A DIDACTIC TOOL TO TEACH AN INTRODUCTION TO SYSTEMS SCIENCES

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ABSTRACT

We present a brief description on a teaching-learning process of Systems Sciences using the proposed structural approach published in the Journals ISSS of the 55th Conference.

The proposed structure follows the domain of Science Model developed by Warfield wich helps to integrate in four main components all the body of knowledge of Systems Sciences as follows:

The domain of Systems Science

The conceptual space and language of Systems Science

The theoretical relations within Systems Science

The methods of Systems Science

At the end of the paper we present an application of the didactic tool.

Keywords: Systems, Science model, domain of Systems Science, concepts, theory, methodology.

INTRODUCTION

The traditional approach to educate human resources is oriented to form specialist with advanced experience in one discipline, however “neither nature nor society is organized as the university or into disciplines” (Ackoff 1999) both nature and society presents very complex issues which require a different kind of education to face them.

Most of the graduate schools where systems Science is learned accept students coming from traditional organized higher education’s schools which are organized into specific disciplines like engineering, Management Sciences, Law, Medicine, etc.

The graduate department of Systems Engineering of the Instituto Politécnico Nacional accept students coming from traditional Higher Education Schools, organized into specific disciplines like mathematics and natural sciences, biology and medicine, Social Sciences and Business management.

However a big problem was detected in the learning process of how to change specialized and fragmented way of thinking of the tradition disciplines to a systems/holistic way of thinking.

In order to help students to change to a new way of thinking (in a Systems/holistic way) a didactic tool was developed into the propaedeutic curricula. For didactic porpoises, initially we call this tool "The Structure of System Science" but could be called a model of System Science, a simplified paradigm of System Science, etc. Normally each component is described in a lecture of one hour.

STRUCTURE OF SYSTEMS SCIENCE

Systems education place higher emphasis on learning processes rather than teaching, however some didactic tools are used only when they seems to contribute to the learning process. This is the case of proposed structure of Systems Science which help to integrate in four main components the body of knowledge of this Science.

The proposed structure of System Science was inspired by the Domain of Science model developed by Warfield (1986) and the writing a new story of education" by Banathy (2001), as follows:

After reviewing diverse definitions of science, e.g., Campbell (1952), Chalmers (2006) and Kerlinger (1973), we observed that there are some common concepts of what constitutes a science. For example, all authors agreed that a science should have: 1) a field, object or domain of study, 2) a set of concepts defined by special language, 3) a theory/philosophy and 4) a method for applications (Fig. 1).

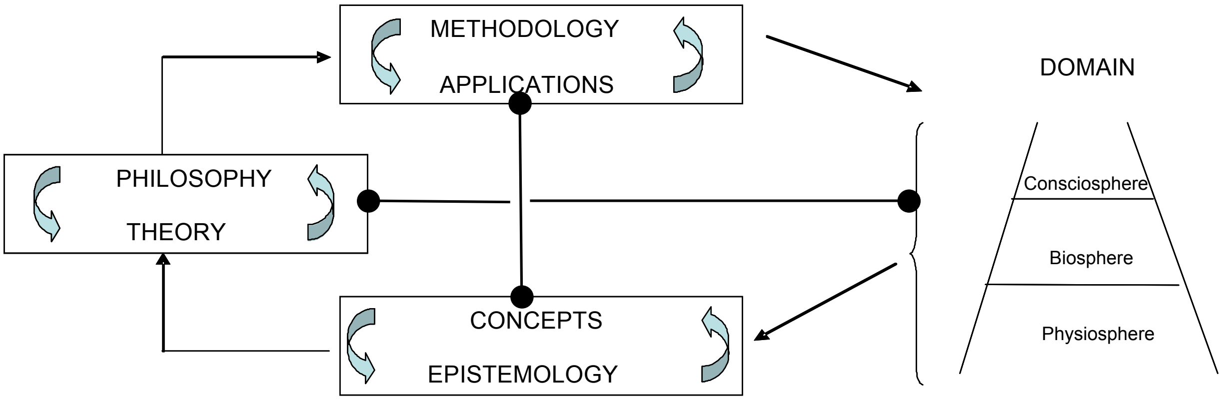


Figure 1. Main components of Systems Science

A Tool to Teach Systems Sciences

According to Warfield (1986, 2006), Systems Science should be able to cover four groups of activities, for which he proposes four basic components that integrate Systems Science and allow it to play the role of a transdisciplinary science. Briefly, the basic components are four sciences, as follows:

1 – The science of description: to describe problematic situations of any nature within the **domain** of Systems Science.

2 - The science of generic design: to design systems by means of applicable trans-disciplines through different disciplines, cultures and organisations that take into account the human being, the thought and the language of the systemic **concepts**.

3 – The science of complexity: to develop a metric and a modelling **theory** that facilitates the measurement and interpretation of the complexity of the problematic situations and the design of systems and methodologies.

4 – The science of action: to specify **methodologies** for solving problematic situations within the domain of Systems Science, including laboratories for practicing Integrative Management, Team Syntegrity, Agoras, etc.

The bold terms denote the four basic components of Systems Science. The four integrated subsystems forms Systems Science for which the practical purpose is to contribute necessary and sufficient knowledge to design new systems, diagnosing existent systems and solve problematic situations of any nature arising in any part of the domain of Systems Science. The four sciences hinge on the neutrality of the definition of a system:

There are many definitions of what a system is, in this paper, we adapt it: System is any portion of the known universe (objective and subjective) that is selected mentally as separated from the rest of the universe, with the purpose of considering the different changes that can happen inside this portion of the universe under different conditions, organizations, structure, processes and environments (Warfield, 2003).

Brief description of the four components:

1. Dominium of Systems Science

Due to the general trans-disciplinary character of Systems Science, the domain of this science is constituted by the whole known universe in which many systems exist. To facilitate the study of these systems, several taxonomies have been developed by research areas, by evolutionary approaches, by objectivity-subjectivity approaches, and by complexity approaches.

