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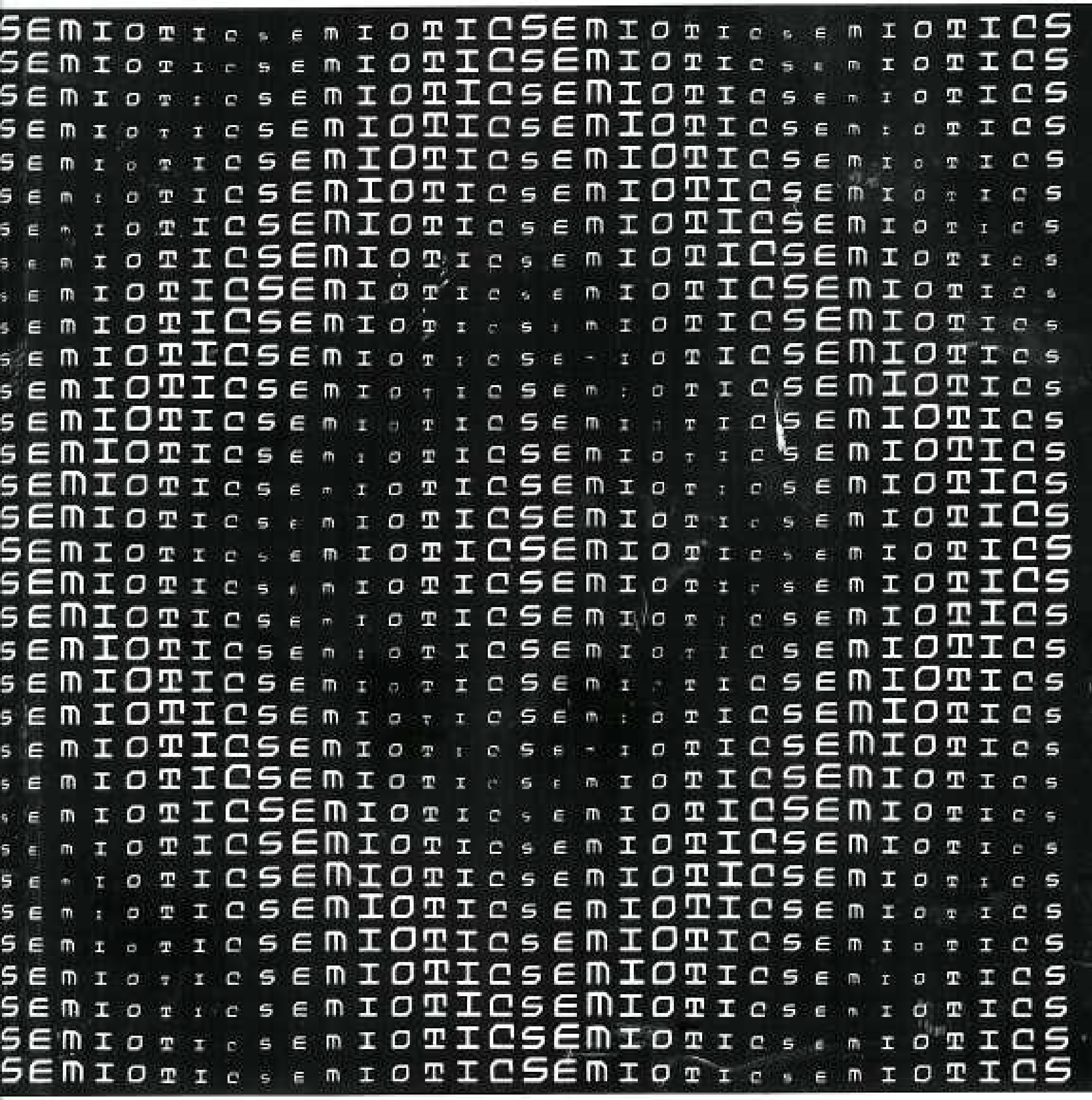

Editor-in-Chief Thomas A. Sebeok

Mouton de Gruyter

A periodic system of system concepts

PETER WINIWARTER

Systems science, system concepts

What do an atom and an individual have in common?

