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THE USE OF A NETWORK ENERGY SIMULATOR TO SYNTHESIZE SYSTEMS AND DEVELOP ANALOGOUS THEORY: THE ECOSYSTEM EXAMPLE[1]

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In the previous talks today, we have had examples first of the large central computer and then of the desk-size computer available for the laboratory. Now we go to the extreme indeed; we shall deal with a simple apparatus with which the operator feels satisfied only when he solders each unit into place. This is because the first purpose of the simulator is to develop analogous theory rather than to get a computational result. It will not suffice for these purposes to use an existing computer because one is interested in making each component represent the proper component function as well as in making the over-all function realistic. One can solve a particular equation in many different ways on a mathematical computer as far as final results are concerned, but for the network system to have the maximum usefulness, the system should be significant in every part. For maximum validity in each of its details, it should be possible for every measurement made in nature to be fitted into the network. So this is an attempt, then, to build up a little system from the bottom, checking each function as one goes.

An ecological system (ecosystem) is something like a bay, a forest, a chemostatic algal culture, a sewage pond, or any kind of self-maintaining, self-repairing entity of nature. There is enough in common among these different systems so that one can generalize about the ecosystem just as one can generalize about the cell. Just as some biologists think that the principal purpose of their existence is to understand the cell, so in environmental science one is concerned with understanding the ecosystem, first, in its generality, and then in the comparison of different ecosystems. In the field, one measures things like total photosynthesis of a bay, total respiration, chlorophyll, species diversity, and biomass. Ecological science is now overloaded with a tremendous amount of detailed numerical data. What has been lagging is the theory. We are on a threshold with an opportunity for rapid advancement, if we can develop quantitative theory to go with these detailed numbers.

This little example has one other significance to biomathematics. In trying to solve the ecosystem, one compares it to an electrical system, for which the synthetic knowledge is much greater, and also one attempts to generalize more or less in the way of steady-state thermodynamics. In the attempt to find generalizing functions, one may get a feedback into the physical sciences. The biological systems

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we are talking about here, like a fishpond or a marine bay, have the power to self-regulate and self-maintain, something not yet achieved in physical science. With actual values from ecosystems, one may possibly predict what kind of force flux adjustments and what kind of efficiencies one may expect when and if a physical automaton, completely self-maintaining and self-repairing, is developed.

In Figures 1 and 2, P represents photosynthesis and R is respiration. Briefly, each system can be described as a cycle of nutrients, carbon, etc., with a definite ratio of phosphorous, nitrogen, zinc, cobalt, and all the other elements which are bound into organic matter by use of an energy source. The processes in the chloroplasts of plants raise dispersed materials from a low level to a concentrated state at the top of the diagram; all the animal consumers, bacteria and fishes, respire and return the elements in the same ratio to the medium. The first principle of biological oceanography concerns the tendency for the surface zones of photosynthesis and the deeper zones of regeneration and respiration to get into a mutually self-regulating system with elements moving in similar ratios.

If one considers the cycle in a little more detail, P represents the elevation of carbon from an inorganic form (carbon dioxide) to organic carbon, the higher free-energy state, with the storage of photosynthetic energy. P_{net} represents the cytoplasm of the plant, which immediately starts to consume organic storage at the same time synthesizing some new growth. The new growth then goes to another class of organisms (H), like cows or parrot fishes, which is

