ENTROPY AND EVOLUTION

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THE conception of entropy came from the theoretical study of the steam-engine, and, neglecting refinements of mathematical treatment, can easily be illustrated. The motive power of the engine comes from the transformation of the heat generated by the combustion of the fuel. The mechanism transforms the kinetic energy of the molecules of heated steam into the kinetic energy of the parts of the engine. Consider a steamship under way: for a brief period of time this can be regarded as an automatic physical system. Some of the heat conveyed by the steam transforms directly into mechanical energy and some passes out into the ocean in the condenser water. We take the latter fraction: in the boiler there is a certain quantity, Q_1, at a temperature of, say, 200° C., that is, 473° absolute, and its entropy is simply $Q_1/473°$ ab. The same quantity passes out into the ocean where its temperature falls to, say, 10° C., or 283° ab., and its entropy is now $Q_1/283°$ ab. Plainly the former quantity of entropy is less than the latter, so that *in the transformation of heat into mechanical energy entropy has increased.* The conception has been generalized so as to include all forms of energy and all physical transformations, and it can be shown that in all physical events *that occur of themselves* entropy increases. The conception includes these notions: (1) Available and unavailable energy; (2) greater or lesser improbability of the elements of the systems contemplated; and (3) the physical meanings of before and after. (1) The existence of a quantity of heat at the temperature of 473° ab. implies the availability of this energy for the performance of work, but this work having been done, and the temperature of Q_1 (the quantity of heat-energy) having fallen to 283° ab., the latter cannot now be made to undergo any further transformation which will result in the performance of more work. It has become unavailable, but the unavailability is relative to human power of control of the energy concerned. It is perfectly conceivable that the molecular motions in sea-water at 10° C. (283° ab.) might be so utilized, and Maxwell's fiction of the "sorting demons" demonstrates this. The "demon" was regarded as a being with finite powers similar to those of man, and differing from man only in size, and it is quite possible that micro-organisms which approximate in size to that of large molecules may utilize the molecular motions of water at the temperature of the ocean so as to do work—the possibility may, perhaps, even be capable of experimental verification. (2) Heat, *of itself,* "flows" from regions of higher to regions of lower temperature, and so the existence of a quantity of heat at 473° ab. anywhere on the surface of the earth is improbable, for soil, ocean, and atmosphere are at a temperature approximating to 283° ab., and therefore this heat will tend to flow and become uniformly distributed throughout its environs. The higher heat-potential in the boilers of the steamship must therefore be maintained by human agencies (feeding the furnaces with fuel). Along with availability and unavailability of energy there goes, respectively, greater or lesser improbability of the distribution of the latter. (3) The succession, before and after, is given to us directly in intuition: we experience the succession. But there may be nothing in the bare physical descriptions of two events, say, two lunar eclipses, to indicate which was earlier and which later. Such events occur in physical systems that are already "made"—that is, in those where energy is wholly dissipated. But if dissipation is incomplete, time has (in Eddington's phrase) its "arrow," or direction. Let there be two events, *a* and *b*, and let the entropy of the system in which *b* occurs be greater than that in which *a* occurs: *b*, then, is the later event. Imagine a sun-earth-moon system in which energy were wholly dissipated, that is, in which entropy has already attained its maximal value. There would be periodically occurring constellations of positions of the three bodies, but no one constellation could be regarded as earlier or later than any other one. Time would have lost its arrow and become eternity, or, at any rate, pure extension.

Energy that is "free," or is available for the performance of work, or is susceptible of transformation into other forms, is therefore energy which, relatively to the stock of universal energy, occurs in some improbable state, or aggregation. Value, or availability, can be related to improbability without directly considering physical energy. It would be easy, for instance, to devise a card-game in which the "value" of a "hand" depends only on the number of "trumps" held. Obviously, when we consider four players, the most probable number of trumps held by each will be three. Six, say, is less frequently held, or is more improbable in its occurrence, and thirteen trumps in one hand will be possible, but highly improbable (when the cards are dealt "methodically at random"). Now the value of the hand, from the point of view of winning tricks, is some function of the probability of the distribution of the cards.

