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Microbes and Man

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This is a book about germs, known to scientists as microbes (or to some, who cannot use a short word where a long one exists, as micro-organisms). These creatures, which are largely invisible, inhabit every place on Earth where larger living creatures exist; they also inhabit many parts of the Earth where no other kinds of organism can survive for long. Wherever, in fact, terrestrial life exists there will be microbes. Conversely, the most extreme conditions that microbes can tolerate represent the limits within which life as we know it can exist.

The biosphere is the name biologists give to the sort of skin on the surface of this planet that is inhabitable by living organisms. Most land creatures occupy only the interface between the atmosphere and the land; birds extend their range for a couple of hundred metres into the atmosphere, burrowing invertebrates such as earthworms and nematodes may reach a few metres into the soil but rarely penetrate further unless it has been recently disturbed by man. Fish cover a wider range, from just beneath the surface of the sea to those depths of two or more kilometres inhabited by specialized, often luminous, creatures. Spores of fungi and bacteria are plentiful in the atmosphere to a height of about a kilometre, blown there by winds from the lower air. Balloon exploration of the stratosphere as long ago as 1936 indicated that moulds and bacteria could be found at greater heights; more recently the USA's National Aeronautics and Space Administration has detected them, in decreasing numbers, at heights up to thirty-two kilometres. They are sparse at such levels, about one for every fifty-five cubic metres, compared with 1,700 to 2,000 per cubic metre at three to twelve kilometres (the usual altitude reached by jet aircraft), and they are almost certainly in a dormant state. At the opposite extreme, marine microbes flourish at the bottom of the deep trenches of the Pacific Ocean, sometimes down as far as eleven kilometres; they are certainly not dormant. Living microbes have been found 750 metres deep in sediments beneath the sea bed, and in sedimentary rocks beneath the land surface down to 500 metres. They are abundant at comparable depths in oil formations, and highly specialized types of bacteria have been found much deeper: in samples of hot telluric water emerging from oil-bearing strata three kilometres beneath the bed of the North Sea. The current record depth for microbial life inside this planet is held by certain heat-tolerant bacteria living three and a half kilometres down a gold mine in South Africa, where the ambient temperature is about 65°C. Thus one can say, disregarding the exploits of astronauts, that the biosphere has a maximum thickness of about forty kilometres. Active living processes occur only within a compass of about ten kilometres: in the sea, on and beneath the land, and in the lower atmosphere, but the majority of living creatures live within a zone of thirty metres or so. If this planet were scaled down to the size of an orange, the biosphere, at its extreme width, would occupy the thickness of the orange-coloured skin, excluding the pith.

In this tiny zone of our planet take place the multitude of chemical and biological activities that we call life. The way in which living creatures interact with each other, depend on each other or compete with each other, has fascinated thinkers since the beginning of recorded history. Living things exist in a fine balance, a balance often taken for granted because, from a practical point of view, things could not be otherwise. Yet it is a source of continual amazement to scientists, because of its intricacy and delicacy. The balance of nature is obvious most often when it is disturbed, yet even here it can seem remarkable how quietly nature readjusts itself to a new balance after a disturbance. The science of ecology – the study of the interaction of organisms with their environment – has grown up to deal with the minutiae of the balance of nature.

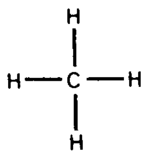
At the coarsest level, living creatures show a pattern of interdependence which goes something like this. Humans and other animals depend on plants for their existence (meat-eating animals do so at one remove, because they prey on herbivores, but basically they too could not exist without plants). Plants, in their turn, depend on sunlight, so the driving force that keeps life going on Earth is the Sun. So much every schoolchild knows. But there is a third class of organisms on which both plants and animals depend, and these are the microbes. I shall introduce these creatures more formally, as it were, in the next chapter, but I think it will be helpful to give here a sort of preview of what their importance in the terrestrial economy is, to show broadly how basic they are to the existence of higher organisms before going more deeply, in later chapters, into aspects that most influence mankind.