If you ask a nuclear physicist, he would probably answer that all individuals are composed of atoms. A social psychologist might answer that the idea of atoms has been conceived and elaborated by individuals like Demokrit and Niels Bohr. Any transdisciplinary communication stops right there.

A linguist, however, would say that both words — atom and individual — have the same origin and underlying meaning: the Greek '$\alpha\tau o\mu o\sigma$' means *not able to be cut, indivisible*, while the Latin '*individuum*' means *unseparable.*

Transdisciplinary system concepts

The objectives of Systems Science were formulated more than forty years ago by the founders of the International Society for General Systems Research (now called the International Society for the Systems Sciences):

- to investigate the analogy of concepts, laws, and models from various fields, and to help in useful transfers from one field to another
- to encourage the development of adequate theoretical models in fields which lack them
- to minimize the duplication of theoretical effort in different fields, and
- to promote the unity of science through improving communications among specialists.

Effective transdisciplinary communication, however, can only be achieved through a common language, based on a common set of concepts. Despite the crucial importance of cross-disciplinary concept

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definition, very little work has been undertaken to classify and standardize the language components of diverse disciplines in order to arrive at a set of truly transdisciplinary system concepts (Young 1964; Ackoff 1970; Troncale 1978; Robbins and Oliva 1984).

My personal research has focused on modeling evolving hierarchical systems, which can be observed in virtually all fields of science ranging from astrophysics to geophysics, biochemistry, biology, ecology, social sciences, economics, and linguistics to technical systems. A first attempt to represent a set of concepts and notations common to all evolutionary systems can be found in Winiwarter (1986).

Formalize the meaning of transdisciplinary system concepts: Conceptual isomorphies (transdisciplinary conceptual semantics)

A formal notation of basic system concepts allows us to map words from different disciplines with similar or identical meaning to unique transdisciplinary symbols called 'conceptual isomorphies'.

Coming back to the above-mentioned 'atom' and 'individual', we can look at the terms from a general systems point of view. Both words can be defined as a concept of *local structural existence* and be associated with a unique symbol. This symbol 'encodes' the entire set of words with the same underlying concept of local structural existence: quarks, nucleons, atoms, molecules, macromolecules, genes, cells, organs, organisms, individuals, words, computers, etc., can each be considered as a locally existing structure. The concept is truly transdisciplinary and can be applied on any level of description.

In this article, I will define a basic set of 48 system concepts and associated formal notations.

Arrange the formal concepts according to rules: Linkage propositions (transdisciplinary conceptual syntax)

Further on, I will arrange the transdisciplinary concepts in an organized way in three conceptual dimensions. In each dimension a metric defines conceptual coordinates, so that every concept has unique coordinates in a conceptual space. This formal organization of concepts forces the user of a given discipline to adhere to a clearly defined framework or metasystem shared by users of other disciplines.

Due to the recursive (self-similar) character of the periodic table, rules formulated for the interrelationship between several concepts on one level of observation — called 'linkage propositions' — may apply likewise on other levels. The formulation of level-independent system rules may be an important step towards truly transdisciplinary communication and research.

Reductionism vs. holism: The duality of left brain vs. right brain concepts

When describing a system, we can apply essentially two approaches, which correspond to two ways of 'seeing' things:

- a local point of view, and
- a global point of view.

The two viewpoints can be associated with the left brain and the right brain hemisphere. Following an evolutionary epistemological approach in accordance with Gasparsky (1996), the origin of this conceptual symmetry break is probably found in early tools of primitive man:

- The left brain can be associated with the cutting tool of the hunter (male). Discrete objects are cut up and inquired locally.
- The right brain can be associated with the cup tool of the cook (female). Fluid objects are poured into containers and inquired globally (taste, smell).

In fact, all concepts we use can be classified into either of the two domains: reductionist or holistic.

Reductionism; local bottom-up integration of parts; analytic atomistic concepts

In reductionism,

- Systems are analyzed based on local concepts of parts. System inquiry zooms into the parts looking for explanation.
- Systems are built by integrating parts into more complex units. De Lorenzana and Ward (1985) speak of 'combinatorial expansion'. We call this process 'bottom up integration' of parts.

Propositional calculus represents the type of formal logic in the reductionist domain and is used for explaining causal relationships.