The development of taxonomies of the universe of systems is not exclusive to a civilisation or time; in Western civilisation taxonomies have been developed and used in European and North American cultures.

For example, to cite a Mexican case, in her 1692 essay "First I Dream" Juana Inés de la Cruz wrote of apprehending the systemic cosmos by making abstractions from particular things to universal things highlighting the harmony of all with everything. In this process, she tried to embrace the entirety of the scientific knowledge of her time, including Plato, Aristotle, Nicolás of Cusa, and R. Descartes (Del Rio, 2006).

A general outline of the domain of Systems Science was formulated by Teilhard (1959, 1967) and Laszlo (1996) (See Figure 2).

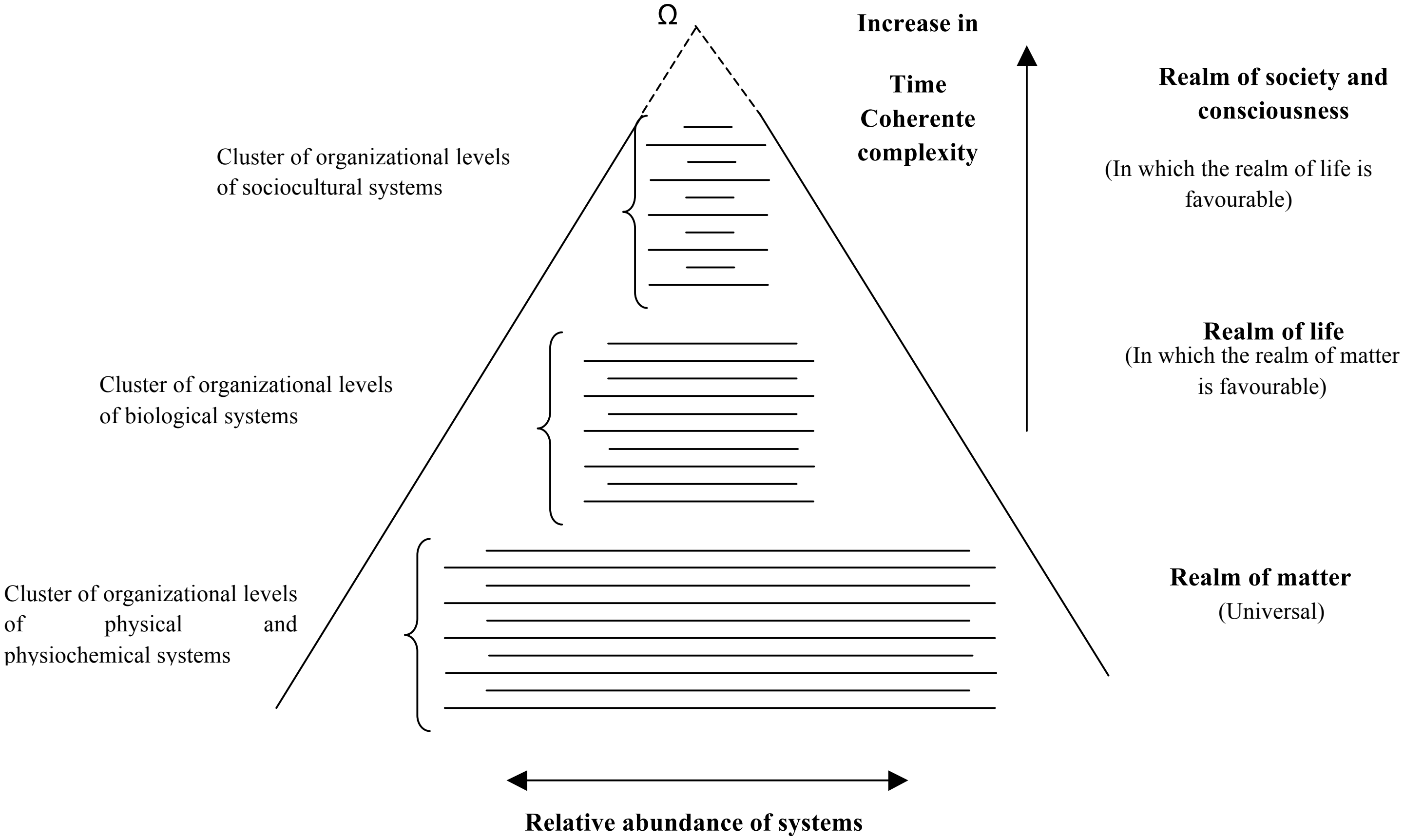


Figure 2. Domain of Systems Science.