Microbes, then, are those microscopic creatures which some call germs, moulds, yeasts and algae – the bacteria, viruses, lower fungi and lower algae, to use their technical names. It will be instructive to give some idea of the abundance of microbes compared with other creatures.

In every gram of fertile soil there exist about 100 million living bacteria, of an average size of 1 or 2 μm (μm, a micrometre, is a thousandth of a millimetre; to use a familiar image, one thousand of them laid end to end would span the head of a pin). One can express this information in a form that is, to me, more impressive: there are 200 to 500 pounds of microbes to every acre of good agricultural soil. In world terms, this means that the total mass of microbial life on this planet is almost incalculably large – it has been estimated at five to twenty-five times the total mass of all animal life, both aquatic and terrestrial, and approaching the total mass of plant life. The actual global masses of any of these, plants, animals or microbes, are very difficult to estimate; it is easier to work out ratios in sample areas and use these to make an educated guess. No doubt that is why the estimates of total masses have been so vague – though the approach has established that animals (including ourselves) add up to but a trivial portion (perhaps a thousandth) of the Earth's biomass. However, the global census is improving. In 1998 a group of scientists at the University of Georgia, USA, were able to make a somewhat more precise estimate of the number of bacteria, a major class of microbes, in the world: it came out at between 4 and 6×10^{30} cells (that is, between 4 and 6 multiplied by 10 with 30 noughts after it!). It is an unimaginably huge number, and though each living cell is so tiny that it weighs only about a thousandth of a billionth of a gram (10^{-12} grams; three-quarters of that weight is water), taken together the world's population of bacteria adds up to around 5 thousand billion tonnes (or 5×10^{18} grams) of living matter. That figure, astronomical though it seems, is actually of a similar magnitude to the total amount of organic matter thought to constitute the world's plants. As I shall tell in the next chapter, there are lots of microbes that are not bacteria, so the global biomass of microbes probably exceeds that of all the plants and animals in the biosphere.

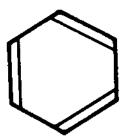
Microbes can multiply very rapidly when food and warmth are available. One type of bacterium divides in two every eleven minutes; many can double in twenty to thirty minutes; the slow ones double every two to twenty-four hours. This, of course, is a fantastic rate of multiplication compared with most organisms – one cell of the bacterium *Escherichia coli* could, if sufficient food were available, produce a mass of bacteria greater than the mass of the Earth in three days. Consequently, since microbes constitute well over half of the living material of this planet, and can multiply almost as fast as they can get suitable food, it follows that they are responsible for most of the chemical changes that living things bring about on this planet.

Now I must digress a moment. At intervals in this book I shall have to bring in a certain amount of chemistry, because it is in chemical terms that one can best understand most of the economic activities of microbes. I shall keep the chemistry as simple as possible, but I shall assume readers have at least some familiarity with chemical symbols: that they know, for example, that N symbolizes a nitrogen atom or Na a sodium atom; that free nitrogen gas occurs as molecules consisting of two atoms, formulated as N_2; that the formula of methane is CH_4 and signifies that its molecule consists of one carbon and four hydrogen atoms; that when one writes methane so:

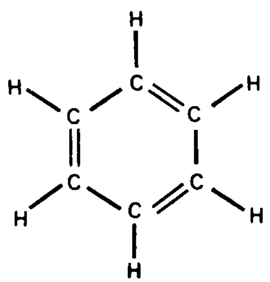


it signifies that the hydrogen atoms are independently linked to the central carbon atom in the molecule and that they are symmetrically arranged around it.

I shall make use of the organic chemist's shorthand of:



for six carbon atoms linked in a ring. Written out in full, the compound above (which is benzene) looks like this:



but chemists learned long ago that writing out all those 'C's and 'H's was generally a waste of time.