Holism; global top-down differentiation of wholes; synthetic field concepts

In holism,

- Systems are analyzed based on global concepts of wholes and 'fields' (zooming out into the 'environment' looking for explanation).
- Systems are built by differentiating global goals and targets into subgoals, creating nested hierarchies of wholes or sub-systems. De Lorenzana and Ward (1985) speak of 'generative condensation'. We call this process top-down differentiation of wholes.

Mathematical set theory can be considered as a formal 'logical' system in the holistic domain being used for explaining system control.

Complementarity of reductionist and holistic approaches; zoom in vs. zoom out

I consider both the left brain reductionist and the right brain holistic domain of equal importance. I think that the two approaches are complementary and neglecting one domain will necessarily lead to incomplete system analysis and to unsuccessful system design.

Classical science and technology has stressed mainly the reductionist aspects of systems and neglected the holistic aspects, probably because holistic tools are more complex to handle. Complex computer simulation has been available only in the last few decades.

Soft systems science, on the other hand, shows a tendency to overemphasize global system aspects and to neglect rigorous analytical approaches.

My advice to the systems practitioner is to give equal weight to each of the two approaches. Koestler's (1967) concepts of Janus-faced 'holons', which can be looked at as wholes when zooming in and as parts when zooming out, illustrate the complementarity of both approaches.

Kant's triad of categories revisited; the three conceptual dimensions: Space or structure, time or process, and causality or control

It is the merit of the solitary thinker of Königsberg to have shown that all of our thinking takes place in space, time, and causality, the a priori 'containers' of all our concepts.

In modern systems terminology, we speak of spatial concepts in terms of 'structure', we speak of temporal concepts in terms of 'process', and we speak of causal concepts in terms of 'control'. The attentive reader will notice that Kant's categories of space, time, and causality are holistic concepts, while structure, process, and control are reductionist concepts. Both are only different views of the same underlying conceptual dimensions.

The conceptual dimension of space or structure (brain stem)

There is no structure without space and no space without structure. In this conceptual dimension a system's architecture or topology is described. In physics we speak of 'statics'. In everyday language we simply speak of 'being'. The location of spatial concepts can be associated with the oldest part of the brain, the brain stem of the central nervous system, common to all animals with organized motor systems.

The conceptual dimension of time or process (cerebellum)

There is no process without time and no time without process. In this conceptual dimension we describe the processes within a system. In physics and chemistry we speak of 'kinetics'. In everyday language we describe 'what is going on' or we speak of change or 'becoming'. The location of temporal concepts can be associated with the cerebellum of the brain. This layer of the brain is developed only in animals with organized visual systems.

The conceptual dimension of causality or control (cerebrum)

There is no control without causality and no causality without control. In this conceptual dimension we describe the regulation of a system. In physics and chemistry we speak of 'dynamics', in automation we speak of 'cybernetics', in business we speak of 'organization'. In everyday language we simply speak of 'rules or laws governing' a system. The location of causal concepts can be associated with the cerebrum layer of the brain, which is developed only in animals with prehension systems, i.e., coordinated control loops between a motor system (such as hands), the outside world, and the visual system (such as eyes).

Metric in conceptual space: The seven conceptual categories

The purpose of the proposed classification scheme is to define 'isomorphies' of systems concepts. According to Thom (1980), in order to be able to speak of isomorphies, one has to define a metric within a space. For the above-defined three conceptual dimensions, we define a metric based on the following seven conceptual categories:

- existence
- complementarity or distinction
- disjunction or unfolding
- conjunction or folding
- transition or sequential branching/compartmentalization
- modular closure, and
- self-similar recursion.

This metric allows us to define coordinates in conceptual space. Any concept with identical coordinates in conceptual space is called a 'conceptual isomorphy'. A conceptual isomorphy can have a great number of different names depending on specific disciplines, but all words describe the same underlying basic systems concept.

In the following, I give a short definition of the seven conceptual categories. I leave it up to the reader to apply each conceptual category to a system with which he is familiar, and to develop in detail the seven conceptual categories along the three conceptual dimensions in both the reductionist and the holistic domain. As an example, I will apply our toolbox to a particular system: a network of formal neurons.