The most convenient model of a physical system for mathematical investigation is a small volume of some perfect, monatomic gas contained in an envelope that has rigid walls. The system, at constant temperature and pressure, and in the absence of any external field of force, consists of a very great number of molecules moving in straight lines and in all directions, and with a certain range of free paths and velocities. The directions of movement are random ones, for the molecules continually collide with each other and with the walls of the container. It is possible, in imagination, of course, to specify each molecule by giving it six co-ordinates, three to specify its position with reference to some origin, and three vectors that specify its velocity and direction of movement. (In the cases of gases made up of complex molecules other co-ordinates are necessary.) The container is divided into a number of "cells," any one of which is very small relatively to the volume of the former, but still large enough to contain all, or a large fraction of all the molecules, if we imagine the gas to be greatly compressed. If, now, we "sample" the system by taking any one cell at random, we shall find that the number of molecules, the mean velocity, the mean free path, etc., will be very approximately the same as they are in any other cell. This is the normal state of the gas—one of maximum probability of distribution—and if this distribution is disturbed by, say, the compression of the gas in any cell, the state of normality will speedily be restored. A rough approximation to the conditions of the model may be pictured by considering the atmosphere of a large workshop in which there is machinery that can compress the air into a steel cylinder. A state of improbable distribution is so established, for the pressure of gas within the cylinder may be, say, a hundred pounds per square inch, whereas everywhere else within the room the pressure is only that of the atmosphere. The distribution is improbable because the compressed air in the cylinder will blow out of itself, and in a very short time the density of gas in all parts of the workshop will be everywhere the same. The improbability implies available energy, for the compressed air of the cylinder can be made to actuate some machine. When, however, uniformity of pressure has been attained, there is no longer available energy in the system. The air is made to assume the improbable condition of pressure (by being compressed), but it is quite conceivable that such an improbable distribution might occur of itself (both in the workshop and in the mathematical model). It is quite conceivable also that heat may be similarly segregated—we find, from experience, that the tip of a poker, made red-hot in the fire, speedily cools, and imparts its heat uniformly to the atmosphere and walls of a room; but it is also conceivable that the cold poker may, of itself, become red-hot by being bombarded, in certain ways, by the molecules of the surrounding air. These extraordinary occurrences are not impossible—they are simply highly improbable. Returning to the gas-model, we see that its normal and most probable state is that of uniform distribution of the molecules of gas, and that if, for any reason, this state is disturbed the return to maximum probability follows. We see also that great improbability implies available energy and decreased entropy, and *vice versa,* and it is easy to show that in such a system the entropy is proportional to the logarithm of the probability—a result of considerable theoretical value.

The gas in our model may, then, be imagined to exhibit many states of departure from uniformity of conditions, and it is possible to construct a system of equations which will represent the probability of every such variation from the most probable state—that of complete uniformity. We now remove a restriction with which we began the investigation: the gas is always acted upon by external agencies. There is the gravitational field of force, for instance, and it would be easy to show (by a delicate aneroid barometer) that the pressure of the air in the workshop directly below the ceiling is just a little less than the mean, and that it is a little greater than the mean just above the floor. We allow for these agencies (which will affect the probabilities already discussed) by inserting certain co-efficients, called "parameters," into our system of equations. The latter now represent the probabilities of all possible distributions of the molecules of the mass of gas that is being acted upon by some external agencies.

