Contributions Towards Unifying System Semantics

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Abstract. What is it that characterizes a system? Certainly as systems engineers this is a vital question to ask. While most will claim that it is a question of perspective (viewpoint and view), this does not help us in identifying key aspects that can lead to useful discipline independent semantics for systems. There have been several system experts that have expressed their perspectives in this regard. The current paper identifies and utilizes some of these contributions and then identifies a key set of concepts and principles as well as a unifying mental model collectively called the System Survival Kit. The survival kit generically identifies the relationship between situation systems, respondent systems and system assets in a manner that can be applied to any system related situation. These contributions are based upon experiences in teaching people from many disciplines to "think" and "act" in terms of systems.

Introduction

The omnipresence of systems was pointed to by von Bertalanffy (1968) in stating that "systems are everywhere." This implies that understanding system properties and utilizing them is independent of the discipline in which systems are considered. Due to this omnipresence there is or should be a wide spread vested interest in gaining a deeper understanding of systems. That is, what they are, how they are utilized as well as how they are managed. Ackoff (1973) provided one of the early attempts at defining semantics for systems. There have been several others that have contributed as well. In this paper we identify and build upon some earlier contributions that assist in isolating key aspects of system semantics. In order to unify these earlier contributions and to further develop a key aspect of system semantics the paradigm of a System Survival Kit introduced. As identified by Lawson and Martin (2008) this paradigm is based upon a limited number of concepts and principles that guide thinking. The paradigm also contains a system coupling diagram that has proven to be a useful explanation of how to view situation systems, respondent systems and system assets as well as their relationship. The survival kit thus provides a discipline independent mental model that can be applied to all types of unplanned as well as planned situations.

Discipline Independence

Let us first consider what is meant by discipline independence. For complex systems, it is the collective understanding of the dynamics of system behavior as well as the life cycle management aspects of systems that is often, of necessity, the result of interdisciplinary efforts. In order to neutralize the discipline effect and focus upon "system content", it is vital to unify *thinking* and *acting* on the part of individuals and groups coming from diverse specialist backgrounds and possessing diverse knowledge, skills and capabilities. In this regard, an important unifying factor is portrayed in Figure 1.

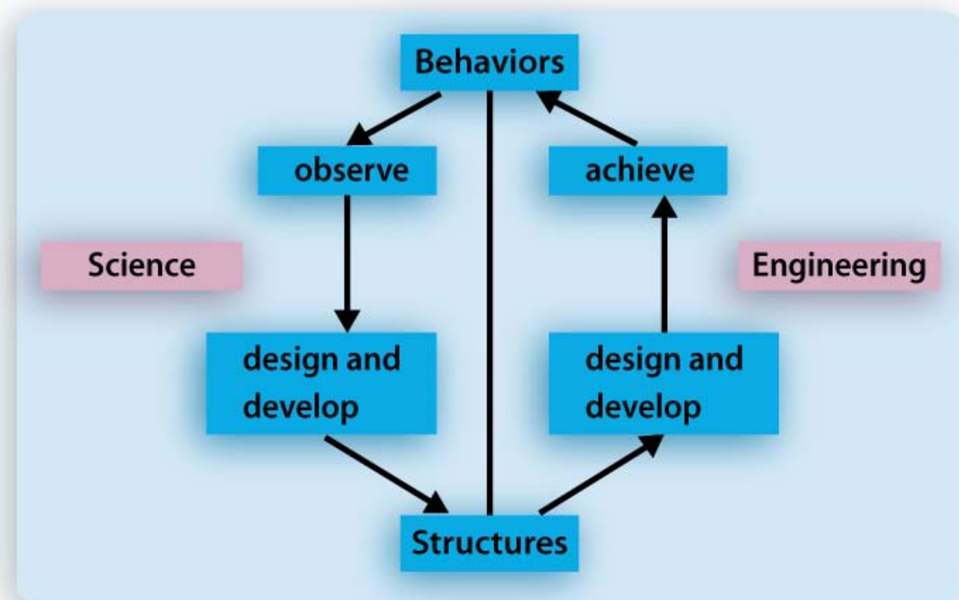

Figure 1. Science and Engineering Relationship to Structures and Behaviors

Both scientific and engineering related disciplines deal with the fundamental system concepts of structures and behaviors. In the case of scientific disciplines, the scientist observes behaviors (in nature or in man-made systems) and then attempts to find and describe structures (in some form of "language") that explain the behaviors. In the case of engineering disciplines, the engineer based upon the need to provide required (specified) behaviors, designs and develops structures that when produced and instantiated achieve behavioral requirements.