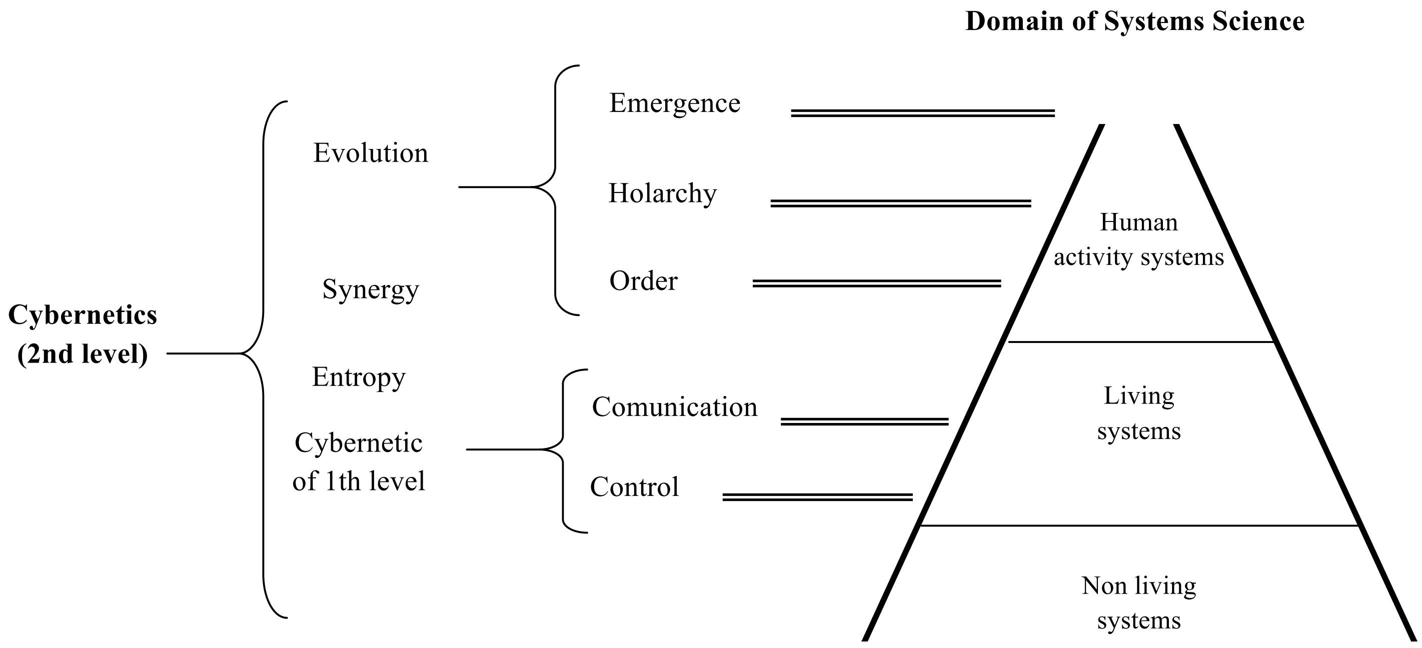
Source: Adapted from Teilhard (1967), Laszlo (1996) and De la Cruz in Del Río (2006)

2. Concepts of The Systems Science.

Concepts represent abstractions formed by the generalisation of particular observed and experimental facts. For example, “complexity” is a concept that represents many observations of systems for which the attributes of system hood are nonlinear, involving multiple feedback loops, while their structures, patterns and processes remain coherent.

Constructs are new concepts created for specific purposes within a research work. Definitions are delimited concepts with other conceptual expressions; Definitions may be descriptive or operational.

The four concepts frequently used in the applications of Systems Science located in the Collective External domain (systems of human activity) are: "emergence", "holarchy", "communication" and "control", which can all be defined operationally starting from observations via phenomenology/hermeneutics of real systems of human activity. In contrast the concepts of evolution, synergy, entropy and first and second level cybernetics can only be defined descriptively using the last concepts. See Figure 3.



— **Relations and constructs defined by phenomenological/ hermeneutical descriptions**

= **Relations and concepts defined operationally**

Figure 3. Constructs, Concepts and definitions

Source: Adapted from Kerlinger (1973)

Checkland (1991) recommended forming an epistemology of systems, gathering the different concepts of the Systems Science coherently in four levels. 1) Basic concepts, 2) Concepts of processes, 3) Concepts of behavior and 4) Perceived concepts, see Figure 4.

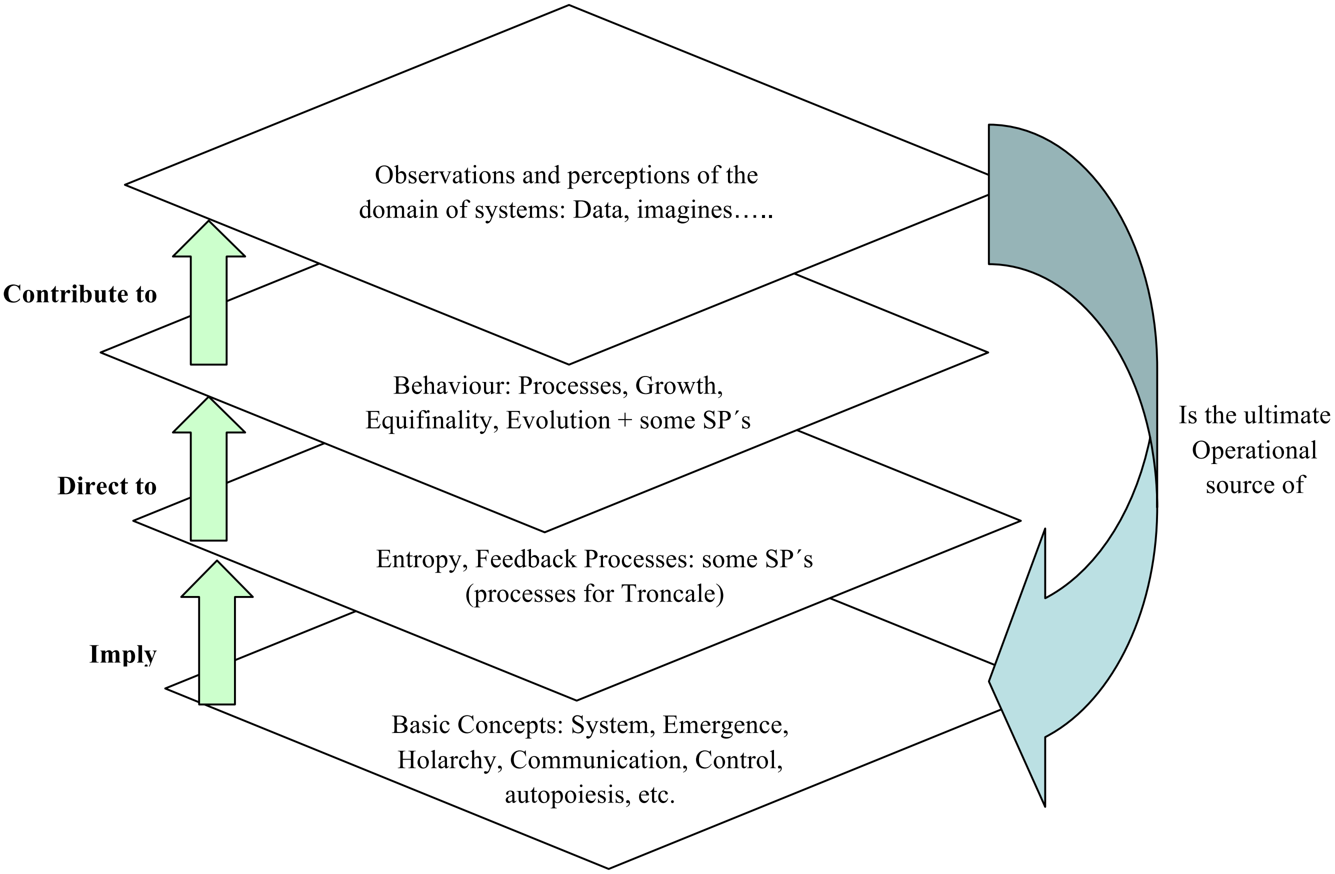


Figure 4. Coherent epistemology of Systems Science concepts
Source: Adapted from Checkland (1991)