I shall also assume an awareness, at least in principle, that dissolved salts dissociate into ions. That sodium nitrate, potassium nitrate and calcium nitrate, for example, all yield nitrate ions in water, so that when a plant uses nitrate from a fertilizer, it is largely irrelevant whether it arrived as sodium, potassium or calcium nitrate. Thus, for many purposes, it is legitimate to talk of nitrate (NO_3^-), sulphate (SO_4^{2-}) and so on, even though it would be impossible to obtain a bottle of sulphate.

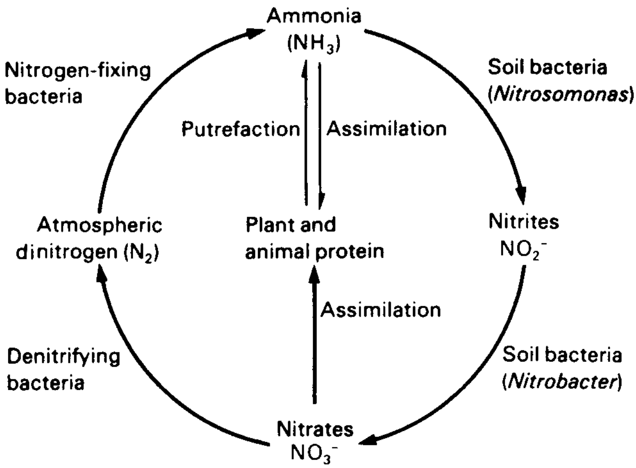
Taking these principles for granted, I shall try to explain any more complex chemical concepts as they arise.

After that brief excursion into what the reader's homework should have covered, let me return to the question of the importance of microbes in the world's chemistry. My next thought on these matters is this: that nearly all the chemical changes that do take place on this planet are caused by living things. A few inanimate processes do occur: volcanoes bring about alterations in the neighbouring rocks and in the atmosphere; lightning causes oxides of nitrogen and ozone to be formed; ultraviolet light from the sun does so as well, and also causes a layer of ozone to exist in the upper atmosphere that protects us from some of the more harmful ultraviolet wavelengths. Rainstorms and erosion by the sea cause gradual chemical changes in rocks and minerals as they are exposed; radioactive minerals induce a certain amount of chemical change in the neighbouring rocks and keep the Earth's interior hot. But at the Earth's surface the purely chemical changes that now take place are trivial compared with those that took place in the infancy of this planet: the Earth's own chemistry has settled down, as it were, to a fairly quiescent state. The most obvious chemical changes are now brought about by plants, with animals as secondary agents, both on land and in the sea, and the energy needed to perform these chemical transformations comes from the Sun. The biosphere, therefore, is a dynamic system of chemical changes, brought about by biological agents, at the expense of solar energy.

I shall tell in Chapter 10 how the emergence of living things wrought dramatic changes many millions of years ago in the chemical composition of this planet's surface. The composition of the atmosphere, soil and rocks underwent gradual changes, often taking tens of millions of years, to yield the sort of biosphere we know today. No doubt that is still changing slowly, but as far as the last million or so years are concerned the average chemical composition of the biosphere has been constant. Another way of putting this point is that all gross chemical changes which occur on Earth, brought about by any one kind of biological activity, are reversed by some other activity. If one considers the elements that undergo chemical transformation on this planet, they are found to undergo cyclical changes, from biological (or organic) combination to non-biological (or inorganic) combination and back again.

