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CONTENTS

Evolutionary Hierarchies of Energy processing in Nature

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Abstract

Types of energy transformation processes are proposed as a basis for determining hierarchical levels in nature. A simple and general model for energy transformation processors with limited transformation capacity leading to the death of the processor is proposed. This model can explain the statistical Pareto-Zipf-Frechet-Weibull behavior which is observed for symptoms of energy transformation at all hierarchical levels in the universe. Based on the formal equivalence between trophic webs of energy transforming (Birth&Death) processors and neural networks a general framework for modeling memory, adaptation/learning and evolution is proposed.

1 Introduction

When we describe the evolution of the universe, from its « origins » up to socio-economic and technical systems of today's mankind, the concept of energy / information transformation is the only feature common to all levels of organization and description.

However, on the various levels we find different types of energy / information transformation processes, which determine the structure of systems and control the system's behavior on that level.

For example nuclear energy is governing the transformation processes going on within massive stars like the sun, while geo-thermal energy is involved and shapes the evolution of the earth-crust.

How many levels of different energy / information transformation can one observe, and how can these levels be ordered in a coherent way?

The goal of this paper is to define clear and explicit order criteria for a coherent distinction of hierarchical levels in nature.

Furthermore we will propose a general model for a basic energy transformation processor, which can be applied to any type of transformed energy.

The behavior of such an energy transformation processor, describing its trajectory from birth to death, will be looked at from an informational point of view in terms of binary state transition.

This formal equivalence with a formal neuron will allow us to draw an analogy between trophic webs of energy transformation processors and neural networks.

Based on this analogy we will outline a conceptual framework for modelling adaptive and evolutionary processes leading to the emergence of hierarchical levels.

2 Hierarchical structure of nature

The concept of *hierarchy* is used by many authors to describe and to analyze complex systems in an ordered fashion. The order criteria for slicing nature into hierarchical or organizational levels are not always clearly stated by the different authors, and in most cases they are only implicit.

In the following we will analyze some examples of hierarchical ordering. But we do not pretend to give an exhaustive overview on literature covering this topic already published. Summarizing one can say, that there are as many « hierarchies of nature » proposed as there are authors.

We are convinced, that it is necessary to introduce some explicit order criteria in order to arrive at a coherent approach when cutting up nature into hierarchical levels.

Further on in this paper we will show, that the type of energy and information processing can be used as a common order criterion for establishing « levels » in all types of systems ranging from astrophysical to social systems.

2.1 Boulding : control-oriented hierarchy

A *hierarchy of levels* was formulated by Boulding, [1956], as cited by Blanchard and Fabrycky [1990], and is summarized below. The implicit order criterion used here by Boulding to derive levels 1 to 4 is the type of control mechanism governing the system, while the levels 5 to 9 are ordered according to information processing types within certain entities.

	Level	Short description
9	unknowable	no description
8	social organization	meaningful messages, value systems
7	human	self-consciousness, symbol processing
6	animal	mobility, teleological behavior, self-awareness
5	plant	genetic-societal structure
4	cell	open self-maintaining system
3	thermostat	cybernetic systems
2	clockwork	simple dynamic systems
1	framework	static structures of the universe

Table 1. Boulding's hierarchy of nature

2.2 Miller : energy transformation and information transformation

In his magnum opus « Living Systems », Miller [1978] postulates 7 hierarchical levels as below.

It is the great merit of Miller to have pointed out that, despite the apparent differences of structures and processes on the different levels, **self-similar system concepts** can be used for the description of each level.

	Level	Short description
7	supranational system	composed of two or more societies
6	society	large living system composed of organizations
5	organization	systems with multi-echelon deciders
4	group	set of single organisms called members
3	organism	in its usual biological sense
2	organ	subsystems of organisms, animals and plants
1	cell	living organized protoplasm

Table 2. Miller's hierarchy of living Systems

Millers implicit order criterion for establishing levels is **modular decomposition.** An organ is composed of cells. An organism is composed of organs etc. ...

It is important to note, that on all levels Miller clearly distinguishes between energy transformation and information transformation processes.

On each of the seven levels, a system can be described by the same set of 10 energy transformation subsystems and 9 information transformation subsystems.

The **energy transformation** subsystems are : Reproducer, Boundary, Ingestor, Distributor, Converter, Producer, Storage, Extruder, Motor and Supporter.

