

## ENERGY CIRCUIT LANGUAGE AND ENERGY TRANSFORMATION IN ASYMPTOTIC GROWTH

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### INTRODUCTION

The studies of complex networks which have flows and storage of energy in ecosystems, biological systems, electronic networks, chemical engineering chains, and social systems have been facilitated in recent years by systems languages as well as by the more traditional expressions of kinetics with differential equations. Thus mathematical flow diagrams, analog computer diagrams, signal flow charts, and electronic equivalent circuits often present complex networks with as much precision and clarity and with more overall understanding for some human minds than the older languages, especially where many components are involved. Emerging in ecological studies, but general and suitable for social, biochemical, economic, and electrical systems as well, are operational measures of energy flow that require a new language, that of energy circuits. Using symbols that are each mathematically defined for an energy transformation operation, networks of potential energy and heat flow are drawn for food chains in seas, streams, and forests. A set of symbols for the operators was introduced in the previous papers (Odum, 1967a, 1967b, 1968, 1970a, 1970b). In this work we build on ideas for general system theory set forth by von Bertalanffy (1968).

Since the basic equation for growth performance of one of the basic operation modules has been associated with

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papers of Ludwig von Bertalanffy, it is appropriate to name this unit a "von Bertalanffy compartment." In this essay the properties and performance of the von Bertalanffy compartment are described in several other languages. Another module is the cycling energy receptor which includes a von Bertalanffy compartment, and its performance is also described. Finally, the properties of the energy circuit that combines the von Bertalanffy compartment and the cycling energy receptor are considered as a self-organizing reward loop.

#### ASYMPTOTIC VON BERTALANFFY GROWTH COMPARTMENT

In many branches of biology the asymptotic equation (1) that describes many classes of growth carries the name von Bertalanffy, acknowledging his contribution in deriving its differential form from biological premises which are often applicable and measurable (von Bertalanffy, 1938, 1960). The same equation carries other names in other branches of science. Von Bertalanffy (1938) acknowledges some precedence by Pütter. In the paragraphs that follow, the equation is expressed in several languages now in use and as a property of a compartment in energy circuit language. See Fig. 1.

##### *Differential Equation*

The rate of change of organic matter in a growth compartment ( $Q$ ) is a balance between an input flow ( $J$ ) and outflows, such as respiration, which may be proportional to the mass stored in the compartment ( $-k Q$ ). The flows and differential terms are given as equation (1). The balance of the two flows is the rate of change of storage ( $dQ/dt$ ).

##### *Integral Equations*

The integral form of the above expression is indicated in equation (2), which states that the value of organic matter storage is the integral summation of the balance of the inflows and outflow. If one carries out the integration mathematically using initial conditions of zero and  $J$  as a constant ( $J_{in}$ ), one obtains equation (3), a form of the expression which is often evaluated in biological studies, although not always under conditions where the two limitations apply. Equation (3) is often expressed with

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## VON BERTALANFFY COMPARTMENT

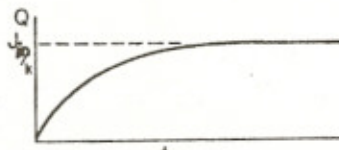
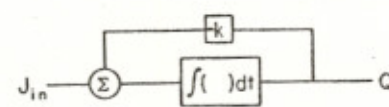
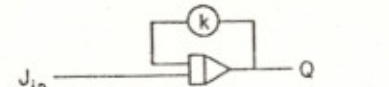
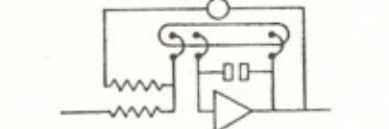
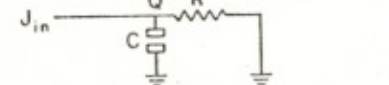
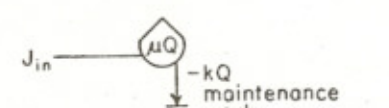
- (1)  $\frac{dQ}{dt} = J_{in} - kQ$  Differential
- (2)  $Q = \int (J_{in} - kQ) dt$  Integral
- (3)  $Q = \frac{J_{in}}{k}(1 - e^{-kt})$  Zero start  
 $J_{in}$  constant  
 $N=0$  at  $t=0$
- (4)  Charge graph
- (5)  Block
- (6)  Operational analog
- (7)  Machine detail
- (8)  Equivalent circuit
- (9)  Energy circuit

Fig. 1

the constants arranged differently, but the form here shown has constants in form significant to energy flow notations. The form of the growth and asymptotic levelling of  $Q$  with time is shown as (4) in Fig. 1. With different initial conditions somewhat different expressions and curve shapes result. For example with  $Q$  large at the start, there is an exponential decay to steady state level and the integrated equation has two exponential terms.