Consider the element nitrogen, nowadays plentiful as the free molecules of nitrogen gas that comprise four-fifths of our atmosphere. Nitrogen gas, known to chemists as 'dinitrogen', is normally rather inert; it is harmless to living things, neither burning nor supporting combustion, and is generally reluctant to enter into spontaneous chemical combination. Yet all living things consist of proteins: their muscles, nerves, bones and hair, and the enzymes that manufacture these and everything else, that provide energy for growth, movement and so on, all consist of protein molecules. And something like 10 to 15 per cent of the atoms in every protein molecule are nitrogen atoms. The nitrogen atoms are combined with others: carbon, hydrogen, oxygen and sometimes sulphur. Compared with dinitrogen, N_2, molecules, protein molecules are huge and complicated, containing tens of thousands of atoms; this is why proteins can be so diverse in appearance and function. And since they constitute the major part of most living things, one can safely say that most living creatures consist of between 8 and 16 per cent of nitrogen, animals being on the high side, plants on the low side. The main exceptions are creatures that form thick chalky or siliceous shells: they seem to have low nitrogen contents, but even they have the usual chemical composition if one regards the shell as a non-living appendage and excludes its composition from one's calculations.

Living things therefore need nitrogen atoms to grow. When they die, they rot and decompose, and their nitrogen becomes available for other living things. Rotting and decomposition are largely the result of the action of microbes on the organism and, of course, microbes die too, either naturally or by being consumed by protozoa, nematode worms and so on. Gradually the nitrogen is assimilated by larger living things – plants, worms, birds, etc. – and so it becomes part of new creatures. (A process dramatically enshrined in that essentially macabre Yorkshire song *On Ilkley Moor baht 'at*: 'Then shall ducks have eaten thee . . .'.) So a process of constant transformation of the state in which nitrogen atoms are combined takes place, which is known to biologists as 'the nitrogen cycle'. In this cycle certain microbes return nitrogen as N_2 to the atmosphere (the denitrifying bacteria) and others bring it back to organic combination (the nitrogen-fixing bacteria). One can write the biological nitrogen cycle schematically as below.

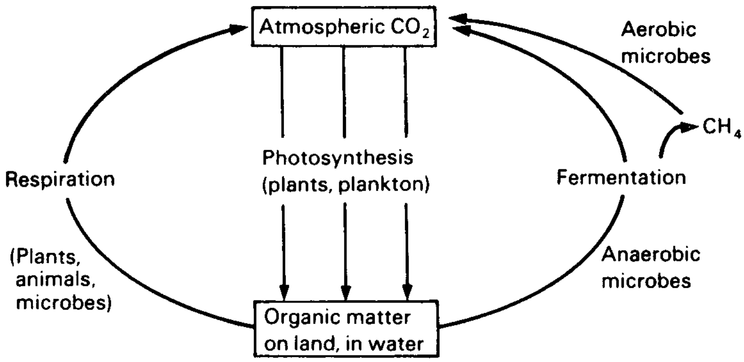


In this scheme nitrates in the soil are used by plants for growth and become plant and animal protein. Later these decompose through the action of microbes, releasing ammonia. Plants can recycle this, but they prefer nitrates, and two groups of soil bacteria convert ammonia back to nitrate by way of nitrite. Denitrifying bacteria, found in soil, compost heaps and so on, can release the nitrogen of nitrates as free nitrogen molecules, and this loss of biological nitrogen to the atmosphere is compensated for by the activities of the nitrogen-fixing bacteria. Some of these live in association with the roots or leaves of plants, other live freely in soils and water. I shall return to them in Chapter 5, but for present purposes the important point is that, in many soils, particularly agricultural soils, the supply of fixed nitrogen (ammonia or nitrate) determines the productivity of that soil. Hence the number of animals, or people, that can feed from that soil depends on how rapidly the nitrogen cycle is turning, on how actively nitrogen-fixing bacteria are performing.

Of course, the cycle may be bypassed to a limited extent. Artificial nitrogen fertilizers made industrially from atmospheric dinitrogen increase soil productivity by bringing chemically fixed nitrogen to the soil. Thunderstorms, and ultraviolet light from the sun, generate oxides of nitrogen in the atmosphere without the intervention of living things, and rain washes these into the soil as nitrates. These processes have been left out of the scheme above because, although together they account for over a third of the newly fixed nitrogen in soils, on a world scale the Earth's productivity of vegetation, and hence of food for man and animals, still depends primarily on the activity of the nitrogen-fixing bacteria. In a year, something in the region of 3 thousand million tonnes of nitrogen as N pass through the cycle, and nearly 10 per cent of this turnover involves loss of N to the atmosphere as dinitrogen and its return to the biosphere by nitrogen fixation. C. C. Delwiche has calculated that every nitrogen atom in the atmosphere passes through organic combination on an average once in a million years. Obviously the microbes are of crucial importance to the economy of living things on this planet.

