of little help if its first warning is the pain of talons in its back.) The survival value of heterotelic feedback is greatly enhanced if it is accompanied by an ability to receive notice of present danger without protected states S being put at risk. This is the role of sentient feedback.

Further protection of S can be achieved if the system is able to respond to threatening environmental states O before they occur, and to take action preventing their actual occurrence. In point of fact, many organisms are capable of sentient feedback in which their behavior is governed by sensory response to *antecedents* of external states that would affect them adversely, in lieu of responding to these states only when actually present. This enhanced capacity may be designated *anticipatory* feedback.

On the part of nature at large, anticipatory feedback is supported by patterns of regular association among event that allow reliable expectation of a particular event before it occurs. On the part of behaving organisms, this facility is enabled sometimes by behavioral conditioning (Pavlov's dog was led to anticipate food by the sound of a bell) and sometimes by advanced cognitive faculties like memory and reason. As with sentient feedback generally, all anticipatory capacities involve the processing of information originating in the external environment.[6]

This brief discussion of sentient and anticipatory feedback has been confined to their usefulness in responding to potential dangers. It should be noted that there are parallel advantages to be had in pursuing opportunities from which the organism can benefit directly. A rabbit being chased will be served by these capacities, but so will the hound that is giving chase. An animal's role in the food chain (Chapter 5) depends substantially upon the nature of the negative feedback capacities its employs.

[Technical Addendum. Sentient feedback involves receiving notice of impending danger before it occurs, and receiving this in a form not likely to harm the organism. These general features are illustrated in the following diagram:

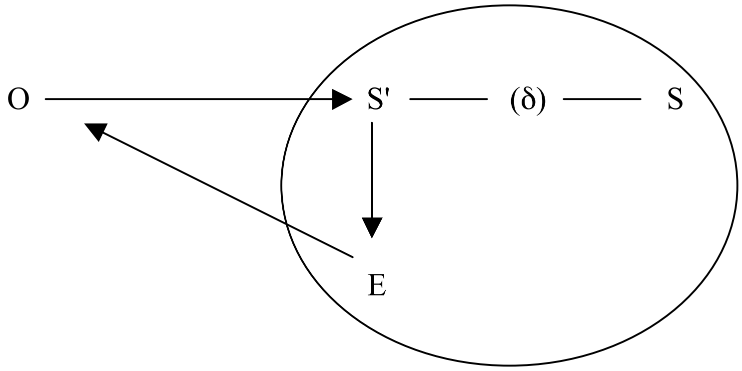


Figure 3.3

The significant difference here from Figure 3.2 above is that S has been displaced by S' and connected to it by a delay factor (δ). The relation between S' and S is such that (1) for every circumstance O of the operating environment that affects a protected system state S there is another system state S' that is induced by O, (2) S' is not vital to the system's continued operation (and thus does not require the same level of protection), and (3) change in S' is temporally prior to change in S should the latter occur. The symbol '(δ)' is intended to indicate the temporal delay of S relative to S'.

In actual biological systems, provisions (1), (2), and (3) may be achieved by the development of specialized receptors (S') that respond more quickly to O than do the variables S protected by the system. As figure 3.3 makes apparent, these vital variables S are more fully protected than in simple heterotelic feedback by being removed from the primary feedback loop (O→S' →E →O). The increased survival value of such features would normally provide impetus for their development in the context of natural selection.

The enhanced protection afforded by anticipatory feedback, in turn, is illustrated by the features added to the figure below:

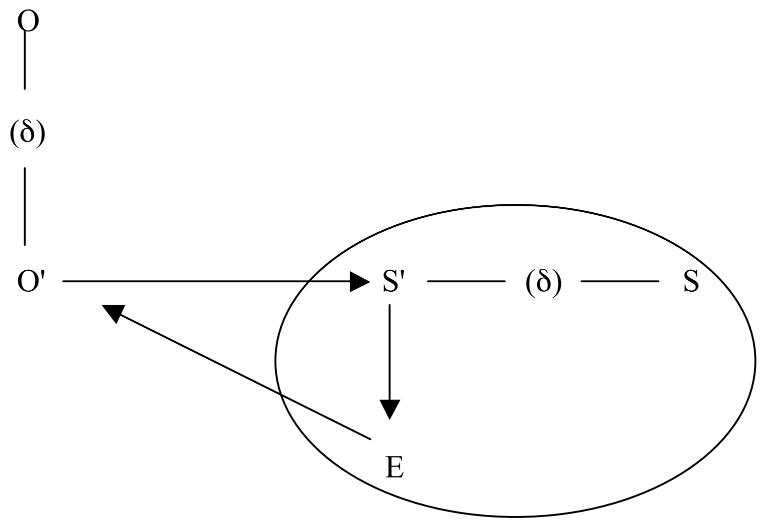


Figure 3.4

In this depiction, O' is an environmental circumstance that regularly precedes a threatening event O, and (δ) is a temporal delay as before. Figure 3.4 shows how protected system-state S is isolated from threatening event O by two distinct levels of "cushioning," in that both S and O are now removed from the primary feedback loop. The survival value of this addition should be obvious.

In section 3.6 it was noted that homeostatic feedback is a more rudimentary process than the heterotelic version. An organism might have homeostatic without heterotelic capacities, but probably not vice versa. A similar relation exists between sentient and anticipatory feedback. Generally speaking, an organism with both heterotelic and homeostatic feedback is more complex than one with homeostatic alone, and among the former an organism with anticipatory feedback is more complex than one with sentient feedback only.]

3.8 Ecosystems based on feedback processes

By way of review, we may recall that most energy exchanges in the natural world involve a flow from higher to lower levels (e.g., hot toast to cold butter). A distinguishing feature of living organisms is that they are sustained by energy flows in the opposite direction (section 3.3). In Schroedinger's picturesque phrase, living creatures are capable of "sucking up" energy (and its equivalent, orderliness) from their environments. The capacities enabling living organisms to participate in this counterflow of energy are based on various forms of negative feedback (section 3.5).

Plants typically receive their energy from solar radiation, acting through the process of photosynthesis. This process is served by the plant's ability to orient its leaves and blossoms for maximum exposure to sunlight, a trait known as heliotropism. Heliotropism is a classic example of negative feedback (section 3.6). Inasmuch as herbivores feed on plants, and carnivores on herbivores, heliotropism is an essential aspect of the food-chain generally.

Although parasite larvae (e.g., those of the gypsy moth) feed on plants they already occupy, most herbivores (think of deer and rabbits) need to find suitable food sources before they can start feeding. This requires some form of sentient feedback (section 3.7; visual, tactual, olfactory, etc.). The same may be said of the carnivores that feed on the herbivores. As the squirrel relies on smell to find its buried acorn, so the hawk relies on vision to locate the squirrel. And so both squirrel and hawk fall prey o the great horned owl, guided by both sight and hearing in its nocturnal predations.

Regardless of place in the food chain, negative feedback is essential to the behavior patterns of prey and predator alike. Prey and predator play reciprocal roles that are determined by the feedback loops in which they participate. To be a member of a food chain ipso facto is to belong to a system of feedback loops that establish pathways of energy flow from organism to organism.

Imagine a system of this sort keyed to the needs of a particular group of predators—says, a mated pair of great horned owls. To keep it simple, we will assume that this pair exists on a diet of rodents and song birds, supplemented by an occasional raccoon or skunk. During its lifetime of ten or so years, each owl will consume several thousands of these other creatures. And each of these likewise will have its own typical diet. Like skunks and raccoons, most rodents and song birds are either carnivores or insectivores (insect eaters); and all will consume various plant products (roots, leaves, seeds, berries) as well.

To gain the energy they pass on to the owls, individuals of these other groups are occupied with eating during most of their waking moments. A field mouse will consume as much as a quarter pound of grain per month, along with myriads of berries, nuts, and insects. Song birds consume roughly their weight in seeds and insects per week. Being omnivores, skunks and raccoons typically will eat whenever they find an opportunity. Given an ample food supply, individuals of these species can double their weight in a few weeks before hibernation.