*Block Language*

The integral expression (2) can be expressed as a flow of terms in successive operational steps as block language shown in expression (5). In this language the self-regulating, negative, summing feedback property is immediately apparent. Discussions of the equation in this form as control theory are given in Milhorn (1966) and Milsum (1966). Expression of the storage tank modular function in this language reminds us that such units are integrators, and that our world of flows and storages is one of strings of integrators in its own computer.

*Operational Analog Language*

Block language that expresses the flow of mathematical terms is symbol-for-symbol convertible into the language of the operational analog computer hardware as shown in expression (6), which includes an integrator, a constant multiplier potentiometer, and summation of inflow and loop-back. The machine details that one would use to actually set up the problem board on the analog computer are given in expression (7). For this usage in studies of organic matter on the forest floor, refer to contributions of Neel and Olson (1962) and Olson (1963). Such hardware simulates the charge and discharge curves and allows test of the effects of changing parameters or the contribution of the compartment to some more complex circuit of which this is made a part.

*Electronic Equivalent Circuit Language (Passive Analog)*

The charge of an electrical capacitance in an RC circuit is a basic operation in electronics and circuit analysis. It is the balance of an inflow and a discharge that is proportional to storage as defined for the differential equation. Thus the electrical hardware diagram for the RC circuit in expression (8) is another language for the von Bertalanffy equation and another electrical analog which simulates the charges and discharges that follow variations of inflow.

The comparison of the values of resistance and capacitance used in the electrical equivalent analog with the constants in the differential equation, shows that the percent discharge rate ( $k$ ) is the reciprocal of  $RC$ .  $RC$  is called the time constant and is numerically equal to the

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*In Energy Circuit*

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time for 66% of the charging to be accomplished. The statement that outflow is proportional to the storage ( $-kQ$ ) turns out to be Ohm's law ( $J = (1/RC) Q$ ).

*In Energy Circuit Language*

The energy circuit language is related to the equivalent circuit language, but represents the flow of energy rather than the flow of electrical current. Some of the concepts and premises of the language were presented elsewhere (Odum, 1967a, 1967b). The von Bertalanffy growth is represented in energy circuits by expression (9). Although the diagram seems very simple, all of the same quantitative relationships are implied by the lines, tank symbol, and heat sink symbol, including also the representation of energy laws. The diagram is just as precise as the other languages given in expressions 1-8. In energy circuit language, storage of potential energy is indicated by the tank symbol which is fully defined only when the storage function is also written. For the storage of organic matter ( $Q$ ) in many aspects of organic growth, the potential energy is in linear proportion to the number of similar packages and is the product of the potential energy value of each ( $u$ ) and the quantity of units stored ( $Q$ ). When no special storage function is written, the linear relationship is meant ( $uQ$ ). Each line indicates a flow of potential energy driven by a population of forces ( $N$ ) either from the storage ( $uQ$ ) or from an outside source. The drive ( $N$ ) by the storage ( $Q$ ) on the flow out is in proportion to the storage ( $Q$ ) according to the energy-force function ( $N$ ) that is a property of the packaging ( $C$ ) when ( $N = Q/C$ ). This concept is analogous to capacity in electrical examples. Flow is proportional to the population of forces (also called thrust and ecoforce in previous papers) derived from storages or outside sources. Conductivities ( $L = 1/R$ ) are a property of circuits and are affected by work flows and loopbacks that serve as pumps, gates, and circuit maintenance flows across energy barriers. Forward forces from energy storage are balanced by backward-directed frictional forces along the circuit.

As drawn in (9), the tank represents the organic storage of an ecosystem in which the main patterns of the structure are already developed so that the discharge and charge do not involve changes in the number and conductivity of pathways. Populations are mainly constant in this

situation. The storage is not accelerating input flow by lowering input conductivity to the storage in proportion to the storage, as in the logistic relation previously discussed in energy circuit language (Odum, 1967a). The work drain into the heat sink represents steady state maintenance flows as in animal respiration. The statement that flux (J) is proportional to population of forces (N) is the general causal law ( $J = LN$ ) of which Ohm's law is a special case with only one force.