We shall now consider the distributions of the materials and energies of the whole earth by the methods just outlined. The extension of these methods, from the theoretical gas-model, to the sun-earth-moon system is not at all fanciful, for already this small part of the cosmic evolutionary process has received considerable mathematical formulation, with results that are, at the least, very plausible. The state which is regarded as the initial one, then, is the detachment, from the parent sun, of a "filament" of hot gas. This was the result of the gravitational attraction caused by the near approach to the sun of a wandering star of mass that was comparable with that of the sun. After detachment this "filament" of incandescent gaseous materials rapidly gravitated together, and, assuming a certain mass and temperature, its further states can be calculated. It condensed by radiation of heat, so as to form several planetary nuclei. In each nucleus there was formed a central liquid or quasi-liquid core, or centrosphere, composed of metallic materials surrounded by less dense, concentric shells. Next to the centrosphere is the lithosphere, a thick layer of basic rock, consisting of a complex mixture of silicates. Very soon after the initial state the external layer of the lithosphere became solid, and underwent differentiation. During this latter process masses of the underlying molten rock-material, or magma, became extruded to the surface (processes which still go on), with the liberation of water and gases. Thus the two exterior earth-envelopes, the hydrosphere, or ocean, and the original atmosphere, were formed. Neglecting, for the moment, the activity of life, we can easily see how this whole process represents a series of earth-phases, each of which is more stable, or physically probable, than the preceding one. The materials of the original lithosphere became differentiated, so that a less dense, granitic, or acidic, rock-layer became superposed on the basic one. This acidic layer is represented by the materials of the continental elevations, and the original basic lithosphere is probably represented by the deep ocean bed. Water extruded from the underlying basic magma filled up the oceanic depressions, and an original atmosphere, consisting of nitrogen, carbon dioxide, carbon monoxide, etc., formed a uniform layer over the whole surface of the earth. While this was going on the energy of the original, incandescent, vaporous earth was being dissipated, inasmuch as heat was being transmitted outwards to the surface to be radiated into cosmic space, and the internal energy of heavy radioactive atoms was also being dissipated as heat. These latter processes still go on. Thus, with the process of energy-dissipation and entropy augmentation the materials and energies of the earth have been assuming more and more stable or probable phases, and are continually tending towards some future phase in which their distribution will have attained to maximal probability.

Physical agencies have acted, and still act, in such ways as to delay the attainment of ultimate stability. The earth-interior is still strongly heated, and tends to cool very slowly. While it cools the already cold layers of the lithosphere fall inwards upon the contracting, but still hot, basic layer. There are volcanic eruptions, lava outflows, diastrophic movements of the "crust," with mountain formations. There is sub-aerial denudation of elevated crustal materials, so that mountainous regions are continually being levelled down. There is radioactive disintegration of certain elements and consequent generation of heat. Gravitation maintains the stratification of the atmosphere. The attraction of sun and moon maintain tides in an ocean upon a rotating earth. Solar radiation maintains movements (currents and winds) in the rotating ocean and atmosphere. And so on. These physical agencies so act as to delay the ultimate state of equilibrium of the earth envelopes. If we assume certain physical conditions, mass, temperature, etc., of the original earth-filament, it should (with greater knowledge than we now possess, of course) be possible to construct a system of equations that would represent all phases of the earth-system from its initial one to that ultimate phase which we envisage in the remote future, when solar and terrestrial energy will have become completely dissipated, and when our solar system will have attained final equilibrium. In this series of phases an initial earth-system characterized by its high degree of physical improbability proceeds to a phase of high probability. Initial, minimal entropy continually tends towards final, maximal entropy, and time flows in the direction, lesser to greater entropy of the system.

We shall next consider the various earth-envelopes just as we have considered our theoretical gas-model. We imagine the lower strata of the lithosphere partitioned into cells of appropriate magnitude, and we then sample these cells at random. There is evidence that tends to show that everywhere under both the oceanic depressions and continental elevations the basic lithosphere has the same thickness, density, and chemical constitution. If we partition Eurasia into sub-regions of, say, several thousands of square miles of area, we shall find that the acidic continental rocks are much the same in any cell sampled at random. We divide the ocean into similar cells and find that the mean depth in each and the chemical composition of the water are approximately the same. We partition the atmosphere into cells and find that the chemical composition is everywhere very nearly the same. We do find departures from strict uniformity of conditions. Thus the surface of the earth is not that of the theoretical geoid, for there are continental elevations and oceanic depressions (though these are so minute, on the earth-scale, that they cannot be represented, visibly in relief, on a 20-inch terrestrial globe). The temperature of the ocean water and the atmosphere vary with the latitude. The motions of the ocean (waves, tidal-streams, and wind-drifts) may be compared with the motions of the molecules in the gas-model, inasmuch as they are largely random motions and are approximately the same in all the cells. Nevertheless, there are slow resultant currents in the ocean that vary in direction as we pass from cell to cell. The motions of the atmosphere (winds) are largely random ones, yet there is a large-scale atmospheric circulation as an earth feature. There is some kind of pattern (not yet explained) in the distribution of land and water on the surface of the earth. And so on. But just as we accounted for the departures from strict uniformity of distribution in the gas-model by the parameters of the amended equations, so we can deal in this way also with the distributions in the inorganic earth envelopes. What we find, then, is that we can partition the lithosphere, hydrosphere, and atmosphere into cells and then sample these cells at random, with the result that the distribution of materials and energies is approximately the same in all the cells sampled: that is, that in the evolution of the earth conditions approximating to those of greatest probability may be observed. Where we find marked deviations from such conditions we attribute these to the action of physical agencies that are fairly well known to us, and which correspond to the agencies represented by the parameters in the equations that describe the theoretical gas-model.