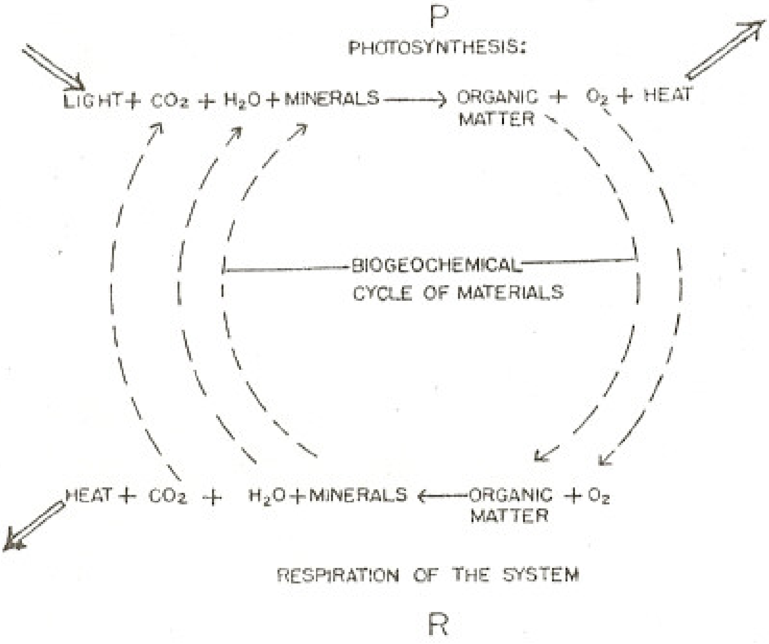

Figure 1. Definitions of P and R

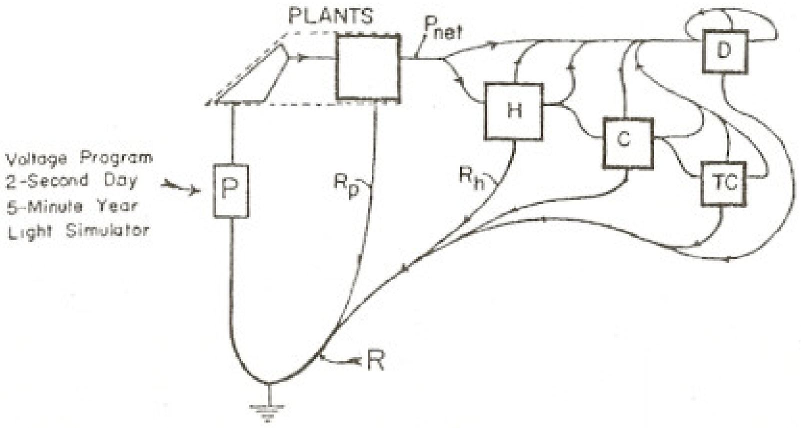

Figure 2. Main circuits of the ecosystem simulator. Flow and storage of electrons represent the flow and storage of carbon. See Figure 3 for the details of each box.

one step removed in the utilization of the energy and is called herbivores. R_h is their respiration; P_h is their growth synthesis which then goes to the next class of processors, the carnivores, the third removed from the production source. These animals, the fishes particularly, also have a respiration which releases nutrients to the pool, and a net growth, which is then eaten by something larger, like a shark. As you go down the circuit, you are losing energy of concentration of organic matter into heat, just as you are going down the voltage scale from the top to the bottom. Finally, there is a miscellaneous category of things associated with leakages out of these other circuits that are utilized by the decomposing (D) bacteria, which also respires. The total respiration is the sum of the respiratory circuits.

As you see, there are circuits in the ecosystem, biogeochemical circuits, and, since the component elemental cycles are in somewhat similar ratio, we can, in the abstract, talk about one cycle. It is natural to think of an electrical network circuit as a counterpart of the ecosystem. All we need to do is put the wires in place of the ecocircuits. Then we put in various particular electrical parts and try to define exactly to what each corresponds in the ecosystem. In this way, the system behavior will be the sum of the various functions that we already know how to measure. If this is done, the over-all system will automatically behave properly.

The basis of the circuit analogy is Ohm's law; the current is proportional to the voltage (J=CX), according to conductivity of the wires. We search for comparable items in the ecosystem. Here is the main point; we find that the analogous relationships are new concepts. We are using the system analogy to ask nature what we should try to define. The flux, J, is a known concept, the metabolism (amperage in the electrical case); this flux is often measured as the metabolism of an individual population or the metabolism of the whole system. Conductivity is a food chain circuit. We already identify both of these in ecology. Voltage or driving force is related to something we have measured for years, the biomass, pounds per acre. The analogous concept required is the biomass activity, that is, its thermodynamic thrust, which may be linear. Exactly what this is in nature is still uncertain. It is a new concept. If you have no fish population, you have no circuit--infinite resistance.

This system gives us many ideas. The more organisms there are, the more circuits. If there are two populations of organisms eating the same thing, there are two parallel circuits, a familiar situation known as competition in the same niche. For another example, capacitance in an electrical system is the amount of charge one can accumulate from the same voltage. This suggests biomass storage.