#### CYCLING ENERGY RECEPTOR

Whereas much of the potential energy in the systems of man and nature is associated with material positions and relationships, the energy that flows in from space to support the basic plants and agriculture is a pure energy, a wave-like dilute flow of photons which must be captured and transformed into more concentrated potential energy storages that drive the various biochemical food processes of the ecological or social systems. To receive any kind of wave energy requires a cycling receptor system in which matter is passed around in a circle between a state of high potential energy and one of low potential energy, the pure energy inflow causing the elevation of state from which a downhill flow drives other activities of the system downstream. Thus the inflow of tide of the sea may be caught in a basin by tidal water flow that is raised to an elevated storage, from which it can drain through an electric generator. The reception of light energy by the biochemical chlorophyll system is a cycling receptor system of this type in which chlorophyll is circulated from a low energy state by the incoming reaction of photons to a high energy state which drains back into a low energy state driving oxidation-reduction reactions of plant food production. The cycling receptor operator has the property that there is a set quantity of cycling receptor material circulating (Q), and this limitation is one of the constraints on the performance of the receptor process. The kinetics of the photosynthetic process are given by Lumry and Reiske (1959) and these equations are the same as those for the Michaelis-Menton (1913) enzyme-substrate reaction, where an enzyme is being recycled as the means for receiving energy that is supplied by the substrate. The same expressions appear in various studies of photochemistry (Mitchell and Zemansky,

1934). The same with cycling system of a stream of bacteria paper (Odum,

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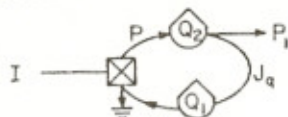
(19)

(20)

1934). The kinetics of a purely physical photocell is the same with cycling electrons (Billig and Plessner, 1949). A system of a rotating wheel of cups catching some of a steady stream of balls was compared qualitatively in a previous paper (Odum, McConnell, and Abbott, 1957). The general

CYCLING RECEPTOR

(10)



(11)

$$P = k_0 I Q_1$$

Energy reaction

(12)

$$Q = Q_1 + Q_2$$

Constant receptor

(13)

$$J_q = L \frac{Q_2}{C} = P$$

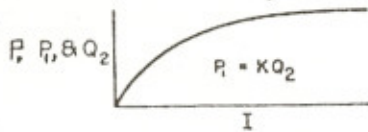
Steady state

(14)

$$Q_2 = \frac{C k_0 Q I}{L + k_0 C I}$$

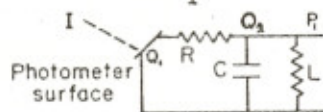
Hyperbola

(15)



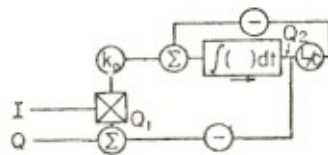
Steady states

(16)



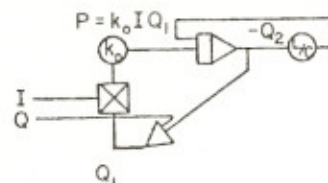
Equivalent circuit

(17)



Block

(18)



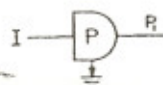
Operational analog

(19)

$$P = \frac{P_{MAX} I}{I_k^2 + I}$$

Alternative form

(20)



Energy circuit

class of system modules with the same cycling receptor kinetics can be represented in various languages, including the energy circuit language as given in Fig. 2. The graph of the effect of input energy is the familiar limiting factor hyperbola.

*Rectangular Hyperbolic Relation of Light and Production Rate at Steady State*

As drawn in (10) of Fig. 2, light reacts with available receptor material ( $Q_1$ ), such as chlorophyll in the photosynthesis case, movable electrons in the selenium photometer, or water in the pools of a wave splash pool with a product relation as in equation (11). The total receptor material is the sum of receptive ( $Q_1$ ) and activated ( $Q_2$ ), as in equation (12). The energy activated receptor tends to fill the temporary reservoir ( $Q_2$ ) from which forces drive external processes and at the same time return the cycling receptor to its low energy state through flow circuit ( $J_q$ ). Some energy goes into the heat sink. The return flow is shown in equation (13) as proportional to the drive generated by the storage ( $Q/C$ ) according to the conductivity of the return flow ( $L$ ). For constant input a steady state of recycling develops ( $J_q = P$ ). Combining expressions produces the rectangular hyperbola (14) which relates energy storage to input energy ( $I$ ) with a form of the graph (15). In (16) is given the circuit for the selenium photometer example with condenser storage which also serves as equivalent circuit for the general case. In the photometer the  $Q_1$ , storage is in the photometer surface.