The conceptual category of existence/perception

This conceptual category comprises concepts of elementary existence/perception, which can be in the structural, process, or control dimension. In terms of logic, this category corresponds to the 'existence (there is)' operator '$\exists$'. In terms of set theory, this category corresponds to the 'element (is part of a set)' operator '$\in$'.

As an example of the concept of existence, let us take the concept with the coordinates: conceptual domain = local, conceptual dimension = structure, conceptual metric = (1) existence. The conceptual isomorphy corresponding to these coordinates of *local structural existence* $\exists_x$ can be named (e.g.) atom, molecule, gene, cell, organism, individual, unit, part, machine, transistor, etc.

The conceptual category of distinction/complementarity

This conceptual category comprises concepts of elementary distinction. The conceptual category of distinction is the complementary concept to the concept of elementary existence. Each concept of existence has a corresponding complementary concept. In terms of logic, this category corresponds to the concept of 'negation' or 'is not', '$\neg$'. In terms of set theory, this corresponds to the operator 'is not an element (is not part) of a set', '$\not\subset$'.

According to Spencer-Brown (1969), the distinction is the most basic conceptual operation and precedes existence. Personally, I think that the concepts of existence and distinction are complementary: there is no existence without distinction and there is no distinction without existence.

Examples of *local structural distinctions* $\neg_x$ are dualities such as particle-antiparticle, or positive-negative charge; for processes we speak in terms of up-down spin, etc.; for control we speak in terms of 0/1 signals, on-off states, etc.

The conceptual category of disjunction/unfolding

This category comprises the concepts of dual disjunction of elementary existence concepts. In terms of logic, this category corresponds to the 'or' operator '$\vee$'. In terms of set theory, this category corresponds to the 'intersection' operator '$\cap$'. Examples for *local processes of unfolding* $\vee_t$ are repulsion, scattering, fission, separation, etc.

The conceptual category of conjunction/folding

This category comprises the concepts of dual conjunction of elementary existence concepts. In terms of logic, this category corresponds to the 'and' operator '$\wedge$'. In terms of set theory, this category corresponds to the 'union' operator '$\cup$'. Examples of *local processes of folding* $\wedge_t$ are attraction, reaction, fusion, etc.

The conceptual category of transition/branching (tree), compartmentalization

This category comprises the concepts of triadic junction of elementary existence concepts. In terms of logic, this category corresponds to the 'implies' operator '$\Rightarrow$'. In terms of set theory, this category corresponds to the 'is contained in set' operator '$\subseteq$'. Examples of *local processes of branching* $\Rightarrow_t$ are reaction chain, sequential branching, formation of chain/tree structure, etc. For *global structures of branching* $\subseteq_x$ we speak of compartments, nested layers, etc.

The conceptual category of modular closure

This category comprises the concepts of organizational closure of elementary existence concepts. In terms of logic, this category corresponds to the 'equivalence' operator, '$\Leftrightarrow$'. In terms of set theory, this category corresponds to the 'true subset' operator '$\subset$'. Examples of *local structural modular closure* $\Leftrightarrow_x$ are when we speak of network, module, etc., while for *global structural modular closure* $\subset_x$ we speak of sub-system, core-space, etc.

The conceptual category of self-similar recursion

This category comprises the concepts of conceptual level transition. The *closed module* concept of a level of description n becomes the elementary *existence* concept on the level of description $n+1$. Recently it has become fashionable to speak of conceptual level transition in terms of 'emergence'.

In terms of logic, this category corresponds to the 'for all' operator (all elementary existences are now treated as one module) '$\forall$'. In terms of set theory this category corresponds to the 'empty set' operator (the conceptual content of the lower level 'disappears', the module becomes conceptually opaque for zooming in): '$\emptyset$'.

For example, a local structural closed module $\forall_x$ of *nucleons* organized within an atom described within the framework of nuclear physics becomes a *local structural existence* $\exists_x$, an atom on the next hierarchical level, which is described within the framework of atomic physics; a closed module of atoms becomes an elementary molecule described within the framework of chemistry. An integrated module of parts (transistors) becomes an elementary chip for the construction of a motherboard, etc.

It is remarkable that the operators of propositional calculus (left brain logic) and the operators of mathematical set theory (right brain logic) can be classified according to our sevenfold metric. To the attentive observer the apparent 'mirror' complementarity of logical and set theory operators reveals a certain beauty.

