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Short communication

The role of passive electrical analogs in H.T. Odum's systems thinking

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In the 1950s and the 1960s H.T. Odum used simple electrical networks composed of batteries, wires, resistors and capacitors as models for ecological systems. These circuits were called *passive analogs* to differentiate them from operational analog computer circuits, which simulated systems in a different manner. While Odum's passive analog models have been recognized as one of the earliest approaches to systems ecology (Shugart and O'Neill, 1979), the purpose of this paper is to emphasize their importance to the development of Odum's approach to systems.

Odum's first published paper on passive analogs (Odum, 1960a) set out the theoretical proposition that Ohm's Law from electronics was analogous to the thermodynamic functioning of ecosystems. He then explored this idea by constructing and simulating an electrical circuit of the Silver Springs ecosystem in which

> . . . resistances are grouped at locations of the producing and consuming populations. Batteries supply the concentrated energy representing the sun and the energy imported as organic matter from the outside. The various branching flows of food energy to consumers are presented with branching electrical wires. Variable resistances and switches permit the observer to set up various special situations and combinations. (Odum, 1960, p. 5)

It seems clear that for Odum the concept that a battery (or more explicitly the solar electricity generator he sometimes used) pushed electrons around a copper circuit in almost exactly the same way that the sun pushed energy (or reduced carbon) around the invisible circuits of an ecosystem. Also in 1960 he recommended the passive analog as an important lesson for teaching ecology to secondary school students (Odum, 1960b). Odum emphasized that simulation was a way of bringing to life the flows of materials in ecosystems and suggested that students find the construction of a passive analog particularly challenging:

> Students with a yen for the soldering iron can be utilized in combining physical and biological science to make a gadget, which mimics in some ways the flow of materials in the ecosystem. (Odum, 1960b, p. 77)

Although his Ohm's Law analogy was quickly criticized on several grounds after the American Scientist paper was published (Kangas, 1995), Odum modified the analogy to address these criticisms and continued to use passive analogs as ecological models for another decade. A number of these models were published (Table 1) for different systems and for different purposes. Each model was a piece of hardware in which there was a one-to-one correspondence between electrical components of the model network and aggregated ecological components of the system being modelled. Physically, the model consisted of a board on which the electrical components were

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Table 1
Passive electrical analog models of ecosystems published by H.T. Odum

Reference	System modelled	Published simulation
Odum (1960a)	Silver Springs, Florida	Biomass distribution
Odum (1960b)	Teaching model	None
Odum (1962)	Logistic growth model	None
Odum (1963)	Seagrass model	None
Odum et al. (1963)	Tropical plankton model	Time transient
Odum (1970)	Tropical rain forest	None
Nixon and Odum (1970)	Photoregeneration	Time transient

mounted and then connected by wires. The flow of electrons in the electrical network represented the flow of materials, such as carbon, in the ecosystem. Storages were represented as charges in capacitors. The model was scaled to a particular ecosystem by quantitatively adjusting the sizes of the electrical components used. Thus, the Silver Springs model was scaled with 13.9 mA/g/m^2/year of carbon flow (Odum, 1960a). Milliammeters and voltmeters were used to make measurements of flows and storages at various locations on the network for examining simulations. Although the passive analog was used as "a computation device" (Odum, 1960a, p. 5), only a few simulations were actually published and these were usually just transient responses of the circuit that represented diurnal curves. In fact, simulations were not easy to carry out on the passive analogs and this feature was probably what caused Odum to switch first to operational analogs and then to desk-top digital computers once they became readily available (Kangas, 1995).