If you take one of the black boxes representing one population (Figure 3) and enlarge it, you find three variable resistances for adjustments, a storage condenser, and a feed-back unit representing reproduction. This feedback from the condenser voltage to the variable resistance with a linear increase of conductivity with voltage. As the charge in the storage accumulates, this resistance goes down. Reproduction supplies new circuits and thus lowers resistance.

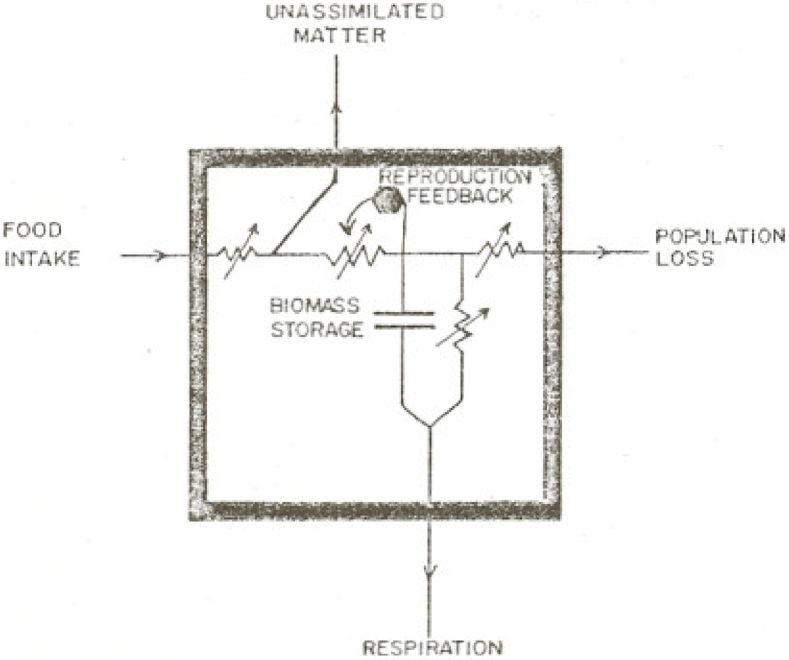

Figure 3. Circuits representing one level of food processing in the ecosystem. A feedback from the condenser voltage to lower resistance linearly represents growth followed by reproduction. Mathematically, this produces a logistic growth curve.

We use these concepts exactly similarly; we don't mean analogy, we mean exact energetic equivalence. This is the difference between the computer under discussion and some other simulators. Here there is an attempt to reach exact energetic equivalence rather than a circuit that merely simulates the end result.

In the case of the capacitance, the amount of biomass that one can accumulate per unit of active expression of organic storage (voltage) suggests the packaging of organic matter in nature, whether one puts it in a layer buried in the sediments, disperses it in a plankton medium in small particles, dissolves it in water, or puts it in a chunky fish. Considerations of ratios of volume to surface thus determine capacitance.

Why should there be a capacitance in ecosystems, which are photosynthesizing the respiring materials? Maximum survival value over other systems for natural selection require maximum steady metabolism. To have the maximum metabolism over a sustained period requires a mechanism for smoothing out fluctuations. The ecosystem is a pulsing system, pulsing daily and seasonally. To smooth out the pulsing input of photosynthetic energy, one must put in something like a condenser. Larger condensers are needed for larger pulses. This may be one role of organisms of different size. Perhaps one reason animals in the Arctic are larger than animals of similar type and similar activities in the tropics may be the need for large condensers with longer nights.

One asks two kinds of questions: (1) What is the electrical significance of a function observed in nature; or (2) given an electrical unit in a circuit, what is it in the ecological system. For example, what is a diode in nature; one needs a diode to allow a biomass to accumulate after the voltage of the sun has gone down. Otherwise the circuit reverses. Higher organisms like fish are diodes. Fish take food in their mouth and put it out through their system in a oneway process. Reversal is more likely in bacterial circuits. If there is an accumulation of organic matter without a diode, the simple circuits can reverse. For example, algae may turn around and be heterotrophic.

What is inductance? Inductive impedance, electrically, is a back resistance to the build-up of voltage. Well, what do we have in the ecosystem that does that? If you throw out a new source of food, the animals have a behavior patter that is very conservative, a resistance to change of habits. So the specialization that includes habits in this respect is an inductive impedance, another device to smooth out pulses.