Towards a periodic system of concepts: The self-similarity of concepts on different levels of description

There is a horizontal symmetry corresponding to the conceptual domains of the left brain (reductionist) and the right brain (holistic) domain. For each domain we define the three conceptual dimensions as possible subscripts. These are shown in Figure 1. The conceptual metrics are shown again with their associated tokens in Figure 2; they are applicable to each vertical column in Figure 3, like the columns in the periodic table of chemical elements.

Figure 3 shows the conceptual toolbox in tabular form. Through self-similar recursion, the entire table can be applied to several levels of description on which we can identify similar concepts reappearing periodically. Hence we have chosen to name the table the 'periodic system of concepts'.

Application of the periodic system of concepts to a system of formal neurons (artificial neural network)

In the following, I illustrate the application of the conceptual toolbox to a neural network. In the local domain, the network is described by formal neurons. In the global domain, the network is described by the relationships between layers of neurons.

$\int$ **left brain (reductionist) and the**

∂ **right brain (holistic) domain.**

For each domain we define three conceptual dimensions noted as subscript :

x **structure in space,**

t **process in time and**

c **control in causality.**

Figure 1. *Tokens for the conceptual domains, and their subscripts*

(1)	$\exists \in$	existence
(2)	$\neg \notin$	distinction / complementarity
(3)	$\vee \cap$	disjunction / unfolding
(4)	$\wedge \cup$	conjunction / folding
(5)	$\Rightarrow \subseteq$	transition / sequential branching (tree) or nesting of compartments
(6)	$\Leftrightarrow \subset$	modular closure and
(7)	$\forall \emptyset$	self-similar recursion

Figure 2. *Tokens for conceptual metrics*

Local bottom-up integration within a formal neuron

As shown conceptually in Figure 4, inputs can be connected or disconnected. Input pulses can be 0 or 1 (silence or firing). The weights are usually real numbers. A set of input pulses $e_{1 \ldots}$ e_n is folded with a set of weights $w_{1 \ldots}$ w_n. The products of inputs and weights are integrated $E = \Sigma e_i w_i$ and compared with a threshold θ. The activation function A 'squashes' the integrated input to a binary value:

- $A = 1$ if $E > \theta$, and
- $A = 0$ if $E < \theta$.

The output function S (usually $S = A$) generates the neuron's output, which becomes an input for further neurons. Figure 5 shows these concepts arranged within the framework of the periodic system of concepts. Note that *all* concepts used in the description of the formal neuron are part of the table.