Although the passive analogs were somewhat awkward to use for simulation, they were very important in the development of Odum's approach to systems ecology. This importance is reflected in several quotes given below:

> The process of setting up flows and functional parts is a powerful stimulant to the imagination, helping one to be precise, to ask new questions about the particular networks, and to secure the right measurements. The electrical flows, being very fast, can simulate the much slower systems. Because electrons and their control pieces are very small, they can model large systems that would be expensive or impossible to manipulate experimentally. (Odum, 1971, p. 256)

In a gray literature report on his rain forest simulator, Odum suggested:

> The model serves as a rallying point for ecological synthesis, which is the most difficult problem in environmental science. Biogeochemistry, productivity, autecology, population growth and death, and control behavior are all represented in the model. (Odum, 1965, p. 6)

In an earlier exchange during a question and answer session following presentation of a paper Odum concluded:

> This is our thinking device . . . The circuit helped us convert biological thinking consistent with structure into theory without going through the math until after the answer was found. (Odum, 1963, p. 229)

This last quote is especially important because it indicates the key feature in how the passive electrical analogs influenced H.T. Odum's systems approach. The hardware was the model of a system so there was no need to write out a set of differential equations in order to "describe" the system. In other words, Odum thought about systems in terms of the electrical networks instead of thinking about them in terms of explicit equations. At least for systems ecology, this was (and is) a completely unique way of thinking. For all other modelers the equations are the model. Thus, the electrical diagrams of ecosystems took the place of equations in Odum's approach and, in essence, they became a kind of visual mathematics for him. In a sense Odum left off a step in the conventional modelling process. He went right to the hardware (passive electrical analog) to simulate while others wrote equations and then went to the hardware (operational analog or digital computer) to simulate. Thus, H.T. Odum, as was often the case in many other realms, used different thought processes from nearly everyone else who was modelling ecological systems. It is not clear whether or not this fact is significant but it may help to explain why he seemed to see nature differently than others working in the field of systems ecology.

Odum created a symbolic modelling language, called the energy circuit language (see Brown, this volume), from the electrical circuit diagrams in the 1960s. This conceptual language was ultimately richer, in its ability to describe systems, than the electrical circuit diagrams yet was still a form of visual mathematics, since each symbol in the language has a mathematical translation. Drawing a diagram is therefore equivalent with writing equations. The following quote touches on these points:

> Whereas operational analog methodology involves the writing of differential equations first, passive analog methodology bypasses the equations except to verify the similar behavior of the particular hardware pieces used. The energy network language and the electrical model are forms of mathematics in themselves, but forms that naturally resemble the normal ways of thinking in biology, ecology, and the social sciences. (Odum, 1971, p. 261)

Fig. 9-1 in Environment, Power, and Society (Odum, 1971, p. 257) shows a correspondence between electrical circuits and the energy circuit language components. Odum credited the heritage of passive analogs when he reviewed the energy circuit language in depth (Odum, 1972, 1983). Since he used the energy circuit language for the rest of his life, the importance of passive electrical analogs to his systems approach is apparent.

Fig. 1 places Odum's initial passive analog publication on a time line for perspective. On the left-hand side of the diagram are listed milestones in the history of systems ecology and on the right-hand side are milestones in the history of electronic computation devices. As noted by Shugart and O'Neill (1979) Odum's publication was at least one of the first examples of electronic simulation of ecological systems. In fact, the first analog computer simulation (Olson, 1963) and the first digital computer simulation (Garfinkel, 1962) came just after Odum's paper. However, credit for "who did it first" is not really important, especially since all of these early papers came out almost simultaneously. What is significant is that a succession in the use of computation devices took place in systems ecology starting at about 1960 (Kangas, 1995). After his initial publication, Odum used passive analogs only through the 1960s and then switched to operational analogs for his modelling work.