To illustrate the difference of approach to structures and behaviors, consider the following disciplines, some of which are traditionally associated with natural sciences, others that have used science in the name of the discipline and a wide-variety of engineering disciplines:

(x) Science	**(y) Engineering**
Biological	Electrical
Physical	Mechanical
Chemical	Chemical
Environmental	Sanitation
Management	Business Process
Computer	Software
System	Systems
Health	Health Care
Military	Military

As an exercise, the reader can consider how these disciplines map into the scientific and engineering view of structures and behaviors portrayed in Figure 1. While these discipline examples have a scientific or engineering relationship to structures and behaviors, it may not be as obvious in other disciplines. For example, it is interesting to speculate about how *art* is related to science and engineering. There are at least two possible relationships:

- Aesthetically pleasing structures that are appreciated in the “eyes of the beholder”. For example, in nature, a rainbow is a pleasing structure. To a mathematician, the structure of a proof may be pleasing. For a software engineer, a clear algorithm that provides a desired behavior in a non-complex manner may be pleasing.

- Another relationship comes from the term “artisan”. The term artisan is typically applied for someone who is mature in his/her discipline. Most typically, artisans are able to design and develop structures that meet needs and thus are most similar to the engineering profession. However, true artisans are most always capable of observing then finding and describing relevant structures.

The artistic relationship introduces the important notion of style into systems related work. The reader is encouraged to consider other relationships between art and science as well as art and engineering. Further, consider structural and behavioral relationships in disciplines such as psychology, sociology or other disciplines with which you are familiar.

Fundamental Concepts

Given this perspective on structures and behaviors, we now introduce a set of concepts and principles that will enable your ability to “think” and “act” in terms of systems. The understanding and usage of the concepts and principles is considered to be a most vital aspect as it will affect your own ability to see the system aspects of any type of system as well as to communicate with others concerning system related problems and opportunities. We begin with the most fundamental concept.

We believe that the essence of a system is <u>togetherness</u>, the drawing together of various parts and the relationships they form in order to produce a new whole that will have its own structure, function, and life cycle.

Boardman and Sauser (2008)

This first fundamental concept of "togetherness" permits us to recognize as von Bertalanffy postulated that systems are everywhere. The additional aspects of the citation points to three additional concepts; namely structure, function (we shall at this point identify this as behavior) and life cycle.

Structures and behaviors are the central properties of all man-made systems. The structure of a system is a static property and refers to the constituent elements of the system and their relationship to each other. The behavior is a dynamic property and refers to the effect produced by a system "in operation. "

Classifying Systems

A system taxonomy would be a useful tool. Such a complete enumeration of systems is in general not possible since the perspective on systems is highly context dependent. On the other hand, for practical purposes the enumeration of systems that are of interest for a particular purpose is quite important and achievable. In lieu of a comprehensive taxonomy and to focus upon various types of systems, the classification by Checkland (1993) provides a useful starting point. The reader will observe that systems can be placed into one or more of these four categories.

Natural systems – These systems have their origin is in the universe and are as they are as a result of forces and processes which characterize the universe. They are systems that could not be other than they are, given a universe whose patterns and laws are not erratic.

Defined physical systems – These systems are the result of conscious design aimed at satisfying some human purpose. They are composed of physical elements that have well defined relationships.

Defined abstract systems – These systems do not contain any physical artifacts but are designed by humans to serve some explanatory purpose. Abstract systems can include mathematical descriptions, poems or philosophies. They represent the ordered conscious product of the human mind. Definitions of systems composed of function and/or capability elements are examples of abstractions that can later be captured in other man-made system forms, physical or as concrete human activities.