As in other sciences, Systems Science requires a certain language consisting of concepts and symbols that express the elements of the systemic speech and the relationships among concepts. This group of concepts and symbols constitutes a notation or a technical language. The effectiveness of a technical language or notation is decisive, as it represents an essential tool for the realisation of the logical or qualitative operations that are made with more facility and less ambiguity than with the symbols and concepts of ordinary language. One of the most frequent languages/notations used to represent systems, with qualitative and quantitative interrelations, is the System Dynamic (SD) set of archetypical patterns/models. For example, the causality relationships in the over exploitation of a resource, known as the "tragedy of the commons", is represented in Figure 5 using the standard SD symbols of arrows, arcs, delays and positive or negative feedbacks.

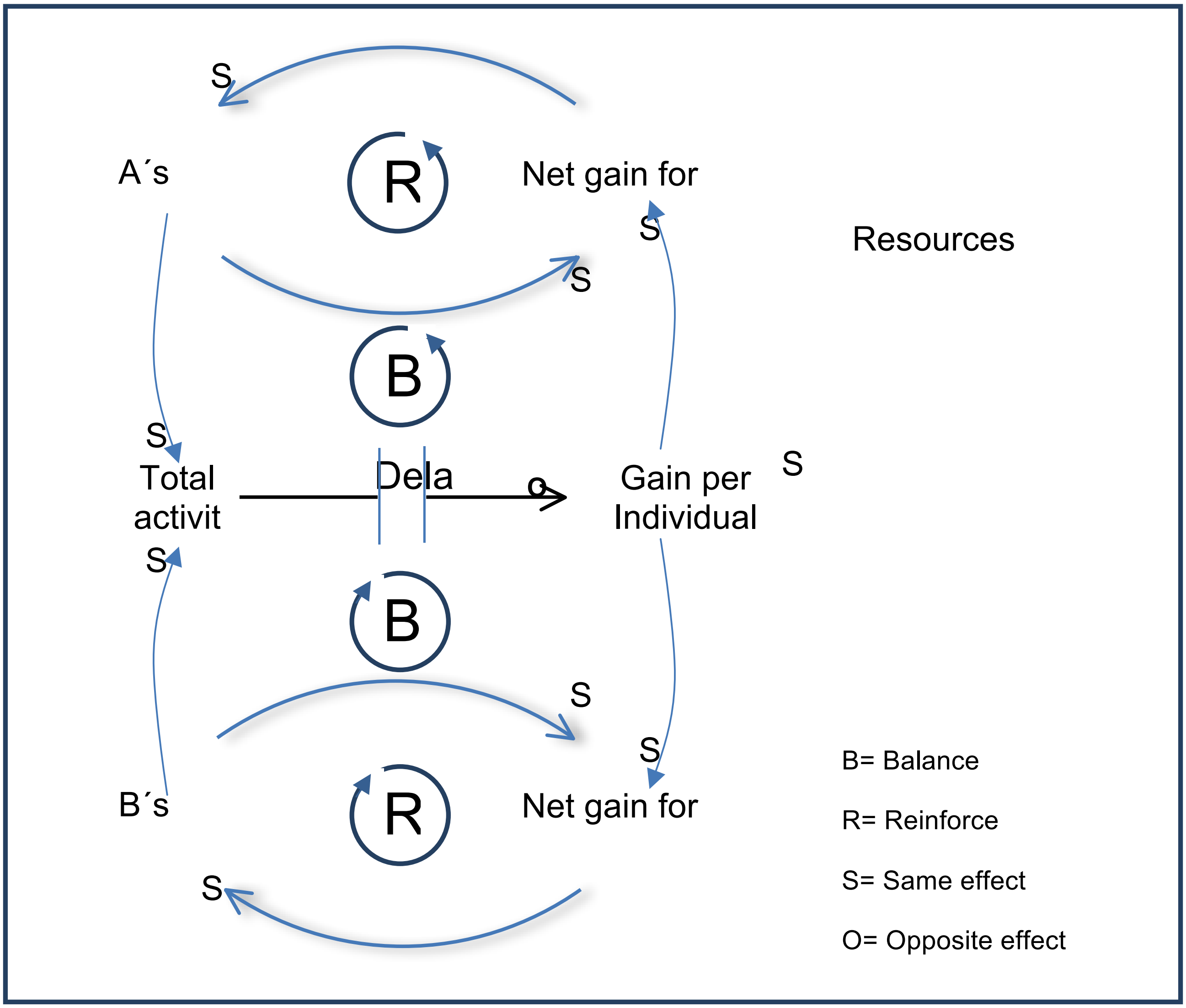


Figure 5. The "tragedy of the commons" archetype

Source: Maani and Cavana (2007)

Meadows (2008:121) explained this systems archetype of systems dynamic as follows: "When there is a commonly shared resource, every user benefits directly from it use but shares the cost of its abuse with everyone else. Therefore, there is very weak feedback from the condition of the resource on the decisions of the resource users. The consequence is overuse of the resource, eroding it until it becomes unavailable to anyone".

Maani and Cavana (2007:40) defined systems archetypes as "generic system models or templates that represent a wide range of situations. Systems archetypes provide a high-level map of dynamic processes. Using the analogy of language to illustrate system thinking, we can say that while variables are 'words' (building blocks) and pairs of variables (and the connecting arrows) are 'sentences', causal loops are stories and systems archetypes are common phrases".