Passive analogs had been used since the 1930s for simulating water flows, neurons and other systems where Ohm's Law could act as a basis for modelling, but basically Odum was the only ecologist to use them for simulating ecosystems. By moving on to operational analogs, he stopped modelling using hardware and joined everyone else in modelling using software. It is interesting to note that at this time at least some neurobiologists continued to model in hardware. Thus, the early neuron models had evolved into hardware systems such as Walter's (1963) electronic turtle (which Odum, 1983 diagrammed in Fig. 6-11) and Ashby's (1960) homeostat, which continued to evolve into today's biologically-inspired robots (Holland and McFarland, 2001; Webb and Consi, 2001). One wonders what would have emerged if Odum had continued to model using hardware systems, as did some of the neurobiologists. As can be seen on the right-hand side of Fig. 1, the microelectronics revolution was just beginning when Odum was using passive electrical analogs. Of course, this was occurring in the research labs of commercial electronics companies and Odum wouldn't have had easy access to this knowledge or to the new pieces of hardware. But what if he had? Odum and his students were developing ever more complex passive analog models of ecosystems (for example, of the rain forest in Puerto Rico) and Armstrong and Odum (1964) were even generating electricity from ecosystems (i.e., from the redox gradient in algal mats)! It can be imagined that Odum might have developed whole new kinds of electronic-based ecosystems, if he had been able to embrace microelectronics. Fig. 2 is a plot of Moore's Law for the increase in computing power. Had Odum continued to model using hardware, he might have constructed very complex "gadget" ecosystems after some 40 years. One only has to think of a passive analog ecosystem model with the computational power of Deep Blue, the chess computer that defeated the human champion (Hsu, 2002), to realize that Odum's work was a forerunner of Kurzweil's (1999) "Age of the Spiritual Machines". Perhaps when Odum coined the term "technoecosystem" (Odum, 1983), he might

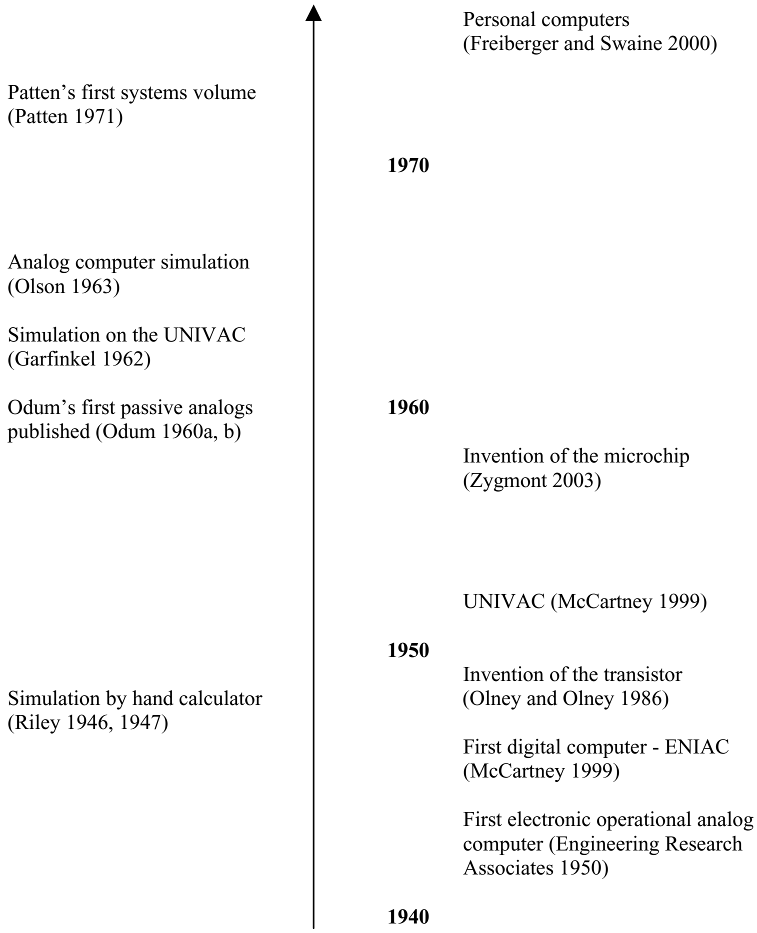

Fig. 1. Time line comparison of the history of systems ecology on the left and computer hardware on the right (ERAI, 1950; Freiberger and Swaine, 2000; McCartney, 1999; Olney and Olney, 1986; Patten, 1971; Riley, 1946, 1947; and Zygmont, 2003).