The block language for the equations is diagrammed as (17) and the operational analog representation is similar to (18). The kinetics of the charging process as steady state is developed follows the exponential pattern as already shown in (4), although cycling receptor systems such as photosynthetic chloroplasts have such small time constants that steady state (equation 14) is achieved immediately.

The expressions for  $Q_2$  and for the dependent productivities  $P$  (11) and  $P_1$  have the property, when the amount of input light ( $I$ ) is very small relative to recycling conductivity ( $L$ ), of approaching the expressions  $P = k_0 Q I$  and  $Q_2 = ck_0 Q/L$ , a linear relations with slope  $k_0 Q$ . Receptor systems which are large relative to available energy

inflow are material, as

When light inductor of (14) and the overall and  $P = LQ/C$ .

Parentheses theory for light (1936) and light (1957) and Verduin empirically a different from manipulates it is still a re intensity at inspection. lines if the is plotted as ent variable

The Baul light intensity hyperbolic re general shape by Verduin (19 theoretical s the cycling re

The cycling with the various energy circuit photosynthesis first stage in reacts with the circles that be light. In phy and may be sep ecological stu initial light overall kinetic expressions in P be used in dif of photon rece the forest, or

inflow are maximized by increasing the amount of receptor material, as do some plants in shade adaptation.

When light input is very large, the  $L$  in the denominator of (14) is small compared to the other term,  $k_0 CI$ , and the overall expressions approach the relations  $Q_2 = Q$  and  $P = LQ/C$ , describing the asymptotic maximum.

Parenthetically, we should mention an alternative theory for light-production curves that began with Smith (1936) and later was used by many others such as Talling (1957) and Vollenweider (1966). The equation derived empirically and used by these authors is supposed to be different from the rectangular hyperbola, but if one manipulates its form one finds the expression (19), which is still a rectangular hyperbola where  $I_k$  is the light intensity at which the curve begins to bend in visual inspection. Rectangular hyperbolas such as (14) are straight lines if the reciprocal of the dependent variable  $Q_2$  on  $P$  is plotted as a function of the reciprocal of the independent variable  $I$ .

The Baule-Mitscherlich equation for photosynthesis and light intensity is an asymptotic exponential instead of a hyperbolic relationship, but can be used to fit data of the general shape of (15) in Fig. 2, as most recently discussed by Verduin (1964). However, it apparently does not have the theoretical significance of the hyperbola that describes the cycling receptor kinetics.

The cycling receptor process as defined and described with the various equations of Fig. 2 is represented in the energy circuit language as (20). In complex processes like photosynthesis the system described in Fig. 2 is only the first stage in a chain of compartments, each one of which reacts with the next with many successive internal material circles that behave as the one which first received the light. In physiological studies these steps are of interest and may be separated in the system diagrams, whereas in ecological studies all the stages closely affiliated with initial light reception may be combined as long as the overall kinetic behavior conforms to the manner of the expressions in Fig. 2. Thus the cycling receptor symbol may be used in different diagrams to be the electron separation of photon reception, the whole chloroplast, the whole plant, the forest or a system of agricultural production.

COMBINATION OF CYCLING RECEPTOR AND VON BERTALANFFY  
COMPARTMENT FOR CONSUMERS

For the balanced aquarium, for plant-animal symbiosis, and for the overall equation for space ship earth, one may combine the cycling receptor module of the energy circuit with at least one more cycle of materials and one more von Bertalanffy compartment representing respiratory consumers that eat plant products as given in Fig. 3. The water tank analogy (21) is useful in teaching the principle. Energy conversion and production of potential energy storage are followed by use of this energy in necessary work. The equivalent circuit (22) serves as a good analog model for the classroom, stimulating the energy flows and mineral cycles in the charge and discharge process.

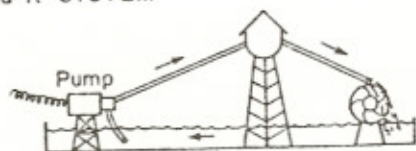
The balanced aquarium is a system of recycling minerals and gases as drawn in (23). The light energy passes in to drive the biological processes. The photosynthesis P of the plants makes chemical potential energy of organic matter which is temporarily stored. This stored energy then drives the respiratory fuel consumption processes and the circular flow of the carbon cycle and with it other minerals such as phosphorus and nitrogen. The storages and metabolisms must be compatible to the regime of light with enough storage to last through periods of interrupted light. Charge and discharge curves are given in (24) simulating the pattern of day photosynthesis and night respiration in many ecological systems.