The **information processing** subsystems are : Input transducer, Internal transducer, Channel and net, Decoder, Associator, Memory, Decider, Encoder, and Output transducer.

Besides of the great conceptual breakthrough we point out two major limitations of Miller's general theory :

- its limitation to « living » systems (i.e. the theory is not applied to geo-chemical and astrophysical systems) and
- the theory does not give much hints on how and why the different levels have emerged.

2.3 Jantsch : phases in the co-evolution of macro- and micro processes

It is the merit of Jantsch [1980] to have proposed a general and systematic approach to the evolution of the universe from cosmic symmetry brakes up to complex societies.

The order criterion of Jantsch's hierarchy are evolutionary phases emerging through primordial « symmetry brakes » occuring within lower levels.

	Level of micro-evolution	Level of macro-evolution	Phase of co-evolution
7	self-image	man-in-universe	integrative
6	self-reflective mentation (socio-cultural dimension)	ideas, plans	re-creative
5	reflexive mentation (gestalt perception)	groups, families	imaginative
4	organism / organismic mentation	societies with division of labor	epigenetic
3	cells (eukariotes)	ecosystems	genetic
2	organelles (prokaryotes)	Gaia	prebiotic
1	dissipative structures (intracellular processes)	primal ocean	chemical
0	Linear irreversible thermodynamics	inorganic chem.-physical macrodynamics	physical

Table 3. Jantsch's evolutionary hierarchy of man in the Universe

According to Jantsch the « driving force » for the emergence of new levels shown explicitly is the **co-evolution** of **microscopic** and **macroscopic** systems.

On each level microscopic entities are described in terms of micro-structures, micro-processes and local control mechanisms.

The microscopic entities evolve within a macroscopic « environment » which itself is described in terms of macro-structure, macro-processes and global control mechanisms (see table 3.)

For example on level 2, the level of prebiotic co-evolution, we observe two complementary trends :

- micro-evolution consists of prokaryote structures undergoing self-reproducing hypercycle processes, being controlled by genes.
- macro-evolution is taking place on Gaia (the macroscopic structure) undergoing bio-energetic processes controlled through synthesis.

The above mentioned microscopic systems co-evolve within the macroscopic systems until a **symmetry break** occurs , which leads to the emergence of the next level 3, the level of genetic co-evolution:

- micro-evolution consists of eukariote structures undergoing endosymbiotic processes controlled by genotypes.
- macro-evolution takes place in ecosystems undergoing specialization processes controlled by chemical and thermal selfstabilization of the biosphere.

2.4 Salthe : ecological and genealogical hierarchies

According to the ecologist Salthe [1985], an evolving hierarchical systems can be described both in terms of **ecological** or organizational **hierarchy** (snapshot of energy transformation hierarchy) and of **genealogical hierarchy** (information transformation, time cross-section of parent-child relations).

	Ecological hierarchy		Genealogical hierarchy
--	---------------	7	total biosphere
6	surface of the earth	6	historical biota
5	bio-geographical regional	5	monophyletic lineage
4	ecosystem	4	deme (set of replicating individuals)
3	population	3	integrated genotype phenotype
2	organismic	2	gene
1	molecular	1	species

Table 4. Salthe's ecological and genealogical hierarchies of nature

The implicit order criterion for Salthe's **ecological hierarchy** is **spatial decomposition** at a given moment in time. It describes the different organizational levels within the energy transformation processes of today's earth. Salthe's **genealogical hierarchy** on the other hand is based on the order criterion **heredity**; i.e. transmission of information in evolutionary time.

2.5 Organizational levels of the central nervous system

To show another example of hierarchical levels in complex adaptive systems we mention the organizational levels of the central nervous system [Sejnowski and Churchland, 1992].

In the example below, the order criterion to construct the hierarchy is explicitly stated! It is the spatial dimension which corresponds to an observable physical structure called organizational level. Note that on each organizational level energy / information transformation processes take place, which are described (or not) by a variety of different theoretical tools.

	Organizational level	characteristic dimension
8	central nervous system	1 m
7	systems	10 cm
6	maps	1 cm
5	networks	1 mm
4	neurons	100 µm
3	microcircuits	10 µm
2	synapses	1 µm
1	molecules	1 Å

Table 5. the organizational levels of the central nervous system and their dimensions

It would be possible to extend the scope of the above hierarchy zooming-out to the dimensions of groups, societies and supranational entities of Miller, and zooming-in to the dimensions of atoms, nucleons and subatomic particles.