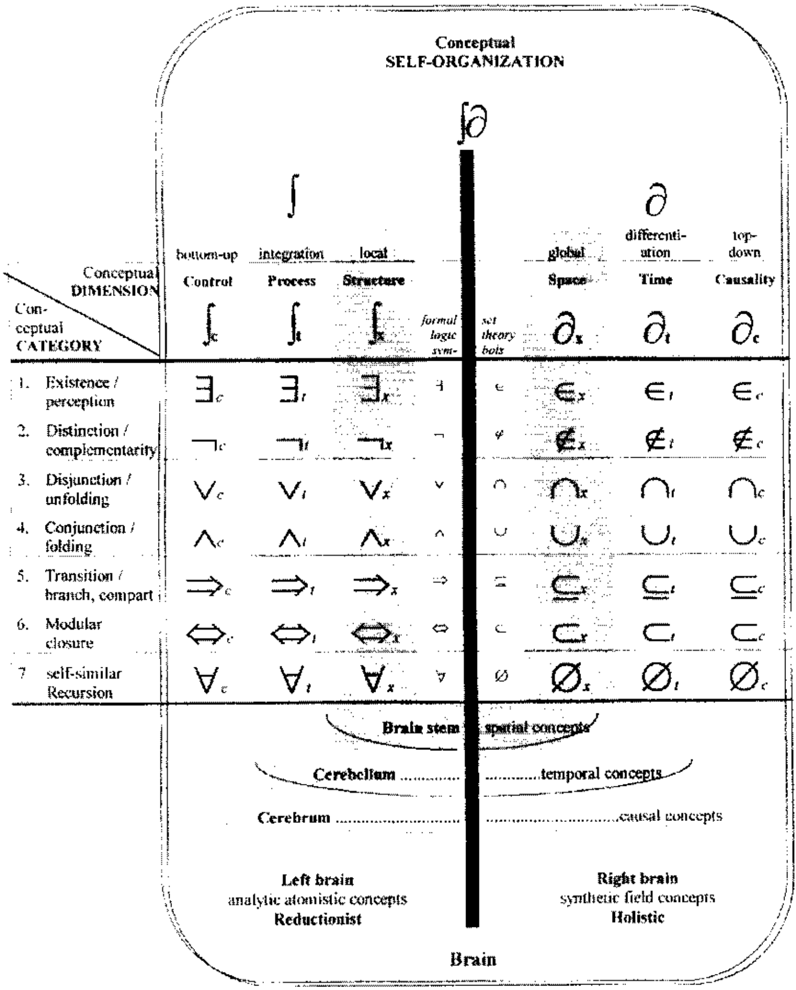

Figure 3. *The periodic system of system concepts: structure, process and control concepts represented by the left and right brain hemispheres*

Global top-down differentiation within a feed-forward network with backpropagation

While the left part of Figure 5 allows us to arrange all concepts used to describe a single formal neuron, the right part of Figure 5 shows the concepts underlying a network of artificial neurons. Since there are a great variety of network topologies, we have selected one specific

Artificial Neural Network

$\int\partial$

Conceptual DIMENSION / Conceptual CATEGORY	bottom-up **Control** $\int_c$	integration **Process** $\int_t$	local **Structure** $\int_x$	*formal logic symbols*	*set theory symbols*	global **Space** ∂_x	differentiation **Time** ∂_t	top-down **Causality** ∂_c
1. Existence / perception	$\exists_c$ weight	$\exists_t$ input signal	$\exists_x$ input connection	$\exists$	$\in$	$\in_x$ target pattern	$\in_t$ target production	$\in_c$ target vector t_p
2. Distinction / complementarity	$\neg_c$ heavy / not heavy	$\neg_t$ firing / not firing	$\neg_x$ connected / not connected	$\neg$	$\notin$	$\notin_x$ output pattern	$\notin_t$ output production	$\notin_c$ output vector out_p
3. Disjunction / unfolding	$\vee_c$ input signals e_i	$\vee_t$ input reception	$\vee_x$ connector	$\vee$	$\cap$	$\cap_x$ input pattern	$\cap_t$ input perception	$\cap_c$ input vector x_i
4. Conjunction / folding	$\wedge_c$ $w_i e_i$	$\wedge_t$ weighting	$\wedge_x$ multiplier	$\wedge$	$\cup$	$\cup_x$ output connections	$\cup_t$ output weighing	$\cup_c$ weight matrix W_{out}
5. Transition / branch. compart	$\Rightarrow_c$ *total input* $E=\Sigma w_i e_i$	$\Rightarrow_t$ summation	$\Rightarrow_x$ integrator	$\Rightarrow$	$\subseteq$	$\subseteq_x$ hidden layer *differentiators*	$\subseteq_t$ summation *squashing*	$\subseteq_c$ hidden weight matrix W_{hid}
6. Modular closure	$\Leftrightarrow_c$ *activation* $A=1$ if $E>q$, $A=0$ if $E<q$	$\Leftrightarrow_t$ comparison	$\Leftrightarrow_x$ threshold	$\Leftrightarrow$	$\subset$	$\subset_x$ self-referential topology	$\subset_t$ feedback *back-propagation*	$\subset_c$ error $=\Sigma_i (t_i-out_i)^2$
7. self-similar Recursion	$\forall_c$ *output function* $S=g(A)$ usually $S=A$	$\forall_t$ output reduction *squashing*	$\forall_x$ output connection becomes input of next layer	$\forall$	$\emptyset$	$\emptyset_x$ heredity of structure	$\emptyset_t$ training cycles *generations*	$\emptyset_c$ successive error minimization

Figure 5. *The periodic system of system concepts applied to an artificial neural network*

The output layer then multiplies vector **y** by weight matrix $\mathbf{W}^{out}$, producing output vector **out**. Hence $\mathbf{out} = f(\mathbf{x}\mathbf{W}^{hid})\,\mathbf{W}^{out}$.