Here are several stages in a network of energy transferal held together by distinctive forms of negative feedback. The owls have capacities of sentient feedback enabling them to locate and to capture their prey. Similar capacities guide the latter in avoidance behavior, and enable them to locate their food in turn. The fortunate song bird can see an owl approaching, and also can pick out edible berries on the basis of color. Sentient feedback enables the skunk not only to avoid its predators but also to seek out vegetation it can use as food. Other feedback loops come into play in the case of the insects (e.g., grasshoppers) that feed the raccoons and field mice, and that feed themselves upon suitable stalks and leaves.

As far as the meat-eaters, insect-eaters, and plant-eaters of this particular food chain are concerned, the system has the configuration of an inverse tree. The pair of great horned owls is on top, followed by large numbers of rodents and song birds, skunks and raccoons. On another level we find countless insects that complete the diets of the other species. Tying these levels together are various forms of sentient feedback, serving purposes of pursuit and avoidance alike.

The pattern continues on the level of the plants with which the upward flow of energy begins. At this fundamental stage, however, sentient feedback becomes less a factor and other forms of negative feedback take over. One form mentioned previously is the process of heliotropism by which plants orient their leaves for maximum reception of energy from the sun. Other forms are the processes by which plants exchange oxygen for carbon dioxide and those by which matter from decomposing organisms is recycled in growing vegetation. These other forms of feedback will be examined in subsequent chapters.

Despite the ultra simplicity of this imaginary network (the great horned owl in fact preys on roughly 250 species), it serves as a model of what biologists call an ecosystem.[7] As we shall see, there of course is more to an ecosystem than its interactions between prey and predators, and more to these interaction than the feedback loops that sustain them. It remains the case, nonetheless, that ecosystems maintain their integrity through the operation of feedback loops among their constituent organisms. The flow of energy from plant to herbivore to carnivore to omnivore follows channels established by these feedback operations. In a manner of speaking, these feedback loops are the ligatures by which ecosystems are held together.

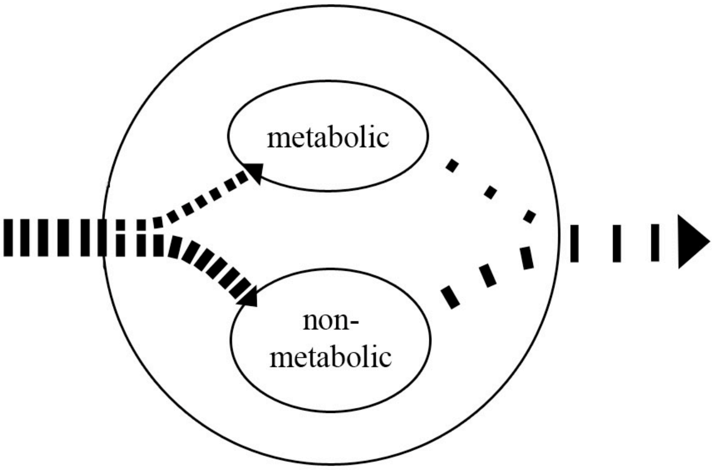
The same may be said of the biosphere at large. As may be recalled, this discussion of feedback and energy flow began with a previous concern (section 3.1) with the effect of life on energy flows on and about the earth's surface generally. If we think of the biosphere as the totality of ecosystems on the face of the earth (more on this later), our initial interest boils down to a concern with energy flows pertaining to the biosphere at large. The final section of this chapter sets the stage for a more detailed discussion in the chapter 4.

3.9 Energy flows through the biosphere

Apart from occasional excursions into space by astronauts and cosmonauts, life as we know it is confined to a thin envelope around the earth's surface. This envelope is known as the biosphere. By definition, the biosphere includes all organisms living within that envelope. As early researchers were quick to realize, it also includes the many geological features of the surface (land masses, water ways, atmosphere) on which living organisms rely for existence.[8] The biosphere may be described as the totality of living creatures, together with essential nonliving resources provided by their surrounding environment.

One feature of the biosphere that early researchers generally overlooked is its discharge of "used up" energy in the form of low-grade heat. Although it has long been obvious that life depends upon an input of solar energy, it has become apparent only recently that life is no less dependent upon the radiation of low-grade heat energy back into space.[9] By its very nature, metabolic activity within the biosphere produces heat. This heat is passed off into the surrounding environment, where it joins heat produced by nonbiological activity and eventually leaves the earth in the form of low frequency radiation.