Human activity systems – These systems are observable in the world of innumerable sets of human activities that are more or less consciously ordered in wholes as a result of some underlying purpose or mission. At one extreme is a system consisting of a human wielding a hammer, at the other international political systems that are needed if life is to remain tolerable on our small planet. This will include the utilization of *a priori* defined sets of processes composed of activities (not explicitly addressed by Checkland) as well as sets of activities viewed from a particular perspective of interested parties.

For systems engineering, focus is placed upon the man-made systems and system situations that are of importance for individuals as well as for various groups including public and private organizations and their enterprises in developing capabilities for learning to think and act in terms of systems. Thus, the understanding defined physical, defined abstract and human activity systems are all important for achieving this goal. Natural systems are, of course, not excluded since natural occurring elements may be incorporated as elements of a man-made system or as elements in the environment in which the man-made system operates.

System Topologies

There are two fundamental topologies for systems that form the basis of "togetherness"; namely the hierarchy and the network as illustrated in Figure 2.

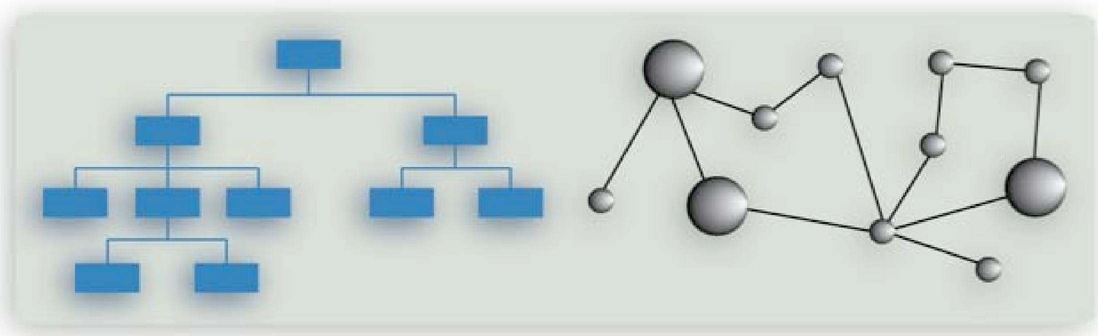

Figure 2. Hierarchy and Network System Topologies

The hierarchy topology is the result of a defined system that is developed to meet some need. The system results from an analysis that decomposes a system into constituent parts at two or more levels. This decomposition leads to a logical basis for understanding, partitioning, developing, packaging, and managing the system in a prudent manner. This topology is typical for the planned development of products (physical and/or abstract), but also can be found in the planned development of an organization, enterprise or even project. Such human activity organization chart usage of hierarchy is quite common for explaining who has responsibility for parts of the system as well as for establishing a chain of command (who reports to who).

The network topology can be used to capture essential properties of defined physical systems; for example networks of plumbing, highways, train tracks, power transmission, telecommunications and, of course, the internet. At a higher level, network topologies can capture defined abstractions such as capabilities or functions to be provided and as stated earlier can then form the basis for physical system realizations. Such systems physical or abstract are typically designed for change; that is, the topology is changed over time where nodes and/or links are added or removed.

The network topology is also relevant for human activity systems including social systems where various forms of relationships between human elements (individuals and/or groups) can be expressed. Such systems may or may not be planned. If they are planned, they can be used to regulate relationships. However, they can arise due to elements and relationships that evolve and in this case attempt to portray, even difficult, conflicting interpersonal relationships. Networks arise due to a problematic situation when multiple elements interact in a manner that is dangerous. For example, a terrorist, a bomb, a subway, and passengers become the elements of a dangerous network of elements and relationships.

The two system topologies are not exclusive in and of themselves. It is quite clear that an organization described as a hierarchy does not always function according to a strict line of command. Networks, even though undefined, arise between individuals and groups that provide the necessary elements and relationships to get things done. Further it is clear that individual elements in a physical network such as a transformer in a power grid are products that deliver services and have been planned and developed as systems for their individual purpose or need. These elements are systems, in their own right, that can have been decomposed, developed and managed according to a hierarchy.