The picture that the earth-scale, statistical investigation of the original planetary filament, presents to us is that of a physical system that is passing through a series of phases that result from the dissipation of the original energy of the filament. The series is such that each phase is characterized by greater physical stability, greater probability of distribution of the materials and energies, and greater entropy than the preceding phase.

We may now consider the corresponding phases in the "biosphere," that is, the film of organic or living things that exists on, and just below the surface of the dry land, in all depths of the ocean and the fresh-water masses, and in the lower strata of the atmosphere. The view still held by most biologists is that, at some early phase in the evolution of the inorganic earth-envelopes, some materials and energies so interacted as to give rise to living organisms. We do not know what were these conditions in which the first forms of life originated, for they do not appear to have recurred, and it has been impossible to reproduce them experimentally. Present physical conceptions appear to suggest that this origin of living things occurred, of itself, simply as "a fortuitous concourse of atoms," that is, as a highly improbable physical event. This is quite conceivable—just as conceivable as would be the "spontaneous" segregation of, say, a litre volume of a gas into two regions, one of which had a much greater density than the other one. The probability of occurrence of such an event can approximately be evaluated. It is not "impossible," and though its probability is extraordinarily small, that is not an *a priori* reason for refusing to contemplate the possibility of the event. We incline to think of such a primary life-material as similar to the "undifferentiated protoplasm" of the lower organisms. It would be capable of assimilation, for it would assemble the carbon dioxide, water, nitrogeneous substances, etc., that were in its environs in forms similar to itself. It would be capable of reproduction, for small parts detached from the original mass would still possess the power of assimilation. It would tend to be distributed, to an indefinite extent, throughout all adjacent regions of lithosphere and hydrosphere wherein the necessary materials for assimilation were existent. It would be somewhat similar to the substances called catalysts, but we must not labour this analogy when we consider the failure of all attempts to give experimental verification to the speculation. In spite of the enormous difficulties presented, we must consider the possibility of such an "origin of life."

But there has been a process of organic evolution in the course of which the primary forms of life have undergone differentiation. We must distinguish clearly between what we have called the "differentiation" of a volcanic magma and that of the primary living physical systems. The magma changes in such ways that its chemical constituents fall into the forms of stable silicates, water, carbon dioxide, carbon monoxide, nitrogen, metallic oxides, carbonates, sulphides, etc., and free metals. In present conditions, whatever of these materials can do so are oxidized from the atmosphere. Thus the whole system assumes physical and chemical simplicity and stability, that is, conditions of increased probability with entropy-increase. On the other hand, the primary forms of life have become more complex. They had an original morphology (shape, consistency, colour, etc.), and they had original chemical constitution. But evolution means the origin of novelties both in morphology and chemical state. There has been a continual new formation of species of plants and animals, in the course of which the morphology became progressively more complex. From one original life-material many kinds of life-material have proceeded, for "all flesh is not the same flesh, but there is one kind of flesh of man, another flesh of beasts, another of fishes, and another of birds." Probably there are as many kinds of "protoplasm" as there are species, or particular kinds, of organisms, and there does not appear to be any limit to the species of organisms that may arise during an evolutionary process. Thus the evolution of living things presents to us a picture of a series of phases, each of which is characterized by greater complexity of organization—morphological and chemical—than was the preceding phase. Now we have suggested that the origin of the primary life-material was conceivable as a physical event of great improbability, and it may seem as if we might extend this notion so that each increasing differentiation of the original forms of life were also an increasingly improbable event. It does not seem possible to argue against this speculation, but presently we shall see in what direction it leads us.