These flows of radiational energy into, through, and out of the biosphere are represented in the following diagram.



Energy flows through the biosphere

Figure 3.5

Here the circle represents the biosphere, the arrows with the densely packed line-segments to the left represent incoming solar radiation, and those with less densely packed segments to the right represent outgoing radiation in the form of low-grade heat. After entering the biosphere, solar energy is redirected in part to metabolic activity and in (larger) part to non-metabolic activity, both of which produce low-grade heat to be discharged back into space.

The difference in amplitude between metabolic and non-metabolic flows is intended to indicate that relatively little of the solar radiation reaching the earth's surface becomes involved in biological activity. About one quarter of the sun's rays penetrating the atmosphere are in wavelengths useful for photosynthesis, and of these only about one percent contribute to biomass production.[10] Most solar radiation entering the biosphere falls on surfaces where it is converted directly into heat. Solar energy impinging on desert surfaces during the day, for instance, is converted into heat and radiated back into space at night without being engaged in biological processes.

Even flows of energy with no biological involvement, however, pass through the biosphere before being released into space as infrared radiation. The reason is that all radiation arriving at and departing from the earth's surface passes through the atmosphere, and that the earth's atmosphere at this point in time is heavily influenced by biological activity. It is in this respect that life has become a major force determining the character of energy flows on and about the earth's surface, as observed at the beginning of this chapter.

This gives us a distinctive view of the phenomenon currently known as global warming. Human industry contributes significantly to the accumulation of "greenhouse gases" in the atmosphere, which impede the radiation of low-grade heat into space. The build-up of waste heat that results in currently working dramatic—and often harmful—effects upon the biosphere generally. We return for a closer look at global warming in Chapter 5.

Another feature of the biosphere to which early writers paid little attention is its distinctively hierarchical structure. Like the countless ecosystems contained within it, the biosphere consists of organisms that feed on other organisms, which feed on yet other organisms in turn. Our consideration of energy flows through the biosphere continues in Chapter 4 with reference to the hierarchical arrangement of the ecosystems involved in those flows.

Notes

1. The Sagan quotation is from his entry "Life" in the 1974 *Encyclopaedia Britannica*, Vol. 10, p. 894. Lorenz's remark appears in his *Evolution and the Modification of Behavior* (University of Chicago Press, 1965), p. 32. Firsher's description was previously quoted by Julian Huxley (biolgoist) in L. B. Young (ed.), *The Mystery of Matter* (Oxford University Press, New York, 1965), p. 521.

2. Erwin Schroedinger, *What is Life*? (Cambridge University Press, 1967), p. 79.

3. *What is Life*?, p. 76.

4. An example of a thermodynamically reversible process is the freezing of water (at 0º C and one atmosphere of pressure), since ice can melt under the same conditions without additional

expenditure of energy. But energy is expended in all metabolic processes, which means that all life-processes are irreversible.

5. As defined in Chapter 1, an operating system is a configuration of interacting variables whose values change with time. Several examples are discussed in Chapter 2.

6. An information-theoretic analysis of sentient and anticipatory feedback is put forward in Chapter IV of the present author's *Cybernetics and the Philosophy of Mind*.

7. In the words of James Kay, in "Ecosystems, Science and Sustainability" (http://www.ecoogistics.com/nesh/scisust.html), ecosystems are self-organizing, meaning "that their dynamics are largely a function of positive and negative feedback loops." In his view, ecosystems have multiple operating states, depending on the feedback loops within them that happen to be dominant.

8. The term 'biosphere' was coined in 1875 by the geologist Eduard Seuss. Study of the biosphere was established on a scientific footing by the biogeologist Valdimir Ivanovich Vernadsky in the first quarter of the 20th Century. Vernadsky stressed the extensive interaction between the living and the nonliving components of the biosphere. See his *The Biosphere*, (Springer-Verlag, New York, 1998).

9. One of the first to focus on this was H. T. Odum, in his influential *Environment, Power, and Society* (Wiley-Intersciences, New York, 1971), p. 11.

10. See the articles by A. H. Oort and G. M. Woodwell in *The Biosphere* (Scientific American, 1970) and "Biosphere" by D. M. Gates in *Encyclopaedia Britannica*, 1974.