Systems-of-Interest

All of the forms of man-made systems as well as natural systems potentially contain large numbers of elements as pointed to the following:

> *At this point, we must be clear about how a system is to be defined. Our first impulse is to point at the pendulum and to say "the system is that thing there." This method, however, has a fundamental disadvantage: every material object contains no less than an infinity of variables, and therefore of possible systems. The real pendulum, for instance, has not only length and position; it has also mass, temperature, electric conductivity, crystalline structure, chemical impurities, some radioactivity, velocity, reflecting power, tensile strength, a surface film of moisture, bacterial contamination, an optical absorption, elasticity, shape, specific gravity, and so on and on. Any suggestion that we should study all the facts is unrealistic, and actually the attempt is never made. What is necessary is that we should pick out and study the facts that are relevant to some main interest that is already given.*
>
> R.W. Ashby (1956)

Thus it is important to identify: Where is your system-of-interest? What are its salient elements? and How is it related to other systems and to the environment in which it is contained? These are vital questions to ask. Flood and Carson (1998) provide a useful perspective in this respect as portrayed in Figure 3.

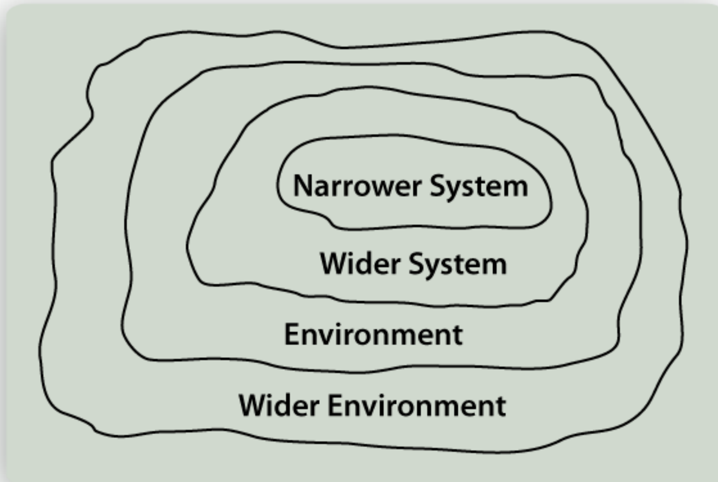

Figure 3. Systems-of-Interest in their Environment(s)

A system can be categorized as being a *closed system* in which no elements of the system are found to have relationships with anything external to it. For example, a perpetual motion machine that continues to operate based upon counterbalancing weights without any influence from the environment in which it operates. In contrast, an *open system* is characterized by exchanges of material, information and/or energy between itself and its environment across a boundary.

Thus for open systems while we might focus upon the elements and relationships of a narrower *System-of-Interest* (NSOI) we must also consider its context in terms of a wider System-of-Interest (WSOI) and well as the environment(s) in which they operate. Let us consider two examples:

A business that sells toys is a system composed of corporate planning, marketing and sales, management, research and development, production and distribution elements. Thus the business can be considered as a narrow System-of-Interest (NSOI) upon which we can focus. However, it is part of a wider System-of-Interest (WSOI) that encompasses their customers as well as their suppliers of raw materials. The business is operated in an environment where the toys are marketed and changes in that environment due to consumer attitudes towards the toys, economic factors, competitors and so on will have an affect upon the wider System-of-Interest and in turn the narrower toy business System-of-Interest. There is also a wider environment that can also affect the closer environment as well as the other Systems-of-Interest. For example, governmental regulations that can affect the consumption of the toys based upon pressure groups demanding regulation.

As another example of the relationships portrayed in Figure 3, consider an action composed of a terrorist, a bomb, a subway, and passengers as elements and relationships of this dangerous situation. This narrower (NSOI) is tied to a wider (WSOI) by amongst other elements, contacts with a terrorist organization, the supply of materials, know how to make the bomb, the subway system and the composition and mental framework of the passengers. The NSOI and WSOI exist in an environment where there is a system based upon for example political, economic and religious beliefs. This environment in turn is encompassed in wider environment in which decisions in the form of laws and regulations concerning political, economic, and religious aspects are taken into account.