The nitrogen-fixing bacteria are of basic importance to the nitrogen cycle, but one should not underestimate the rest. The putrefying microbes return protein nitrogen to circulation by forming ammonia and, since most plants prefer to assimilate their nitrogen as nitrate rather than ammonia, the two groups of bacteria which convert ammonia to nitrate (collectively called nitrifying bacteria) perform an economically useful function. This is not an unqualified virtue, however, because nitrates are washed out of soils by rain more easily than ammonia; to avoid such waste, agricultural chemists sometimes advise the use of ammonia fertilizers, which most plants can manage with perfectly well, together with chemicals that inhibit multiplication of nitrifying bacteria.

Another biological cycle, of equally basic importance to the biosphere, is the carbon cycle. This, as far as higher organisms are concerned, is intimately involved with the cycle of changes undergone by oxygen. All living things respire; in effect, respiration is the transformation of the carbon and hydrogen compounds that constitute food into carbon dioxide (CO_2) and water, usually with the aid of the oxygen of air. Thus living things tend to remove oxygen from air and replace it by carbon dioxide. The reverse process, that of fixing carbon dioxide as organic carbon and of replenishing the oxygen of air, is conducted by green plants: they absorb CO_2 to form the constituents of their own substance with the aid of energy derived from sunlight and in so doing they release the O of H_2O as oxygen (O_2). Today, on a world scale, these processes are more or less in balance, such that the atmosphere consistently contains about 21 per cent of oxygen and just over 0.03 per cent of CO_2. The main contribution of microbes to this cycle is in decay and putrefaction, whereby they break down residual organic matter such as wood, faeces and so on, and thus return carbon dioxide to the cycle. In so doing, they often provide an important diversion of the carbon cycle, because their carbon turnover need not necessarily be tied to the oxygen cycle. I shall introduce in Chapter 2 the anaerobic bacteria, which have no need of oxygen for their respiration and which can produce such materials as methane, hydrogen or butyric acid from organic matter. They are most important in deposits of organic matter to which oxygen does not readily penetrate, such as vegetation decaying deep in a pond, and methane in particular is important in the carbon cycle, because it is a gas and, by diffusing away from the deposits, it transposes carbon from air-free zones to aerated zones. Here the methane is oxidized; indeed, on a world scale, most of the products formed by anaerobic bacteria are oxidized by other microbes, using oxygen, to yield finally CO_2. Thus the carbon is returned to circulation and the cycle proceeds. The turnover rate of the carbon cycle overall is about 10 thousand million tonnes of carbon a year. On land, most of the CO_2 fixation is conducted by higher plants, but in the sea microbes are still the most important CO_2 fixers: microscopic cyanobacteria, algae and diatoms, microbes that float in the plankton layer of the sea surface, together with more dispersed microbes called picoplankton, form the bulk of the organic matter that fish feed upon. One can present the carbon cycle so:



The microbes of plankton use sunlight, as land plants do. I shall introduce in later chapters several groups of microbes that can fix CO_2 using chemical reactions, not sunlight, but, though they may have been important during the early history of life on this planet, they now contribute little to the carbon cycle except in certain very special environments.

Today environmentalists are rightly worrying about how balanced the carbon cycle really is. The proportion of CO_2 in the atmosphere has risen during the latter part of the twentieth century and continues to do so, which means that more CO_2 is appearing than plant and microbial photosynthesis can cope with. It appears that mankind is responsible: by burning fuel, especially coal, oil and natural gas, but in some other ways too, we are adding significantly to the amounts of CO_2 reaching the atmosphere. Because CO_2 traps heat from the sun and so helps to keep our planet warm (it is a so-called 'greenhouse gas'), the fear is that the extra CO_2 will gradually make the world warmer. The consequent disturbances in weather patterns may not be as pleasant as one might at first imagine, but as they are still being debated I must refer readers to current magazines and quality newspapers for details.