2.6 Cempel : energy hierarchy

According to dictionary definition « energy is one of the characteristic scalar quantities describing the state of the system, being the equivalent to the possible work, associated with proper form of matter and fulfilling the transformation and the conservation principles. » Based on this definition one of the authors has proposed the energy-matter hierarchy as below.

strong interaction potential upwards

	type of energy
10	unknown
9	mental
8	emotional
7	bio-chemical
6	chemical
5	mechanical/acoustical
4	thermal
3	gravitation
2	strong and weak nuclear interaction
1	electromagnetic

weak interaction potential downwards

Table 6. Cempel's energy hierarchy

Here the hierarchical levels are ordered according to transformation potential (construction and destruction potential) in association with matter-energy entities :

- A lower energy level has the potential to transform (destroy in the extreme case) all upper energy levels; e.g. thermal energy can destroy mechanical, chemical, biochemical etc. entities.
- A higher energy level has the potential to transform entities on lower mater-energy levels only by weak intensity and over long period of time; e.g. chemical corrosion can transform the shape and performance of mechanical entities.
- A higher level can emerge only when the lower level is complete, so one can say that a higher level « feeds » upon a lower level.

The levels as ordered above correspond also to the historical emergence of particular forms of matter-energy during the evolution of the universe.

The passage from one level to another, however remains unexplained.

2.7 Winiwarter : evolutionary hierarchy of energy / information transformation

Refining the above hierarchy, and taking into consideration the major aspects of Miller's and Jantsch's approaches we propose a hierarchy of nature as below.

Here the ordering of the levels is based on the sequence of emergence of new types of energy / information transformation processes during the evolution of the universe.

In the hierarchy below each level is characterized by a macroscopic system composed of microscopic energy / information processors which interact under the influence of their own characteristic field. This field is generated by the totality of all the processors interacting within the system. For example the bio-chemical field consists of and regulates the interaction of microscopic molecules in the macroscopic ocean as a system.

	Macroscopic Systems	Microscopic Energy/ Information Processor type	New emerging Energy/Information Fields
15	systems science community	formal transdisciplinary (meta-scientist)	meta-theoretical
14	scientific community	formal written symbolic (scientist)	scientific & technological (theories, paradigms)
13	alphabetical community	written symbolic (literate individual)	written tradition / history
12	language community	formal symbolic communication (verbal communicating individual)	oral tradition / culture
11	community	symbolic communication (individual)	social / ethological
10	eco-system	multicellular organism	central nervous (feeling)
9	biotope	cell (eukariote)	genetic/sexual
8	bio-sphere/Gaia	self-replicating metabolic unicellular (prokaryote)	trophic (bio-energy)
7	atmosphere/ocean	macro-molecule	bio-chemical
6	earth-crust, tectonic plates	micro-structure	geo-mechanical
5	planets	physico-chemical element	geo-thermal
4	galaxy, stars	nucleus	electromagnetic +weak nuclear
3	proto-galaxy	hadron	strong nuclear + electro-weak
2	proto-universe	quark	gravitation + grand unified
1	Planck-era of big bang	graviton	super-grand-unified

Table 7. Winiwarter's hierarchy of energy / information systems, processor types, and associated fields of interaction

- <u>**Intralevel** coupling and transformation</u> :
  Climbing up the hierarchy we observe diminishing coupling/transformation energies between processors on each consecutive higher level. e.g. binding energies between nucleons are orders of magnitudes higher than binding energies between chemical elements etc.
- <u>**Interlevel** coupling and transformation</u>
  a) a higher level can only emerge and evolve within all previous lower levels; usually when the field in the lower level exceeds a certain threshold value (bifurcation, symmetry break).
  b) lower levels can destroy higher levels, but higher levels can only constrain lower levels. (see Cempel's energy hierarchy).
  c) lower level processors feed into (or are eaten by) higher level processors.

It follows from the above, that the order criterion for hierarchical levels used by us is the evolutionary sequence of systems with new qualities of energy and information transformation. By new qualities we understand qualities, which cannot be explained in terms of the qualities of the lower levels.