The reader will observe that via these two examples as well as the earlier discussions about discipline independence, that the scope of systems is quite wide. This broad scope certainly indicates that there is a vested interest in removing the much of the mystery and moving towards at least a partial mastery of systems.

Sustained, Situation/Respondent and Thematic Systems

Depending upon the type of value added product or service that a public, private or non-profit enterprise supplies their provisioning related and enabling system assets have varying longevity. Institutionalized systems must be properly *sustained* over long periods of time in order to be in such condition that when put into operation (instantiated) are ready to deliver the desired effect.

The provisioning of value added products and services such as aircraft, telecommunication equipment, banking services, health care, social welfare, etc. requires a long sustained life cycle. Typically such sustained systems result in product or service families. So from a generic system description, variant products and services are produced, each one of which must be life cycle managed.

Systems can arise as a *situation* that may be short-term but may have a long longevity. The situation may be thought of and even described in terms of a network of contributing elements and relationships as illustrated in the terrorist action described earlier. In order to counter-act the situation that has arisen a *respondent* system is created and put into operation. For example, consider as a respondent system, a fire brigade that is assembled from elements (equipment, consumables (water, chemicals, etc.), and personnel) in order to bring a fire under control. Another example of a respondent system is the assembly of a military force in order to pursue a Course of Action to meet a situation that has arisen. Such system services are composed from available assets (equipment. people, methods and procedures) and form a temporary system asset that is defined quickly and put into operation by a mission related task force. During the operation of the system service feedback concerning situation developments are used to rapidly restructure (redefine) the respondent system in order to meet changing needs.

Situation systems also arise in the operation of any organization and represent a challenge to the organization in putting together a respondent system. Typically the situation is met by formation of a task force or project will meet the situation, be it a problem (perhaps crises), or an opportunity for the organization. Depending upon views and viewpoints, the situation and respondent system can be seen as coupled into a single larger WSOI where the elements (situation and respondent) interact.

In relating situation systems to respondent systems and sustained system assets, consider the introduction of a system-coupling diagram as portrayed in Figure 4.

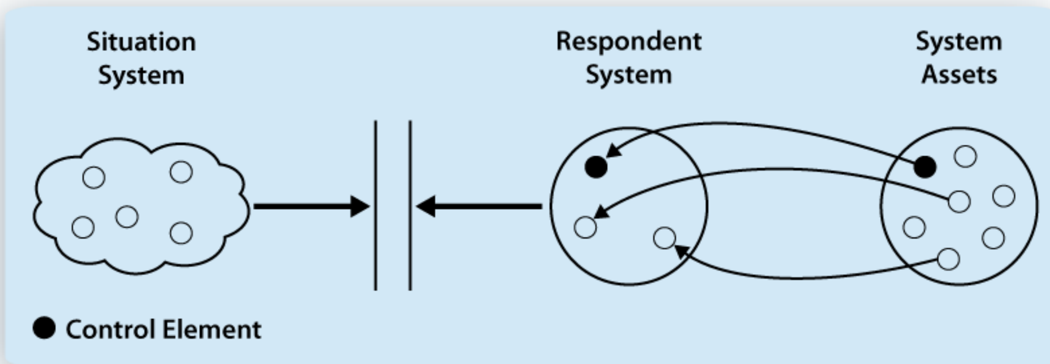

Figure 4. System-Coupling Diagram

Here we see clearly the formation of a respondent system based upon system assets. One of the elements to be incorporated must be a control element that directs the respondent system in its activities in responding to the situation system. The situation system provides both input to the respondent system and is the recipient of outputs from respondent system actions. The reader should keep this coupling diagram in mind since it is a basis for unifying "thinking" and "acting" in terms of systems. It should be a familiar scenario for everybody. Consider the situation of getting somewhere by some means of public or private transport. We are always building respondent systems in our mind based upon system assets such a knowledge of routes, available transportation media, time schedules, and so on. Indeed as von Bertalanffy stated, systems are everywhere. In organized forms, there are various names for respondent systems such as mission, project or task force.