The equivalent circuit for a production and consumption system was used previously (Odum, Armstrong, and Beyers, 1963) for interpreting diurnal patterns of maximum photosynthesis and respiration at the start of the day and of the night. The time response to an on-off forcing function was of the pattern of (24). Milsum (1966) used this example to show the self regulating aspects of the mineral cycle using the block language as in (25) and the simulation diagram (26). The near temperature independence of one set of microcosms due to the loop properties was demonstrated by Beyers (1962). Margalef (1962) discusses our circuit models including one with a photocell. The single von Bertalanffy compartment in Fig. 3 may be divided into two and more compartments in diagrams where the species that are the natural population compartments are separated in function (Odum, 1971), some in parallel and some in series. For systems of

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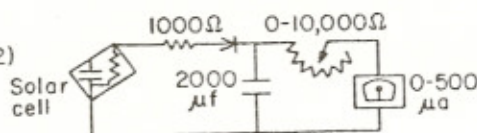
P and R SYSTEM

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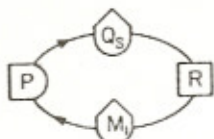
Water

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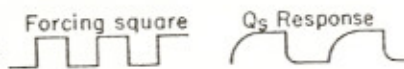
Equivalent circuit

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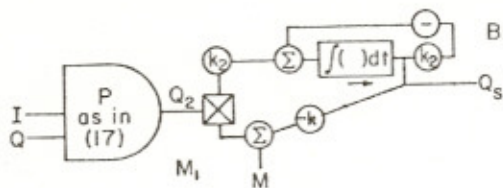
Mineral cycle

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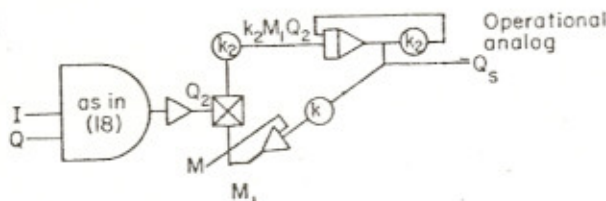
Charge-discharge

(25)



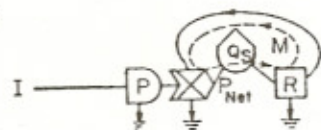
Block

(26)



Operational analog

(27)



Energy circuit

Fig. 3

man and nature the various occupations and industries become the separate compartments and the various plant species become separate circuits for energy reception. The great stability of small terraria (Odum and Lugo, 1970) may be due in part to this self regulation of storages and flows.

In the energy circuit language (27) the cycling receptor system is shown with some of its output energy driving the isolated von Bertalanffy compartment. Since the by-products of respiration are the substances needed for reaction in the photosynthetic overall mineral cycle (carbon dioxide, phosphates, nitrates, etc.), these must be provided back to the initial receptor as a reactant and thus take part in multiplicative action forming another limiting factor, hyperbolic action. Thus the mineralization of consumers serves as a pumping work process and fertilizes the plant primary process, whether in small scale as the symbiotic zooxanthellae of animal corals or in the reprocessing of city wastes to serve agriculture.

Since small amount of energies may be involved in the loopback of the work pump to deliver the minerals back to plants, there is a low energy means for stimulating the system upstream for the success of the types downstream. Thus the work from downstream serves as a control in the form of a limiting gate (Sugita, 1962). By such patterns as ratios of element ratios delivered, the downstream favors and rewards the plants upstream that are of a type that can be consumed. The downstream consumer unit is like a farmer, whether it be a simple biochemical stage or a whole system of agriculture and man. Because the loopback reward has its actions increased by the power circuit of plant flow, the loopback effect is amplified. What is the amount of control energy that is necessary to successfully develop the two into a self-rewarding pair? Loop rewards in other systems are termed learning. The development of self organization by loopback rewards is also called succession.

These definitions of new symbols serve here as a general systems summarization, showing the broad meaning of the von Bertalanffy compartments in the macroscopic and microscopic world. Greater possibilities of the energy circuit language may lie in the diagramming of more complex networks so as to show conductivities, the patterns of work, the limitations provided by the energies involved, the pathway directions of force populations, the locations of storages, and the way known kinetics of components make up a larger pattern. Just as block language leads easily into operational analog simulations, so energy circuits with their emphasis on flows lead easily into passive analog simulation with equivalent circuits. Energy circuits may

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further help to bridge the gaps in communication between those studying ecological and social systems and those working with other systems languages in electronics and information science. For further examples, see Odum, 1971.

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