3 Energy / Information transformation processors (Birth&Death processors)

In recent papers [Cempel, 1987; Cempel, 1992; Cempel, 1992; Winiwarter, 1983; and Winiwarter and Cempel, 1992] we have presented and elaborated a theory of generalized energy and information processors.

The model (see fig. 1 below) is characterized by energy input, a limited internal capacity of transformation, upgraded and degraded energy outputs and some important statistical features.

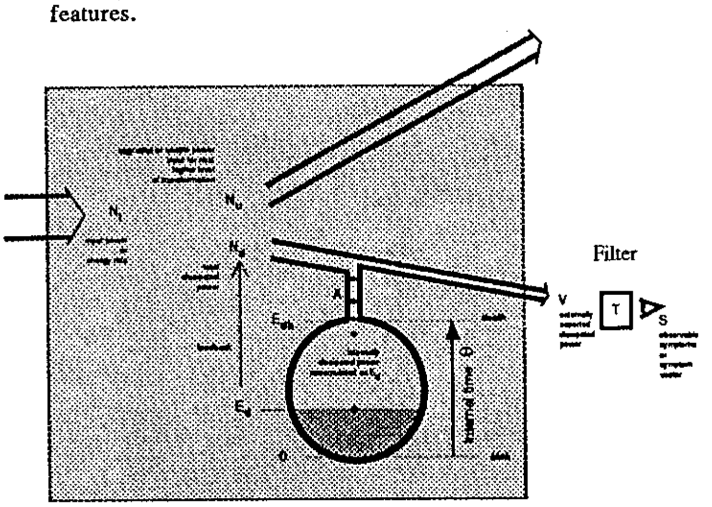

Figure 1. Elementary Birth&Death processor, the building block of the self-similar hierarchical energy transformation process in operating systems.

3.1 Symptom statistics over the life-time of a single processor (time cross-section) :

Observing one processor over its entire life-time from birth (internal time $\theta = 0$) to death (breakdown time $\theta = \theta_b$), we find its asymptotic behavior of transformed energy. Hence when the breakdown of the processor is approached, the transformed energy goes to infinity (see figure 2a).

But in most cases we can neither directly observe nor measure this transformed energy, but only some covariant symptoms by means of some filter T as illustrated in figure 1.

If we observe a given symptom of one processor at regular time intervals over its life span we can make a cumulative probability of symptom occurrence. It can be shown [Cempel, 1992] - analytically and experimentally, that such a cumulative probability is of the Zipf-Pareto-Frechet-Weibull type (called ZPFW distribution hereafter) [Pareto, 1897; Zipf, 1948; Winiwarter, 1983 and Cempel, 1992].

Moreover, there is strict equivalence between the type of symptom life curve observed and the observed symptom probability distribution.

3.2 Symptom statistics for a population of energy processors (snapshot) :

Observing a population of energy transformation processors, which belong to the same operating meta-system and which are in different advancement of processor life, we can make a cumulative probability distribution of symptom occurrence within the population.

It can be shown also [Cempel, 1992; Cempel and Natke, 1992], that the distribution is again a long-tailed distribution of the ZPFW type as above.

In the case of processors which are identical (or similar in a first approximation) the parameters defining the ZPFW distribution are identical in both domains; i.e.; in the symptom life domain of a single processor and the symptom behavior in the population domain. Therefore we can make inferences about the evolution of a single processor based on parameters derived from measurements of a population of processors, and vice versa.

4 « Generalized Life Symptoms » of energy processing systems

Empirical evidence for PZFW symptom distributions exists on almost all known levels of energy transforming systems as seen below in Table 8.

In our terms, the table gives us an overview of systems with processor populations for which PZFW symptom distributions are empirically observed [Winiwarter, 1983; Winiwarter, 1985; Winiwarter, 1987; Winiwarter, 1995a; and Zipf, 1948]. As can be seen from the cross-references to the hierarchical levels of table 7, the observations of PZFW regularities, which we called « generalized Life Symptoms », are found on all emergent levels of energy transformation in the universe.