The situations described above are *real*, that is they actually occur. Another form of situation system is *thematic*. That is, they are constructed for the purpose of studying the systemic aspects of a potential problem or opportunity situation as a theme. That is (what if ?) a particular problem situation or opportunity arises. In addition to studying the problem or opportunity situation one or more respondent systems may also be created in order to study the effect produced by potential courses of action or to actually practice in the form of a simulated situation/response environment. Such training sessions are quite common in military environments and for civilian crises management. They can also be used as a basis for business games and management exercises in any type of organization.

To illustrate a context in which the treatment of problem and opportunity situations are treated; consider the international operations established for the purpose of creating peace and stability in countries in which some form of turmoil situation exists forms a vital system. In this context, elements from multiple spheres are referred to by the acronym PMESII (Political, Military, Economic, Social, Infrastructure and Information) Joint Publication (2007). The coupling of elements between the spheres is illustrated in Figure 5. The network can represent the system coupling of elements contributing to or being effected by a problem situation, or the elements of a respondent system to meet the problem, or both.

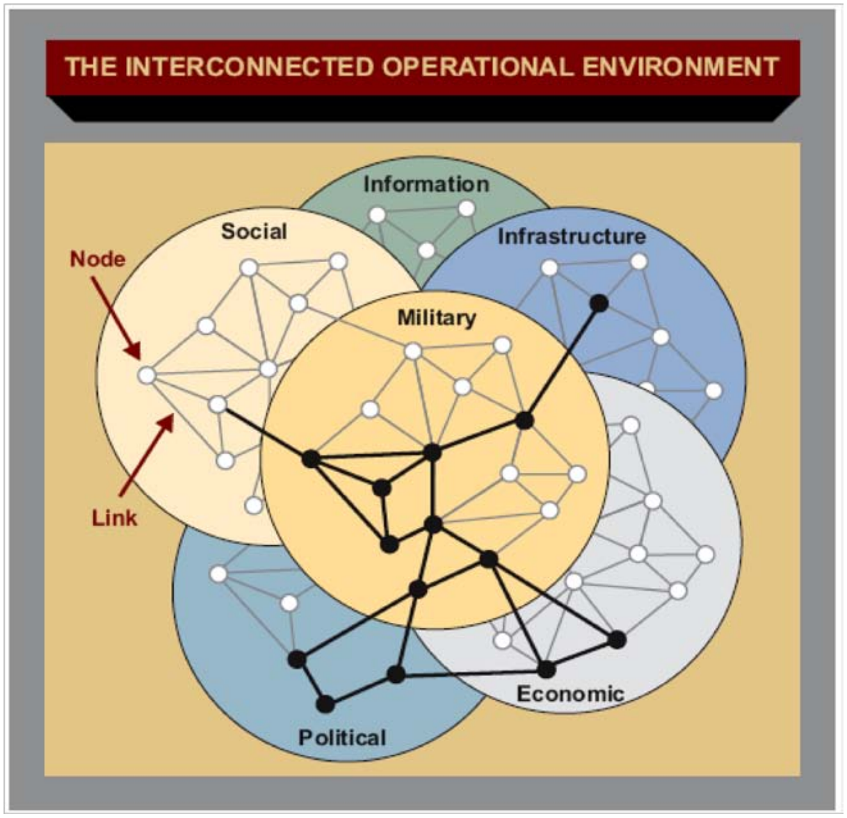

Figure 5. Network of Political, Military, Economic, Social, Infrastructure and Information Elements

The composition of real situation or thematic situation systems from the elements of multiple systems and their interrelationships is often temporary and thus the respondent systems are typically not defined as sustained assets and are typically not life cycle managed. However, some respondent systems treating longer term problems or opportunities may have a long life time in which case they should also be life cycle managed.

A Systems Survival Kit

Based upon the contributions of others as identified above and the perspective of the system coupling diagram, we now formalize the concepts and principles of systems by providing concrete system semantics. Together these contributions form a systems survival kit. That is, when understood and appreciated they will continually come to your aid individually and in groups as a means of focusing upon the essential properties of any type of man-made system. Thus, they contribute to what Senge (1990) terms a learning organization.

Concrete Concept Definitions

The concepts that have been introduced are categorized and given the specific definitions provided in Table 1. The categories fundamental, types, topology, focus and role convey the essential properties of systems.