Supervised training is used in backpropagation. Therefore, a training set is required consisting of vector training pairs. Each training pair is

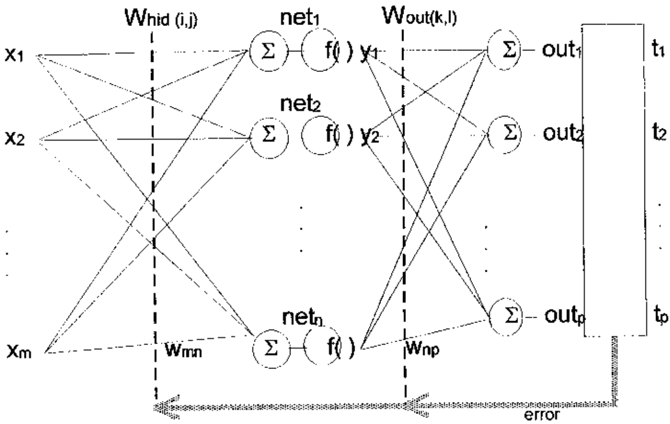

Figure 6. *Feedforward artificial neural network (ANN) with backpropagation*

composed of an input vector **x** and a target vector **t**. The target vector represents the set of values desired from the network when the input vector **x** is applied.

Before training, the network weights are initialized to small, random numbers. The object of training is to adjust the weight matrices so that the network's actual output is more like (approximates) the desired output. More formally, the algorithm minimizes an error measure between the output vector and the target vector. This error measure is computed and the weight adjusted for each training pair.

Often one uses as the error measure sse $= \Sigma[(\mathbf{t}^i - \mathbf{out}^i)^2]$, where i is the number of components in the output vector. The backpropagation training algorithm uses gradient descent, a multidimensional optimization method used for hundreds of years. In essence, the method changes each weight in a direction that minimizes the error. This change may be done at the time each input vector is applied. Training with the so-called 'on-line' method consists in the repetition of the following steps:

- Apply an input training vector
- Calculate the derivative of the error with respect to each weight
- Adjust each weight in the direction of the negative of its derivative (backpropagation or feedback).

The right part of Figure 5 shows that all essential concepts used for the description of the above system can be placed within the organized framework of the Periodic System of Concepts. Note that the concepts of the hidden layer can be extended to an arbitrary number of layers (compartmentalization).

Conclusion

Originally I developed the conceptual framework and notational system classifying the terms and underlying concepts for use in modeling the evolution of massive stars. In this article, I applied the same conceptual framework and notational system to the terminology used in a class of formal systems called ANNs. We postulate that the proposed conceptual classification scheme and notational system can be applied to any adaptive and evolutionary system. Since it is recursive, one can represent several levels of description based on the same formalism:

- On each level of description, system concepts can be classified into two domains, corresponding to 'left brain' reductionism and 'right brain' holism
- In both domains, system concepts can be classified into one of the three conceptual dimensions: space or structure (brain stem), time or process (cerebellum), and causality or control (cerebrum)
- In each conceptual dimension, we can apply a metric based on seven conceptual categories: existence, distinction, disjunction, conjunction, transition, modular closure, and self-similar recursion
- The Periodic System of Concepts gives a tabular view of the conceptual space in terms of domains, dimensions, and metric.

As illustrated in the case of a neural network system, this framework is a valuable tool for structuring systems analysis and description. In the field of bringing systems into being, the periodic system of concepts can be used as a checklist for viable systems design. Cross-level comparisons between different fields or disciplines can be used as heuristic tools to detect general systems properties ('linkage propositions').

In a large variety of evolving systems — ranging from nuclear astrophysics to microcomputers — the structural evolution of local units always follows the same sequence of conceptual metrics:

- existence $\exists_x$ (e.g., a PC)
- conjunction or folding $\wedge_x$ (printer sharing of PCs)
- sequential branching $\Rightarrow_x$ (peer to peer network)
- modular closure $\Leftrightarrow_x$ (a Local Area Network), and

- self-similar recursion $\forall_x$ (Wide Area Networks or the Internet, i.e., a network of networks).

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