Why are there branching circuits? Branching circuits help to control the voltage drop through each circuit so that there is maximum output. What is a short circuit? A short circuit is a fire. In the human system, short circuits are thefts or any other immediate removal of free energy source into heat with no useful accomplishment.

What is migration of a bird flock? What is a transformer? If there is a biomass over an area and one needs to raise the voltage (organic matter concentration) without adding any new power source, one may have the birds flock. In electricity, one raises the voltage when one transmits power across country. When one observes ecological shift of power storage out of one local system into another hemisphere with migration, one observes flocking. Afterwards, the dispersion of the flocks represents the lowering of voltage.

Well, perhaps that is enough to indicate the point of view. In other words, it is quite exciting to think that everything in nature has a purpose related to its function in the system, and that is why it is there. This is the antithesis of the point of view expressed last night. I think that nature is extremely economical in that, for example, things such as the respiration and the photosynthesis of a bay stay balanced through the year, and the logarithmic pattern structure of the different species tends to be very rigid. This may be just pure faith, but I suspect that, if we carried this to its ultimate, we should be able to give behavioral science a new push, because behavioral science is at present looking too much to mechanism; asking what the roles are in the ecosystem that would give a quantitative function for each behavior mechanism. Each item of behavior should then have an analog in the circuit.

Consider next some ideas of growth and reproduction suggested yesterday in the process of talking with many of the people here; consider the feedback (Figure 3). The analogy clarifies the thinking for quantitative purposes. When an organism grows, it has always been considered in two steps. One is the accumulation of organic matter, the synthesis. Second, the organic matter then leads to reproduction by the division of the original unit. The word, growth, sometimes refers to the whole sequence. The accumulation of biomass is the storage of the charge. Reproduction doubles circuits and lowers resistance. The flow through an ecosystem is proportional to the number of circuits. Reproduction follows synthesis,later adding circuits.

If there is a linear relationship between the amount of organic matter accumulated and the number of circuits added by reproduction, there is logistic equation of population growth. In other words, one arrives independently at the logistic equation without any consideration of birth rates, specific growth rates, density-dependent factors, or anything else. The threshold of the logistic is the threshold of voltage input or of the photosynthetic input. In other words, this appears to provide an opportunity that a lot of people have been looking for, namely, a way of relating the energetic side of ecology and the numerical population branch of ecology. The logistics as usually derived and those derived from forces and fluxes are comparable; apparently, they are the same thing expressed, perhaps, in slightly different terms.

Before closing, let us summarize. In addition to the fun and the practical utilization for ecology, this energy simulator provides a methodology that may be used in other senses. One not only develops the simulator to compute for a given operation, but one builds the simulator with each part having a significance. In this way, one can develop new theory from one science to be the analogous theory in the other science. If you have your basic equation in the same units, that is, in energy units, then the two should be actually comparable.

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INFORMATION THEORY IN BIOLOGY[1]

J. D. Cowan

Introduction

It is our loss that Dr. Ashby is unable to be present at this conference. He would have contributed greatly to our understanding of the contributions that cybernetics has made to the study of living systems. He would certainly have stressed the importance of the phenomenon of adaptation and its link with the intrinsic stabilities of dynamic systems. This aspect of cybernetics, to which Ashby (1), Wiener (2), and others have made outstanding contributions, is not, however, an aspect with which I am fully conversant--and rather than discuss it, I propose instead to consider some recent developments in information theory and their possible application to biology. These developments concern the problem of synthesizing reliable organisms from unreliable components.

Before doing so, however, I should like to make some general comments on the validity of information theory in biology. Note that information theory has come to mean many things to many people. In Europe, for example, it is synonymous with the term "cybernetics" introduced by Wiener, to denote the comparative study of communication and control mechanisms in animals and machines. In the United States, information theory is synonymous with communication theory, and includes all possible probabilistic analyses of communications problems, notably those of Wiener (2) on prediction and filtering and Shannon (3) on transmission and coding. We are concerned essentially with Shannon's mathematical theory of communication, on the generation, storage, transmission, and processing of information, in which a particular measure of information is used.

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