Concept Categories	Concepts	Definitions
Fundamental	Togetherness	Two or more elements are related resulting in a new whole.
	Structure	The constituent elements and their static relationship.
	Behavior	The effect produced by dynamic element relationships emerging from operation.
Types	Defined Physical System	Two or more physical elements are integrated together producing a new whole.
	Defined Abstract System	Two or more abstract elements are related resulting in a new whole.
	Human Activity System	Two or more elements, at least one involving a human activity are integrated resulting in a new whole.
Topologies	Hierarchy	A level-wise structure of systems and system elements that is defined recursively.
	Network	A node and links structure of system elements and their interrelationships.
Focus	Narrow System-of-Interest (NSOI)	The system upon which focus is placed in respect to a view.
	Wider System-of-Interest (WSOI)	The systems that directly affect (including enabling) the narrow System-of-Interest in respect to a view.
	Environment	The context that has a direct influence upon the System-of-Interest.
	Wider Environment	The context which has an indirect influence upon the System-of-Interest.
Roles	Sustained System Asset	A system that is life cycle managed and when instantiated provide system services.
	Situation System	Two or more elements become related together resulting in a problem or an opportunity. Alternatively, an objective or end state that defines a desirable situation is established.
	Respondent System	A system composed of two or more elements that are assembled in order to respond to a situation.
	Thematic System	A system that is composed for the study of possible outcomes of a postulated situation system as well as one or more respondent systems ("what if").

Table 1. Concrete Concepts (Categories and Definitions)

System Principles

Building upon the concrete definitions of concepts and the utilization of the system-coupling diagram as a universal mental model, we can now express concrete principles that establish system rules (truths to abide by) Lawson and Martin (2008).

- All systems are composed of two or more elements that constitute togetherness

– Systems are composed of structure elements or behavior elements

– Defined elements and relationships can be abstract, physical or human activities

– Systems are organized as a hierarchy or a network

– Bounding of systems in respect to views are defined by a NSOI, its WSOI, its Environment, and Wider Environment

– Situation systems result from (problems or opportunities) or from defined objectives in the form of end states

– Respondent systems are developed and utilized to handle situation systems

– Sustained system assets are deployed in respondent systems

– One of the elements of a respondent system must provide control

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The system-coupling diagram presented earlier and portrayed in Figure 4 together with this small set of concepts and principles forms a universal mental model of system semantics. Via the system roles that are portrayed, it becomes a universal mental model for the occurrence, composition and deployment of systems.

Application to Planned Systems

While the application of the system survival kit to situation and respondent systems may be clear it is also applicable to all forms of planned systems. That is during the life cycle management of any system, be it the product or service supplied by an enterprise or any of the infrastructure systems that belong to its systems portfolio.

According to the ISO/IEC 15288 standard (2008) various work products are produced as a result of “executing” carrying out processes during the life cycle as the System-of-Interest evolves from need to concept and to reality in the form of products and services. To portray these transformations, consider the life-cycle structure illustrated in Figure 6.

Here we observe at the top of the figure that the System-of-Interest is first described as Defined Abstract System that is then transformed to a concrete Defined Physical and/or Human Activity System when it becomes a product, that is instantiated. An eventual retirement of the System-of-Interest involves disposing of instances and can also involve retirement of the system definition, that is, the Defined Abstract System.