It is in the nature of living things that they should reproduce acceleratively, so that they must tend continually to increase the area over which they are distributed. The analogy to this increase in region of distribution in the case of the gas-model is the diffusion of the molecules. If the atmosphere is suddenly loaded by increase of carbon dioxide resulting from combustion, the local concentration is only a transient one for the molecules of CO_2 become uniformly distributed, if only by their own motions, throughout the entire atmosphere. But it is characteristic of races of organisms that migrate that the movements into new habitats are, sooner or later, accompanied by morphological and functional changes. These changes we call "adaptive" ones, since it is often the case that the natural conditions of the new habitat differ from those of the old one, and the morphological and functional changes accompanying the migration "fit" the organisms to the new conditions. Thus aquatic vertebrates respiring by means of gills came, in the course of their evolution, to inhabit dry land, whereupon the respiratory organs became lungs, which were developments of the piscine air bladder. But in the further evolution of the vertebrates, some of the land-living mammals again migrated into the ocean, whereupon the respiratory organs continued to be lungs. Cold-blooded amphibians evolved into warm-blooded mammals, but the assumption of a marine habitat by some of the terrestrial mammals was not associated with a renewed cold-blooded condition. Many cases of adaptations consequent on change of habitat might be instanced, but it would be just as easy to quote cases of morphological changes accompanying migration that have no adaptive significance. It has, indeed, been the custom in the past to trace some advantage, or disadvantage, to all such morphological changes, and to explain those phenomena in the light of the hypothesis of natural selection, but a candid and critical inquiry into many of these cases will certainly show that the explanations are unconvincing ones. It is true that, in the extreme cases, at least, the physical conditions of the new habitat adopted by a migrant stock may impose limits or confer direction upon the changes associated with the migration; thus the bodies of mammals that have become marine are "stream-lined," and their quadrupedal limbs have become flippers adapted for locomotion in water. But in the much more numerous cases of environmental changes that are less violent than that just mentioned, it may be quite impossible to trace relations of functionality between changes of habitat and morphological changes. There may, indeed, be no such morphological changes (as in the case of the introduction of rabbits into Australia), and on the other hand, when a race continues to inhabit the same region for a very long time, there may still be evolutionary change.

Clearly there is a tendency for every kind of organism continually to enlarge its region of distribution. These migratory movements are restricted by the existence of "barriers," that is, wide or deep oceans, high mountain ranges, deserts, etc., and biologists (who migrate in steamers and railway trains, taxi-cabs, etc.) are inclined to emphasize the effect of natural barriers in minimizing migrations. All animals, either throughout their entire life-periods, or in some phases of the latter, are mobile. Immobile, rooted plants may nevertheless be "dispersed" by their seeds. Accidental circumstances may enable animals to pass barriers, and in the course of geological changes the barriers themselves may, for a time, be removed. There are thus both the tendency and the means for the almost indefinite mixing of the races of organisms inhabiting the ocean (where there are no barriers), or of those inhabiting, say, Africa or Eurasia. And even in the cases of land regions that are separated, as the Americas and the old world, Africa and Madagascar, or Australia and Asia, the opportunities for intermigration of their faunas and floras certainly existed in the past. Thus the complete "mixed-up-ness" towards which (Willard Gibbs said) all physical systems tend of themselves ought, apparently, to characterize the distribution of organisms over the face of the earth. It does not, as we see, because the migrations of animals and the dispersals of plants are usually associated with morphological changes. On the other hand, the isolation (or prevention, by physical barriers, of migrations and dispersals) leads also to the evolution of new faunas and floras. In respect of the life-envelope, or biosphere, that tendency towards a state of complete "mixed-up-ness" clearly does not exist.

We may now consider the state of the biosphere in the same way as we have considered the state of, say, the hydrosphere, or the classical gas-model: that is, in the way that adherence to strict physical methods—those of thermodynamics and statistical mechanics—obliges us to adopt. We shall take the land fauna and flora of the whole world, and we shall partition the land surface into cells, each of, say, several thousands of square miles in area. We proceed to sample, at random, these cells, one at a time, expecting to find, from purely physical considerations, a condition of distribution of plants and animals that approximates to the state of maximum probability. We remember that, in the physical model, we have to allow for the action of external agencies that set up heterogeneities of distribution; gravity, for instance, leads to the greater density of the gas in the lower part of the gas-container than in the upper part. We seek for analogous agencies in the earth surface which we are studying, and we find them in what are called "climatic" conditions: greater or lesser elevations of the land surface above geoidal level; temperature of the soil and atmosphere; humidity of the atmosphere; turbulence of the atmosphere, etc. We expect that these agencies will lead to heterogeneities. In the gas-model there are precise functional relationships between the values represented by the parameters and the departures from uniformity of distribution in the gas. As some field of force becomes the more intense, so will the distribution of some aspect of the physical system be the more different from that which would have existed in the absence of the field of force. We expect to find in the land fauna and flora of the world a state of most probable distribution—of complete mixed-up-ness qualified only by those physical agencies that we know well and call "climatic factors."