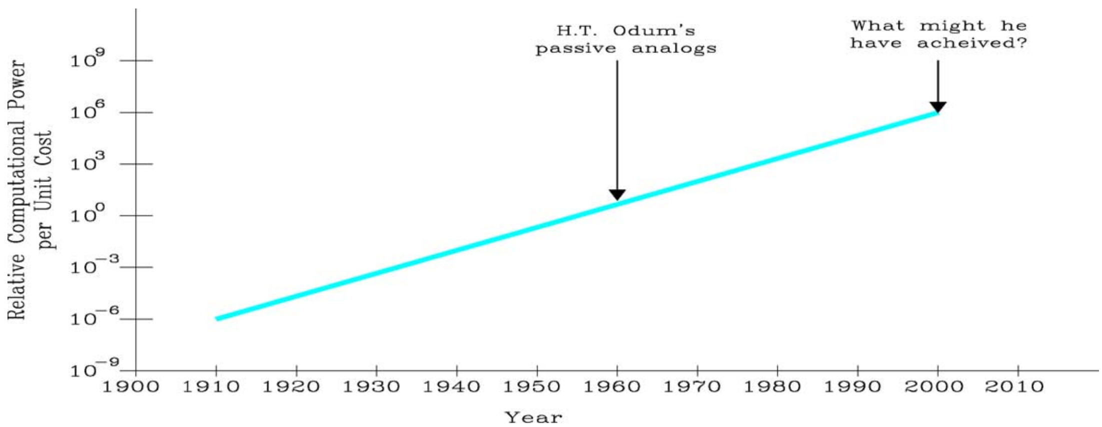

Fig. 2. Moore's Law's plot showing how H.T. Odum's passive analogs may have evolved.

have been thinking of what could have been accomplished by combining his old passive analog approach with the new microelectronics. This imaginary line of work would certainly be recognizable by the present-day artificial life community (Kangas, 1994) and it probably would have opened up new ways of thinking about ecology that we will never know.

A passage from Environment, Power, and Society (Odum, 1971, p. 274) under the heading of "The Network Nightmare" may have been a fictional attempt at imagining the futuristic passive analogs that he never constructed:

> The difficulties of managing nature and man can be stated in circuit terms. Let us first fantasy the nightmare of an electronics technician. After a week of exhausting tedium, soldering circuits and completing a large network of wires connecting thousands of tubes, transformers, and transistors, he goes to bed with the feeling of a design completed. Then with the veil of the dream the parts begin to breathe. Next he sees them grow and divide, making new parts. Then the wires become invisible. The new and old parts disconnect themselves and move into new patterns, reconnecting their inputs and outputs, replacing worn members, and together generating functions and forms not known before. What was neat and known becomes unknown. Soon the new system with its vast capabilities is growing, self-producing, and self-sustaining, drawing all the available electric power. Our hero awakens when he pulls the switch removing the energy source. To some visionary engineers the nightmare may seem a preview of a machine world. Our ecosystem, however, is already the nightmare.

Was this passage autobiographical? Was Odum actually the hero mentioned in the quote above? We can only speculate on what kinds of artificial ecosystems he might have constructed, but we are fortunate that his "yen for the soldering iron" gave us some insight into his unique view of systems.

In conclusion, H.T. Odum's early use of passive electrical analogs as ecological models represented at least one of the original lines of research leading to modern systems ecology. The passive analogs allowed for an early form of simulation to be performed and they provided a foundation for the energy circuit language which is now widely used for describing systems. Although Odum largely abandoned hardware modelling after the 1960s, the use of passive analogs was a continuing inspiration to his thinking and interest in the approach may be renewed by new developments in various forms of artificial ecosystems.

References

Armstrong, N.E., Odum, H.T., 1964. Photoelectric ecosystem. Science 143, 256–258.

Ashby, W.R., 1960. Design for a Brain, The Origin of Adaptive Behaviour. Chapman & Hall, Ltd., London, UK.

Engineering Research Associates, Inc., 1950. High-Speed Computing Devices. McGraw-Hill Book Co., New York, NY.

Freiberger, P., Swaine, M., 2000. Fire in the Valley, The Making of the Personal Computer. McGraw-Hill, New York, NY.

Garfinkel, D., 1962. Digital computer simulation of ecological systems. Nature 194, 856–857.

Holland, O., McFarland, D., 2001. Artificial Ethology. Oxford University Press. Oxford, UK.

Hsu, F.-H., 2002. Behind Deep Blue, Building the Computer that Defeated the World Chess Champion. Princeton University Press, Princeton, NJ.