cross-ref. to levels of tab.7	operating System	Birth&Death Processors	observed symptoms of energy transformation
14	computer system	micro-processors	produced files
14	technical production system	machines of the same type	produced dissipation energy
13	economic system / country	business firms	produced output/profit
13	socio-economic system	human individuals	produced income
12	socio-economic system	cities	produced populations
12	cultural system / language	human brains	produced words
11	bio-social system / colony	animals of same species	produced populations
10	ecosystem	biological species	produced populations
9	biotope	biological genera	produced species
8	biosphere	biological families	produced genera
7	ocean	micro-particles	produced particles
6	earth	tectonic plates	produced earthquakes
5	solar system, planets	chemical compounds	produced compounds
4	galaxy / universe	stars	produced nuclei / chem. elements

Table 8. *Empirically observed generalized Life Symptoms* : Pareto-Zipf (PZFW) distributions for populations of Birth&Death processors in operating systems. For a historical overview and detailed sources see [Winiwarter and Cempel, 1992].

In many cases these empirical observations are formulated even as general laws. e.g. the law of Gutenberg-Richter states, that earthquake intensities follow a Pareto distribution with the exponent $\gamma = 1,5$ for all regions of the globe.

According to our model, and in accordance with the empirical observation stated in table 8 above, we can postulate, that the observation of symptoms following a PZFW distribution may be an indicator for energy transformation systems of processors undergoing birth and death.

As a consequence we suppose, that the energy processing with limited transformation capacity, as in our model, is a feature common to all levels of evolution.

Further we can observe on all levels the organization of energy transformation processors in trophic hierarchies or web-like structures (see figure 3). By trophic hierarchies or trophic webs we understand food chains or energy transformation chains in general, where lower level processors feed into (or are eaten by) higher level processors.

5 Co-transformation of Energy and Information

So far we have considered only the energy transformation aspect of processors during their lifetime (from birth to death). As illustrated in figure 2a) below, this generalized life process at a given level can be described by a continuos function with an asymptotic behavior (*singularity*) at the breakdown of the processor.

The same life-process observed by the metasystem can be described as a binary information process. As long as the processor is in operating state (life) the metasystem observes no change or 0-state. At the breakdown of the processor (death) the metasystems observes a binary state transition to 1-state. This is illustrated in figure 2b) below.

The important idea put forward here is as follows : **continuos energy-transformation** processes on one level are equivalent to **discrete binary information** state transitions as observed on the metalevel.

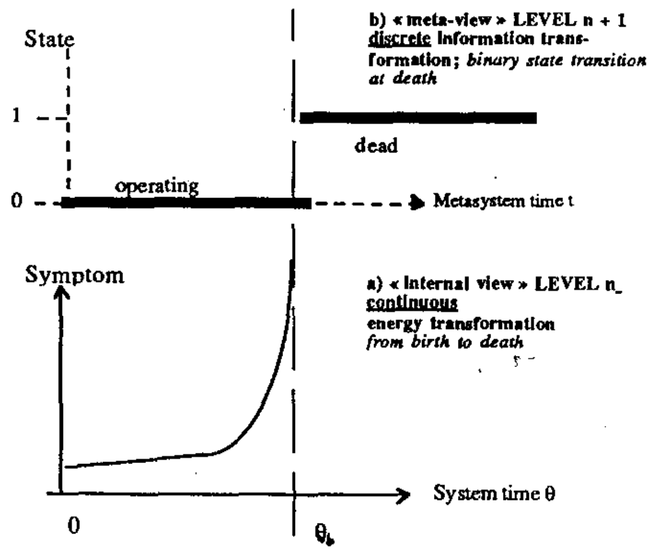

Figure 2. The equivalence of a) continuous energy processing and b) binary information transmission to the metalevel.

5.1 Neural analogy explaining energy / information equivalence :

Based on figure 2 we can draw an analogy between an energy transformation processor (Birth&Death processor) and a formal neuron.

Both can be considered as **threshold automata with binary state changes** as explained below :

- An energy transformation processor sums up internally stored transformation energy up to its capacity E_{db} (see figure 1). When this capacity is reached, (at breakdown-time θ_b) the processor breaks down, which is perceived by the metasystem as a binary state transition.
- A formal neuron integrates weighted input pulses, compares them with a threshold value and fires a binary signal to the next level, when this threshold is reached.

Hence a trophic web of energy transformation processors (with lower level processors feeding into higher levels) - based on the above analogy - can be considered as a neural network.

As it was postulated in [Winiwarter, 1995b] the web can be described as a trophic hierarchy of Birth&Death processors, when looked at from an energy point of view and as a network of binary threshold automata, when looked at from an informational point of view. A network or web of binary threshold automata is also called neural network.