In fact, Systems Science considers more than 3000 concepts described in the International Encyclopaedia of Systems and Cybernetics (Françoise, 2004), and many are interdisciplinary synonyms or "discinyms".

One of the most important concepts, set forth in the objectives of the International Society for the Systems Sciences (ISSS) is the search for interdisciplinary isomorphisms. The word isomorphism was not invented by the scientific systemists. Initially mathematicians used it to describe formalisms and equations that maintain similar forms through many levels and in many disciplines.

3. Theories of Systems Science.

A theory is a system of concepts, definitions and propositions that presents a vision of a class of phenomena by means of specifying the relationships among the concepts, with the purpose of classifying, explaining and/or predicting these phenomena.

This definition highlights three important aspects:

1. A theory is a group of propositions consistent in its interrelations of concepts (a conceptual system).

2. A theory establishes the interrelations among concepts forming a representation of the studied phenomenon.

3. A theory explains the studied phenomenon by means of the specifications by which concepts are related to each other and how these relationships operate, allowing the possible prediction of a phenomenon or certain new concepts derived from others.

The true nature and power of a theory lies in its predictive and explanatory capacity.

Most of the theories of Systems Science are in the descriptive phase, with measurements at the nominal and sometimes ordinal level. Such are the cases of Ashby's law (1958), used to diagnose communication problems within organisations, and Beer's theory of viable systems (1979). The well-known Ashby's law of the requisite variety is expressed as such: "The variety of states of a system is controlled with a quantity of the same or bigger variety than that of the system".

Some examples of Systems Theories:

1.- Living Systems Theory (LST)

The Living System Theory developed by Miller (1978) contains many concepts of Systems Sciences; two of them are the following:

1) A taxonomy of a system can be elaborated according to the common properties of a family of systems. Therefore, if a system belongs to a subdomain of the domain of Systems Science shown in fig 1, then it is possible to infer by abduction, several of the system's attributes. For example if the system under study is a hierarchical organisation that belongs to the consciosphere subdomain, it is possible to infer that it has the attribute of centrality of authority, without empirical verification.
2) Systems are holarchic, which means that the attributes of lower level systems are mixed or subyacent with the new emergent attributes of systems at upper levels.

The living theory identifies eight levels of organisation: 1) cells, 2)organs 3) organisms, 4)groups, 5) organisations, 6)communities, 7) societies and 8) supranational systems.

This eight level system is in accordance with the 12 categories of '20 tenets' of Wilber (2001:43-74), who described and expanded upon the attributes of the holarchy of systems as follows:

1- Reality as whole is not composed of thing of processes, but of holons.
2- Holons display four fundamentals capacities: self-preservation, self-adaptation, self-transcendence, and self-dissolution.
3- Holons emerge.
4- Holons emerge holarchically.
5- Each emergent holon transcends but includes its predecessor(s).
6- The lower sets the possibilities of the higher; the higher sets the probabilities of the lower.
7- The number of levels which a hierarchy comprises determines whether it is 'shallow' or 'deep'; and the number of holons on any given level we shall call its 'span'.
8- Each successive level of evolution produces GREATER depth and LESS span. Addition 1: The greater the depth of a holon, the greater its degree of consciousness.
9- Destroy any type of holon and you will destroy all of the holons above it and none of the holons below it.
10- Holarchies coevolve.
11- The micro is in relational exchange with the macro at all levels of its depth.
12- Evolution has directionality

According to the LST, all living systems have 20 components, recursively situated in the 8 levels of organisation. Miller (1978) classified the 20 component subsystems into 3 classes according to their main functions, as follows:

A) Subsystems that process information only 1- Input transducer 2- Internal Transducer 3- Chanel and net 4- Timer 5- Decoder 6- Associator 7- Memory 8- Decider 9- Encoder 10- Output transducer.	B) Subsystems that process matter-energy only 11- Reproducer 12- Boundary
	C) Subsystems that process information and matter-energy 13- Ingestor 14- Distributor 15- Convertor 16- Producer 17- Storage 18- Extruder 19- Motor 20- Supporter

Some of the most interesting aspects of the LST are the cross-level hypotheses that describes systems behaviour and hold at more than one level in the hierarchy of system levels. Ashmos and Huber (1987:614) state that “This feature offer the potential for organizational scientist to benefit more directly from the research finding of biologists, psychologists, physiologists who study lower order systems, as well as from the research findings of sociologists, economists, political scientists and historians who study higher order systems”

More recently, Nechansky (2010:111) concluded in a study of the relationships between Miller’s LST and Beer’s VSM, that“Miller’s (1978) living system theory has a wider scope, and covers viability more completely than Beer’s (1979) Viable System Theory……”.

Nechansky’s research is a good example of the work needed to bring coherence to the several isomorphic theories of Systems Science.

2.- Recent theory of systems: the system of systems of processes (SoSP)

One of the recent theories of Systems Science is that developed by Troncale (2006) at the California state Polytechnic University. This theory is based on a fundamental conjecture called the **mutuality conjecture**, which posits that “All 55 Systems Processes or concepts of mechanisms, interact mutually or they manifest influences one with another as a system of subsystems". Several ways exist of clustering the 55 concepts. One way is involves following the life cycle of systems in general; another way is a directed graph or web in which the names of the isomorphies (systems processes) act as the nodes connected by lines representing linkage propositions. The SoSP forms a self-organising, self-generating, mutually reinforcing set, (see Figure 6).