It will be clear from the general considerations outlined above that we do not find such a distribution of plants and animals, and this is the conclusion from a study of the records of the geographical distribution of organisms. We can indicate only very summarily some of these results. (1) Regions that are remote from each other on the earth have very different faunas and floras; nevertheless

(2) the same genera, or even species of organisms, may be found in regions that are far apart. (3) Regions that are relatively near to each other have, in general, the same kinds of organisms; nevertheless (4) regions that are relatively near each other may be very different in respect of their general fauna. Africa and Madagascar, for instance, are biologically very different, but these regions are separated by deep sea; nevertheless, Iceland and Ireland have no snakes, though these regions have been continuous with Great Britain (which has snakes) in very recent geological times. The climate of Iceland differs materially from that of Great Britain, but that of Ireland does not. Again, (5) it would be easy to find regions on the earth that are remote from each other, but have similar climates, and yet have very different plants and animals, or both. And so on. Many such apparently paradoxical results might be quoted. We see that there is only roughly approximate association of climatic factors with biological similarities or dissimilarities (or, perhaps, no association at all). Of course, these paradoxes may be said to be resolved by consideration of the biological principles of adaptive radiations; the effect of barriers in preventing adaptive migrations, or radiations; isolation of stocks; intermixtures and competitions between stocks, etc. But clearly these are just the things that are physically to be explained.

We sample cell after cell of the land biosphere, methodically at random, and we do not find distributions that approximate to uniformity. Rather do we find heterogeneities that are not to be "explained" by the physical treatment of the data. The biosphere thus differs strikingly from the other earth-envelopes, where the distributions approximate to uniformity and the heterogeneities can satisfactorily be explained.

Evolution, in general, may be regarded as a series of changes *that have tendency, or direction,* in some physical system. In "cosmic evolution" the tendency is towards complete mixed-up-ness, energy dissipation, the increasing probability of the system considered, and therefore continual entropy-increase. In organic evolution the tendency is towards the continual appearances of novelties of morphology, of functioning, of behaviour and habitat, that is, towards the appearances of new species. The tendency is not inevitable, for we have the "persistent types" of paleontology, but these are quite exceptional. Regarded from the physical point of view, organic evolution means that a system originally highly improbable becomes always still more improbable. We may attempt to generalize the old conception of entropy, as it has been generalized by the methods of thermodynamics and statistical mechanics, and then extend it to biology. We may, of course, apply the conception to the energetics of the individual organism. Then we find that a system, the fertilized ovum, say, that is originally physico-chemically and morphologically complex, becomes still more complex with the process of development. Its entropy decreases as the individual grows in mass and reproduces, but at length there occur the catastrophic processes of somatic death, when the body disintegrates so that its parts assume the physical phase of greatest probability. Life, as a whole, the evolving stock, or race, however, passes through phases of increasing improbability, so that the entropy of the continuous world-life (being proportional to the logarithm of the probability), continually decreases.

Thus there are, in planetary history, two processes, each of which we may represent by series of phases occurring simultaneously; $a < b < c <$, etc., being the "inorganic" series exemplified by, say, the history of the lithosphere, hydrosphere, and atmosphere, and $a' > b' > c' >$, etc., being the organic series, exemplified by the evolution of the forms of living things—the biosphere. The probability of c is greater than that of b, and the probability of b is greater than that of a, and so on; and since time flows in the direction of increasing entropy (or increasing probability), c is "later" than b, c later than a, and so on. But the probability of the organic phase b' is *less* than that of b', the probability of b' is less than that of a', and so on, and there is a corresponding progression in the values of the entropies. And since time flows in the direction of increasing entropy (or increasing probability), it would appear that, in some way, c' is "earlier" than b', b' earlier than a', and so on, a result that seems fanciful but which it is not easy to controvert. It is, of course, implicit in Bergson's conception of "duration," as applied to the living organism, or to life as a whole.