Elements such as hydrogen, iron, magnesium, silicon and phosphorus are all part of the structures of biological molecules and undergo comparable cyclical changes. The phosphorus cycle is also worrying, because it involves a net transfer of something like 13 million tonnes of phosphorus a year from the land to the sea with no obvious return process. Microbes play a certain part in this and in the other cycles just mentioned, but their part is not a major one and I shall not discuss them further. However, there is one cycle of great importance that I must not neglect, if only because it depends almost exclusively on microbes: the sulphur cycle. The element sulphur is a component of protein and of certain vitamins – living creatures contain between 0.5 and 1.5 per cent sulphur – and the biological sulphur cycle is of critical importance in maintaining supplies of that element. But before I discuss it I must introduce a technicality that will be important here and later in this book: the concepts of oxidation and reduction.

Coal, which is carbon, becomes oxidized when it is burned, and the chemical energy of this reaction is dissipated as heat. The process is called oxidation because oxygen atoms are added to the carbon atoms to give carbon dioxide. Using chemical notation one can represent it as a sort of equation so:

$$C + O_2 \rightarrow CO_2$$

If insufficient oxygen is available, some carbon monoxide is formed:

$$2C + O_2 \rightarrow 2CO$$

(This, incidentally, is the poisonous component of motor exhaust fumes.) Thus there are degrees of oxidation in the sense that carbon can be partly or wholly oxidized. In a similar way, other elements may form stable compounds in more than one degree of oxidation.

Food consists of carbon compounds which, when used by the body, are oxidized to form carbon dioxide and water. A typical example is glucose, which has the formula $C_6H_{12}O_6$:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Some of the energy of such a reaction appears as heat; much of it goes to drive the various chemical reactions which keep the body functioning.

All microbes live by comparable oxidative reactions, but there are some that can conduct such processes without using oxygen gas. The sulphate-reducing bacteria, for example, use sulphate:

$$\text{Carbon compound} + CaSO_4 \rightarrow CO_2 + H_2O + CaS$$

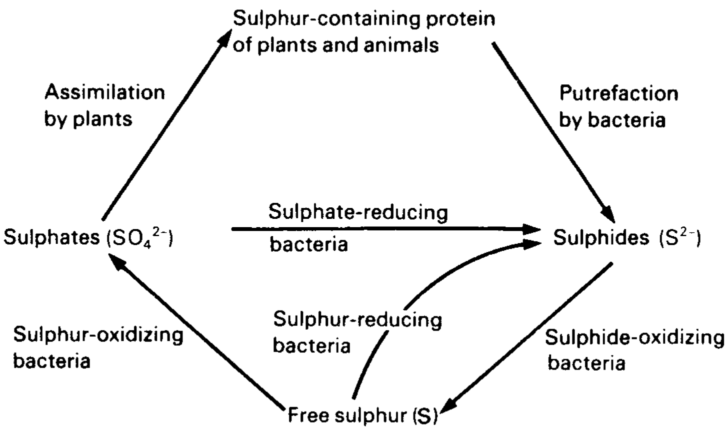
They steal oxygen atoms from sulphate and use them to oxidize carbon compounds. In that reaction, calcium sulphate becomes converted to calcium sulphide. The calcium sulphate undergoes a process called a reduction and, generally speaking, if some chemical is being oxidized, another is being reduced. (In burning, for example, the carbon is oxidized while the oxygen is reduced.) The denitrifying bacteria reduce nitrates in a comparable way:

$$\text{C-compound} + NaNO_3 \rightarrow \text{Na carbonate} + N_2$$

In nitrate or sulphate reduction, the oxygen atoms of nitrate or sulphate are used to oxidize the carbon source, so the ion is said to be reduced.