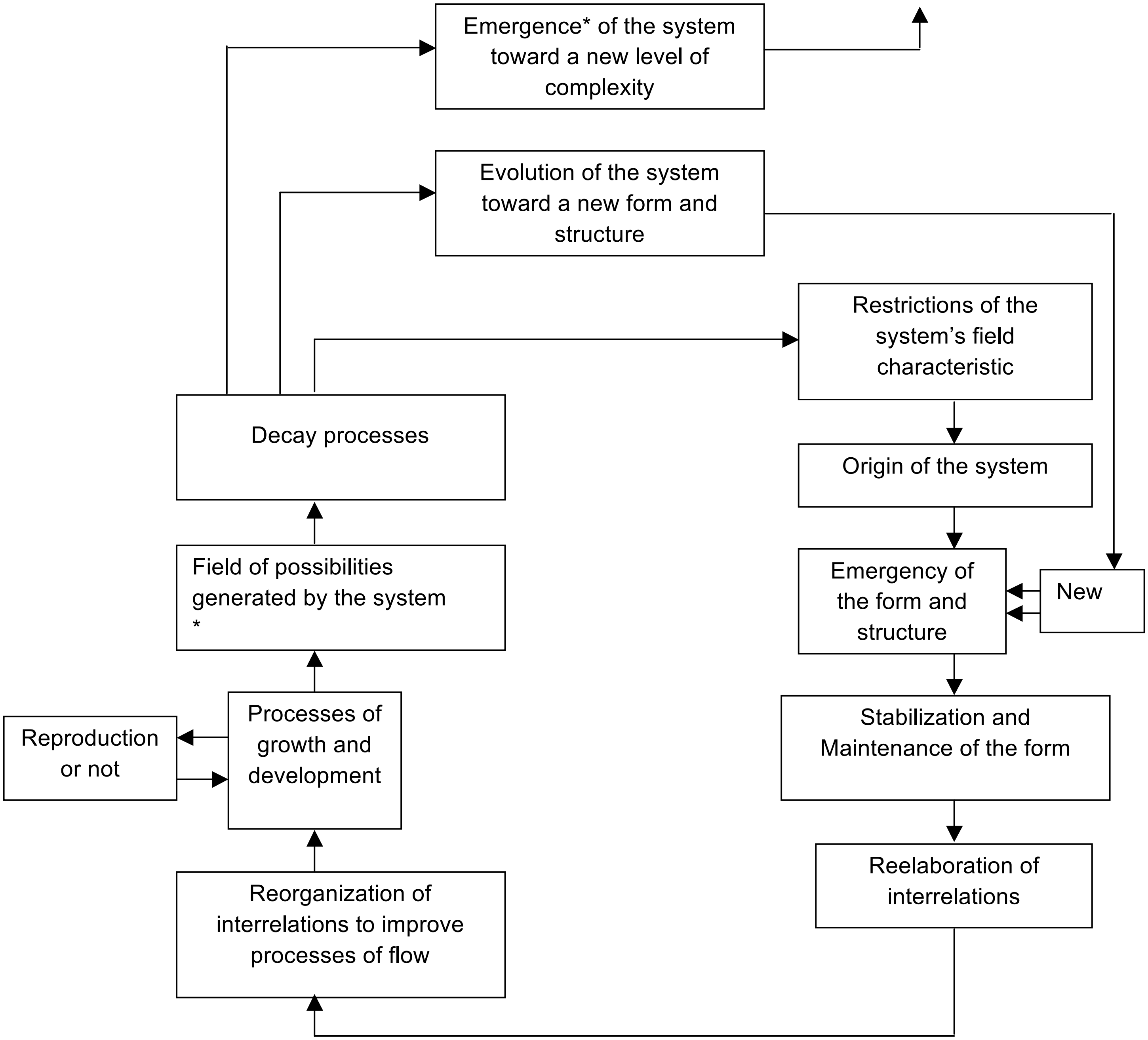


Figure 6. Twelve behaviour functions during the life cycle of a system

Source: course on SoSP Troncale (2008).

The possible applications of the resulting theory of this linked system of systemic concepts include among others, the following:

- To enrich the meaning of each main systemic concept
- To enrich the understanding of the origins of the corresponding phenomenon denoted by each concept
- To be aware of the dynamics of the processes in the systems and so help to discover other isomorphics
- To increase the predictive power of the general systemic models.
- To provide a reference mark for evaluating the rigor and completeness of the models and the simulations proposed for the systems under study
- To provide a precise and efficient tool to facilitate the teaching of the General Theory of Systems.

3.- *A formal theory of systems*

Klir (1991) proposed a formal theory for Systems Science, defining a system as S = {T,R,} where S,T and R denote, respectively, a system, a group of objects, and a group of relationships defined on T. This definition allows us to specify whether a system exists; an object is a system if and only if it can be described by this formula. Consequently, Systems Science is defined as the science that studies the objects (systems) defined by Klir's formula.

The formula contains two basic properties of systems: the concrete reality of the objects denoted **thinghood,** and the properties emerged by their relationships, denoted **systemhood**. Systems Science is oriented basically towards the study of the systemhood properties, i.e. the relationships among the **attributes** of the objects constituting the system more than the objects themselves, whereas the traditional sciences are predominantly concerned with the study of the thinghood properties of the objects.

4. Methodologies of Systems Science.

In Systems Science, a methodology does not mean the treatment of a method or the correct method that it is followed to obtain a result. Rather, it means an organized set of methods and techniques employed to intervene in and change real world situations (Jackson M. 200 pag16).

The method leads the search for knowledge by means of an exact procedure; (for example, the simplex method in linear programming or the scientific method in the traditional sciences), whereas the methodology is based on the use of trial, common sense, responsible principles, metaphors, interpretations and phenomenology that serve as guides to the research.

Diverse systemic methodologies have been developed, most of a qualitative type, in which it is fundamental to consider the interpretation of the data. Two of the authors that have deepened the concept of the interpretation of reality are Husserl (2005), by means of phenomenology and Heidegger in Gaos (1996) by means of the Hermeneutic methodology.

A methodology in general is the vehicle in which a discipline transport itself to the out side world (Jackson 2000).