Kangas, P., 1994. Letter to the editor. Ecol. Eng. 3, 93–94.

Kangas, P., 1995. Contributions of H.T. Odum to ecosystem simulation modeling. In: Hall, C.A.S. (Ed.), Maximum Power, The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, CO, pp. 11–18.

Kurzweil, R., 1999. The Age of Spiritual Machines, When Computers Exceed Human Intelligence. Penguin Books, New York, NY.

McCartney, S., 1999. ENIAC, The Triumphs and Tragedies of the World's First Computer. Berkley Books, New York, NY.

Nixon, S.W., Odum, H.T., 1970. A model of photoregeneration in brines. Department of Environmental Sciences and Engineering, University of North Carolina. ESE Notes 7 (1), 1–3.

Odum, H.T., 1960a. Ecological potential and analogue circuits for the ecosystem. Am. Sci. 48, 1–8.

Odum, H.T., 1960b. Ten classroom sessions in ecology. Am. Biol. Teacher 22, 71–78.

Odum, H.T., 1962. The use of a network energy simulator to synthesize systems and develop analogous theory: the ecosystem example. In: Lucas, H.L. (Ed.), The Cullowhee Conference on Training in Biomathematics. Typing Service, Raleigh, NC, pp. 291–297.

Odum, H.T., 1963. The element ratio method for predicting biogeochemical movements from metabolic measurements in ecosystems. In: Korneday, B.H., Vaughan, W.A., Jamison, D.K., Morgan, J.M. (Eds.), Transport of Radionuclides in Freshwater Systems. U.S. AEC Div. Tech. Inform. TID-7664, Washington, DC, pp. 209–230.

Odum, H.T., 1965. An Electrical Network Model of the Rain Forest Ecological System. PRNC-67, Puerto Rico Nuclear Center, Rio Piedras, PR.

Odum, H.T., 1970. Summary: an emerging view of the ecological system at El Verde. In: Odum, H.T., Pigeon, R.F. (Eds.), A Tropical Rain Forest. Div. of Tech. Information, U.S. AEC, Oak Ridge, TN, pp. I-191–I-281.

Odum, H.T., 1971. Environment, Power, and Society. Wiley-Interscience, New York, NY.

Odum, H.T., 1972. An energy circuit language for ecological and social systems: its physical basis. In: Patten, B.C. (Ed.), Systems Analysis and Simulation in Ecology, vol. II. Academic Press, New York, NY, pp. 139–211.

Odum, H.T., 1983. Systems Ecology, An Introduction. Wiley-Interscience, New York, NY.

Odum, H.T., Beyers, R.J., Armstrong, N.E., 1963. Consequences of small storage capacity in nannonplankton pertinent to measurement of primary production in tropical waters. J. Mar. Res. 21, 191–198.

Olney, R.R., Olney, R.D., 1986. The Amazing Transistor, Key to the Computer Age. Atheneum Books, New York, NY.

Olson, J.S., 1963. Analog computer models for movement of nuclides through ecosystems. In: Proceedings of the First National Symposium on Radioecology. Colorado State University, Fort Collins, CO, pp. 121–125.

Patten, B.C. (Ed.), 1971. Systems Analysis and Simulation in Ecology, vol. I. Academic Press, New York, NY.

Riley, G.A., 1946. Factors controlling phytoplankton populations on Georges Bank. J. Mar. Res. 6, 54–73.

Riley, G.A., 1947. A theoretical analysis of the zooplankton population of Georges Bank. J. Mar. Res. 6, 104–113.

Shugart, H.H., O'Neill, R.V. (Eds.), 1979. Systems Ecology, Benchmark Papers in Ecology, vol. 9. Dowden, Hutchinson & Ross, Inc., Stroudsburg, PA.

Walter, W.G., 1963. The Living Brain. W.W. Norton & Co., New York, NY.

Webb, B., Consi, T.R. (Eds.), 2001. Biorobotics, Methods & Applications. MIT Press, Cambridge, MA.

Zygmont, J., 2003. Microchip, an Idea, its Genesis, and the Revolution it Created. Perseus Publ., Cambridge, MA.