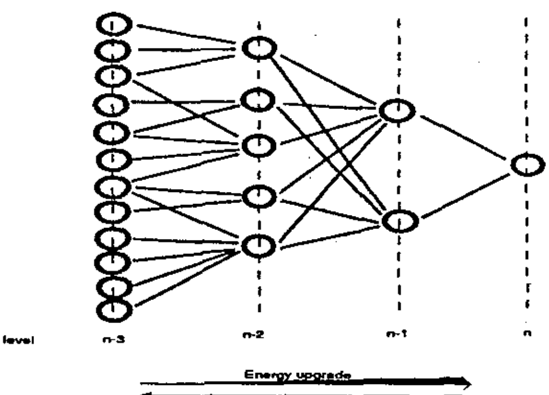

Figure. 3 Simplified representation of an operating energy transformation web formally equivalent to a neural network. Interpreting a node of the graph as energy processor, the link to the upper level is constituted via upgraded energy output of the processor, while the downgraded energy output from the processor to the web constitues the feedback (called backpropagation in certain neural networks).

5.2 Memory

Based on the neural network analogy a web of energy processors should reveal memory features as set of operating/non-operating states distributed over the entire web :

- In the case of a neural network, the memory consists of the threshold values, the input weights and the topology of active connections of all neurons in the network.
- In the case of an energy / information transformation web, the memory consists of the capacities E_{db} or breakdown times θ_b of the processors and the topology of active (trophic) connections.

5.3 Learning / adaptation

Again, based on the above analogy, the learning / adaptation of energy transformation webs organized hierarchically as illustrated in figure 3 could be modeled like the learning in feedforward neural networks with backpropagation.

From an energy point of view each processor transforms input energy. Upgraded energy is fed forward to the next higher level (from left to right). Downgraded energy is fed back to the lower levels (from right to left). This feedback (backpropagation) modifies also the processor parameters of a given level for the next operation/transformation cycle. From an informational point of view the web of energy (Birth&Death) processors can be viewed as a neural network.

Learning/adaptation could be understood here as repeated processing cycles of the energy transformation web. At each trophic cycle the feedback modifies the parameters of the next generation of newly born processors in the web. When the feedback and the processor replacement policy is random, the web would show chaotic behavior. However, when the feedback is correlated to the overall performance of the web (e.g. the gradient descent method for error minimization), the web will reveal goal oriented behavior and learning.

5.4 Evolution of energy / information transformation webs

Based on the fact, that certain classes of neural networks can solve optimization problems (based on the thermal annealing algorithm for example) the « directed » evolution of energy / information transformation webs could be modeled in a similar way. General « cooling » of the web drives it towards minima within a potential landscape [Winiwarter, 1995b]. Short local heating, followed by subsequent cooling can avoid trapping of the web in local minima of suboptimization.

6 Conclusion

1. When speaking about hierarchical or organizational levels in nature, we need to define explicitly the underlying order criterion. Up to now, this was neglected by most authors.
2. We propose a consistent principle for establishing hierarchical levels in nature, based on energy transformation process types and the sequence of their occurrence during the evolution of the universe.
3. We present a simple model for an energy / information processor, which is general enough to be applicable on every hierarchical level independently of the nature of transformed energy. These processors are characterized by a limited transformation capacity leading to birth&death behavior.
4. The statistical behavior of such processors observed as « generalized life symptoms » shows a longtailed behavior which can be described mathematically by Pareto-Zipf-Frechet-Weibull (PZFW) distributions.
5. PZFW distributions are empirically observed on virtually all hierarchical levels of energy transformation in nature.
6. From an energy transformation point of view, a Birth&Death processor continuously transforms energy up to its breakdown (death). From an informational point of view however - as observed by the metasystem of the processor - a Birth&Death processor is equivalent to a binary threshold automaton (formal neuron) with the two possible states : 0-state (operating) or 1-state (dead).
7. Organization of such processors in a trophic web make them formally equivalent to a neural network.
8. Hence all the features of neural networks, like memory, adaptation/learning and optimization can be looked at in an analog way in trophic webs of energy / information transformation processors.

The above approach may be the basis for a general theory explaining self-organization, self-learning and evolution in nature.

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