An example of a *Total Systems Intervention (TSI) Metamethodology*

According to Jackson (2003:285) "TSI should strictly be described as a metamethodology" consisting of three phases labelled: creativity, choice and implementation, as follows:

Creativity	
Task	To highlight significant concerns, issues and problems
Tools	Creativity-Enhancing devices including systems metaphors
Outcome	Dominant and dependent concerns issues and problems identified
Choice	
Task	To choose an appropriate systems intervention methodology or methodologies
Tools	Methods for revealing strengths and weaknesses of deferments methodologies (e.g the SoSM)
Outcome	Dominant and dependent methodologies chosen for use
Implementation	
Task	To arrive at and implement specific positive change proposals
Tools	Systems methodologies employed according to the logic of TSI
Outcome	Highly relevant and co-ordinated change that secures significant improvement in the problem situation

TSI was developed from the Systems of Systems Methodologies (SoSM) which is a taxonomy of systems approach related to problem situation, see Figure 7 and 8.

		PARTICIPANTS		
		UNITARY	PLURALIST	COERCIVE
SYSTEMS	SIMPLE	Simple-Unitary	Simple-Pluralist	Simple-Coercive
	COMPLEX	Complex-Unitary	Complex-Pluralist	Complex-Coercive

Figure 7. Taxonomy of problem contexts

		PARTICIPANTS		
		UNITARY	PLURALIST	COERCIVE
SYSTEMS	SIMPLE	HARD SYSTEMS THINKING	SOFT SYSTEMS APPROACHES	EMANCIPATORY SYSTEMS THINKING
	COMPLEX	SYSTEMS DYNAMIC ORGANISATIONAL CIBERNETICS COMPLEXITY THEORY		POST MODERN SYTEMS THINKING

Figure 8. Systems approach related to problem contexts

An Example of application of the structure of Systems Science.

A DIDACTIC APPLICATION

Let us see how well the four components of Systems Science are applicable to a didactic description of the domain, concepts, theory and methodology for a new branch of complexity theory: Fractal Geometry, (see Figure 9).

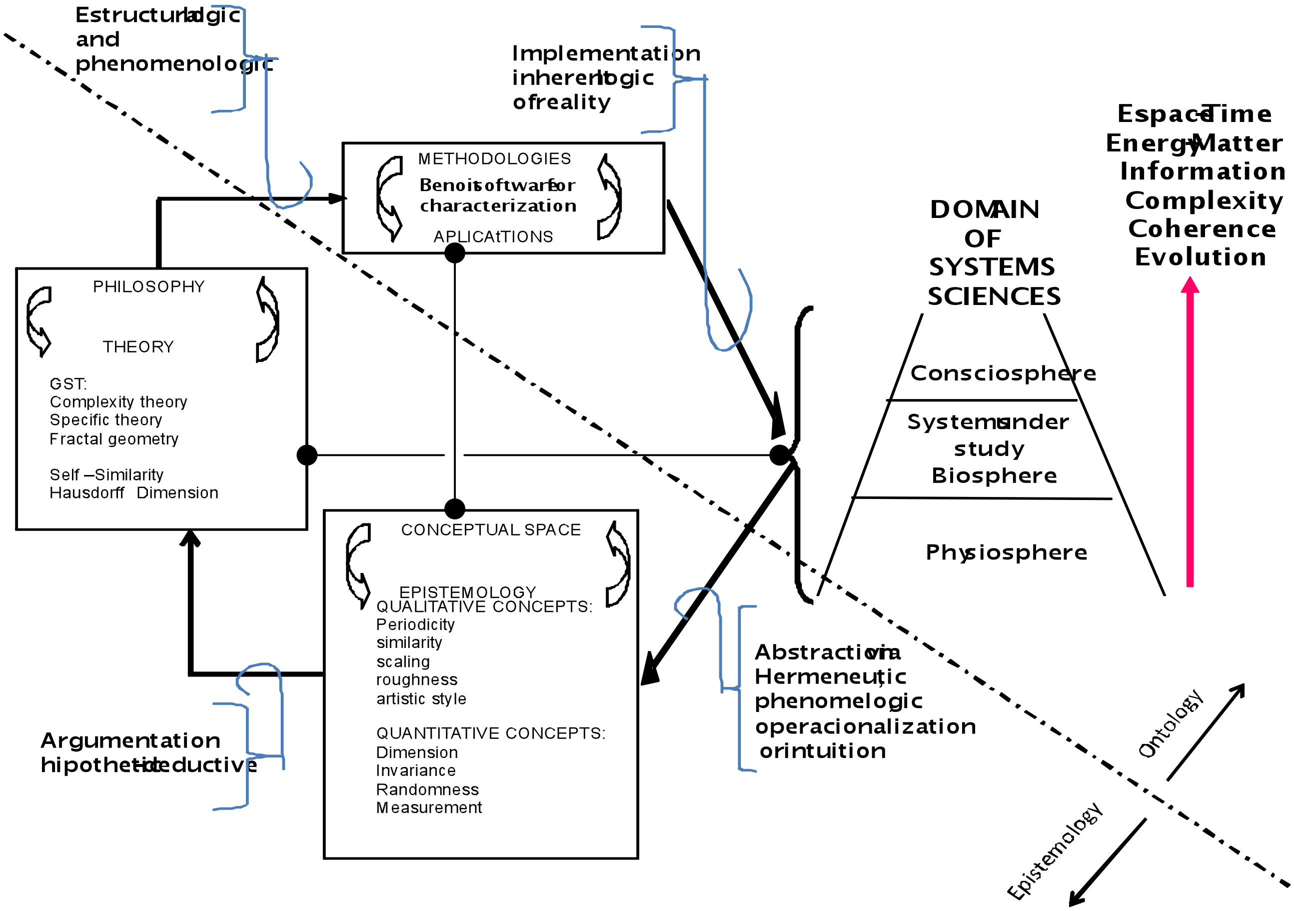


Figure 9. Example of the four component model of Systems Sciences applied to a branch of Complex Theory of Systems: Fractal Geometry.

Domain

There are systems behavior that generate random data series i.e. prices of goods, demand of stocks, internal surface of lungs etc.

Conceptual Space

The dimension of a fractal (rough) object is a real number (DH) that characterizes the way in which the measured attribute of the object increase as scale decrease.