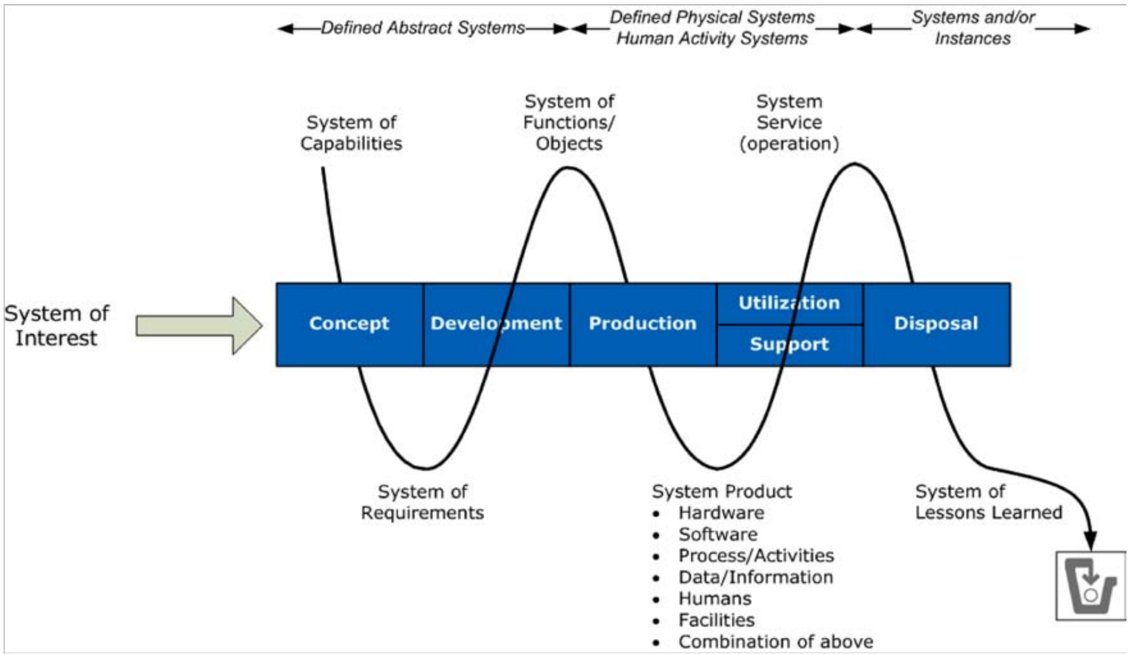

Figure 6. Life Cycle Transformations (System-of-Interest Versions)

It is important to note the perspective portrayed in the figure in naming the various stage and process related work products as "systems". We view the various descriptions as well as the eventual product as "versions" of the System-of-Interest. That is from a need, the first version of the System-of-Interest is created as a System of Capabilities. This description meets all of the criteria for a system as earlier where the most fundamental criteria is the property of "togetherness".

From this System of Capabilities, the next version of the System-of-Interest is created in the form of a System of Requirements reflecting both the functional as well as non-functional requirements to be placed upon the System-of-Interest. The next version of the System-of-Interest is a System of Functions or Objects that describe the basic transformations that the instantiated System Products are expected to perform when they provide their service. Typically, this involves some type of flow of energy, material, data or information.

In order to provide for orderly development, production and usage, it is important to keep consistency between the various descriptions, that is, traceability between the elements of the various versions of the System-of-Interest.

Based upon the description versions, System Products are produced as the result of the integration of elements that can include hardware, software, processes/activities, data/information, humans, facilities, natural elements or combinations thereof. When the product is utilized in its final environment, it provides the System Service, that is the behaviors that it has been designed to achieve.

One further version of the System-of-Interest that is most often forgotten is to capture information about the history of the System-of-Interest in the form of a System of Lessons Learned based upon system conception and development as well as product instances and the services they have provided.

Given this perspective on life cycle transformations, let us now apply the system coupling diagram given in Figure 4 to the life cycle. Prior to each transformation a situation system exists, that is from needs to a system of capabilities from capabilities to a system of requirements, and so on. In order to meet this situation a project (respondent system) is given responsibility to perform the next transformation. The project draws upon institutionalized system assets to perform to the transformation. One of the assets is how projects are managed (controlled).

Summary

In this paper we have provided a basis for understanding the essential properties of systems. This builds upon contributions by colleagues as well as the introduction of a unified means of viewing systems and their utilization in both planned and unplanned situations. The material for the paper is taken from a course compendium (being prepared for publication) that has been successively developed during the last six years Lawson (2009). The course, "Systems Thinking and its Application" was first developed for the Stevens Institute of Technology and since then has been presented at a variety of educational institutions in the USA and Sweden as well for public and private sector organizations. The validity the unified view of system semantics presented in this paper has been verified many times by participants that have applied the system survival kit thinking to a variety of real life system related applications. The authors thus thank all of those who by their active participation have contributed to the continual improvement of this view of system semantics.

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