So far the concepts of oxidation and reduction are easy to follow. Things get a mite complicated when chemists refer to reactions that do not involve oxygen at all as oxidations and reductions, but this only means that the reactions in question have the same general character as those that concern oxygen. Compounds of iron, for example, can exist as ferrous salts (ferrous sulphate, nitrate and so on) or ferric salts; the ferric group are all more oxidized than the ferrous ones from the chemist's point of view, though they need not necessarily contain more oxygen (or, indeed, any oxygen at all: ferric chloride – $FeCl_3$ – is more oxidized than ferrous chloride – $FeCl_2$).

Microbes can make use of all sorts of oxidative reactions to obtain chemical energy for growth, movement and multiplication, including the conversion of ferrous compounds to ferric. Since oxidations are coupled with reductions, they bring about interesting reductions too, and in appropriate circumstances one can find one group of microbes conducting reductions and others oxidizing whatever they have reduced. This occurs particularly clearly in the biological sulphur cycle, which is turned by a group of soil and water bacteria called the sulphur bacteria. (In fact, they have little or no biological relationship: the main thing they have in common is that their metabolism is based on the sulphur atom.) Here is the sulphur cycle:



(Notice that sulphur appears in two oxidation states: sulphur itself is more oxidized than sulphide, though containing no oxygen, and sulphate is even more oxidized.)

In this cycle the sulphur of animal protein comes from plants, which get it from sulphates in soil. In decomposition and putrefaction of dead material, bacteria release the sulphur as sulphide, which is a reduced material. Other bacteria can oxidize this to sulphur, which some can reduce to sulphide again; yet others oxidize sulphide or sulphur to sulphate, which plants can re-use. The sulphate-reducing bacteria can bypass the top part of the cycle, reducing the sulphate straight back to sulphide, obtaining energy to do this by oxidizing organic matter, and thus a microbial sulphur cycle can go on without involving higher organisms at all. Such microcosms of sulphur bacteria are often encountered in nature, in sulphur springs, in polluted waters and so on, and, as I shall tell in Chapter 9, they may have been the dominant living systems during the early history of this planet. They are called sulfureta (singular: sulfuretum) and are responsible for a variety of economic phenomena that will appear in later chapters of this book. The individual bacteria of the sulphur cycle will also appear again later.

Microbes, then, play an important part in the cyclical changes that the biological elements undergo on Earth. In this sense they are of transcendental importance in the terrestrial economy, because without them higher organisms would rapidly cease to exist. Yet they couple these fundamental activities with a number of other functions which may be valuable, trivial or a thorough nuisance to mankind. Most diseases, for example, are caused by microbes. From a biological point of view disease is valuable in that it limits excessive animal or plant populations, but the reader need hardly be told how thoroughly inconvenient it can be in the civilized world today. Pollution and putrefaction are all very well in their place – our sewerage systems depend on them – but out of control they can be disagreeable and destructive. Microbes ferment foods, yielding delicious delicacies and wines, but tainted food is dangerous. Microbes aid our digestion and nutrition, but upset our stomachs in a strange land. Over geological time microbes formed several of the world's most valuable mineral deposits, but when they corrode steel and concrete we do not welcome their peculiar propensities. And so it goes on. Microbes are neither generally good nor generally bad; they can be either. The important thing, which is not widely realized, is that they have an enormous effect on the economy and well-being of mankind. That, in fact, is what this book is about. How do microbes come into our lives? What do they do? And why? These are far-ranging questions because, as the patient reader will learn, it might be more pertinent to ask whether there are any aspects of our daily lives in which microbes are not involved. I shall have to skip and skim in places, but in a book intended to introduce readers to an unfamiliar subject this is, I think, excusable. Let me start, therefore, by introducing that huge group of invisible or scarcely visible creatures we call the microbes.