Theory

The dimension of a fractal course is a real number defined by

$DH = \mathrm{Lim}(\log N/\log 1/r)$

N= Number of segments necessary to cover the points of the curve.

r= length of the segment.

Methodology

For certain data series, the fractal dimension is estimated from the power spectrum or the variogram.

It is important to realize that true fractals are ideal objects. No curve, surface or data series is a true fractal (Green, 1995)

CONCLUSION

The proposed structure of the four main components of Systems Science forms a convenient frame of reference to bring order to the introductory study of its concepts, theories and methodologies, in four session of one hour each.

REFERENCES AND ADDITIONAL BIBLIOGRAPHY FOR THE LEARNING PROCESS

Ackroff, R.L., (1999). Disciplines, the two cultures and scianities. *Systems Research and Behavioral Science* 16(b): 533-537.

Ashby, W. R., (1958). Requisite Variety and Its Implications for the Control of Complex Systems, *Cybernetica*, Vol. 1(2), pp. 83-99.

Ashby, W.R., (1963). Foundations for a General Systems Theory in Views on General Systems Theory, Proceedings of the second systems symposium at Case Institute of Technology ed. Mesarovic M.

Ashmos P.D and Huber P.G (1987). The systems paradigm in organization theory: correcting the record and suggesting the future. *Academy of Management Review*, 12(4):607-621.

Barabási A.L. (2003). *Linked, How Everything is Connected to Everything Else and What It Means*. Plume, USA.

Beer S. (1979). *The Hearth of Enterprise*. Wiley, Chichester.

Bertalanffy, L, (1950). An Outline of General System Theory, *British Journal for the Philosophy of Science* 1: 139-164.

Bertalanffy, L, (1986). *Historia y situación de la teoría general de sistemas, en Tendencias en la Teoría General de Sistemas*, Alianza Editorial España

Bertalanffy, L, (2004). *Teoría General de los Sistemas*, Fondo de Cultura Económica (FCE). México.

Campbell N. (1952*). What is Science?,* Dover, U.S.A.

Chalmers F. (2006). *¿Que es esa cosa llamada ciencia?.* Siglo XXI, México.

Checkland P.,(1981). *Systems Thinking, Systems Practice*, Wiley, UK.

Checkland P.,(1991). Toward the Coherent Expression of Systems Ideas. *Journal of Applied Systems Analysis,* Vol. 18, Pag. 25-28, Mayo 1991.

Checkland, P. & Scholes, J. (1994). *La metodología de los sistemas suaves en acción*, Noriega Editores, México.

Checkland, P. (1993). *Pensamiento de sistemas y práctica de sistemas*, Limusa-Noriega, México.

Del Rio , P.E. (2006). *Sor Juana Inés de la Cruz, Primero sueño y otros escritos*, FCE, México.

Francois Charles (2004). *Internacional Enciclopedia of Systems and Cibernetics*, second edition, KG Saur, Munich, Germany.

Francois Charles (1992). Diccionario, GESI-AATGS y C , Buenos Aires, Argentina.

Gaos J. (1996). *Introducción a El ser y el tiempo de Martin Heidegger*. FCE, México.

Husserl E. (2005). *Ideas relativas a una Fenomenología pura y una filosofía fenomenológica*. FCE, México.

Jackson M. (1991). *Contemporary systems thinking Systems Methodology for the Management Sciences*, Plenum Press New York and London.

Jackson M., (2003). *System Thinking Creative Holism for Managers*, J. Wiley, U. K.

Kerlinger F. N., (1973). *Foundations of Behavioral Research*, Holt, Reinhart & Winston, N. Y.

Kira, M, & Eijnatten, F.M. van (2008). Socially sustainable work organizations: A chaordic systems approach. *Systems Research and Behavioral Science,* 25 (6), 743-756.

Klir, G. (1991). *Facets of Systems Sciences*. Plenum, N.Y.

Lazlo E. (1996). Evolution, Hampton press Inc, New Jersey.

Maani KE and Cavana RY. (2007). *Systems Thinking, Systems Dynamic Managing Change and Complexity*. Pearson, New Zealand.

Meadows DH. (2008). *Thinking in Systems.* Chelse Green Publishing, US.

Mesarovic M. (1963). *Foundations for a General Systems Theory, in Viwes on General Systems Theory*, Proceedings of the second sytems symposium at Case Institute of Technology ed. Mesarovic M.

Miller J. G., (1978). *Living Systems,* Mc. Graw Hill, N. Y.

Nechansky H. (2010). The relationship Between: Miller's Living Systems Theory and Beer's Viable Systems Theory. *Systems Research and Behavioral Science*. 27(1): 97-112.

Rapoport, A. (1963). *Remarks on General Systems Theory in Views on General Systems Theory,* Proceedings of the second sytems symposium at Case Institute of Technology ed. Mesarovic M.

Rapoport A. (1986). *Los usos del isomorfismo matemático en la Teoría General de Sistemas , en Tendencias en la Teoría General de Sistemas.* Alianza Editorial, España

Shwarz E., (2000). *Some Streams of Systemic Thought*, Elaborated for ISSS, Newchatel, Switzerland.

Teilhard, P. (1967) *El fenómeno humano*. Taurus, España.

Troncale, L. (2008) Course on SoSP, Annual Conference of the International Society for the system Science Madison USA

Troncale L., (2006). Toward and Systems Science, *Systems Research and Behavioral Sciences*, 23(3): 301-321.

Warfield J. N. (2006). *An Introduction to Systems Science*, Ed. World Scientific, New Jersey.

Warfield J. (2003). A proposal for systems Science Systems Research and Behavioral Science. 20(6):507-520.

Warfield J. N. (1986). *The Domain of Science Model: Evolution and Design*. In Procedding Itl. Conf Mental Images, Values and Reality, Society for General Systems Research, Philadelphia, May 26-30, Salinas, CA Intersystems; 1:H46-H59

Wilber, K. (2001). *Sex, Ecology, Spirituality: The Spirit of Evolution*, Shambhala, USA.