Defining " System " : a Comprehensive Approach

Conference Paper · July 2017

11 authors, including:

Hillary G Sillitto
University of Strathclyde

Dov Dori
Technion - Israel Institute of Technology

Regina Griego

Scott Jackson
Burnham Systems Consulting

27th Annual INCOSE International Symposium (IS 2017)
Adelaide, Australia, July 15-20, 2017

Defining “System”: a Comprehensive Approach

Hillary Sillitto, CEng
Sillitto Enterprises, Edinburgh, Scotland UK
www.sillittoenterprises.com

Dov Dori, Ph.D.
Technion, Israel Inst. of Technology and Massachusetts Inst. of Technology
dori@mit.edu

Regina M. Griego, Ph.D.
Sandia National Laboratories
Albuquerque, NM
griego@sandia.gov

Scott Jackson, Ph.D.
Burnham Systems
Los Angeles, CA
+1 949 726-2003
jackson@burnhamsystems.net

Daniel Krob, Ph.D.
CESAMES
Paris, France
+33 1 40 15 54 20
daniel.krob@cesames.net

Patrick Godfrey, DEng
University of Bristol
+44 (0)1892750554
patrick.godfrey@systems-thinking.co.uk

Eileen Arnold
ConsideredThoughtfully, Inc.
eparnold5@aol.com

James Martin, Ph.D.
The Aerospace Corporation
Chantilly, VA
martinqzx@gmail.com

Dorothy McKinney
ConsideredThoughtfully, Inc.
dorothy.mckinney@computer.org

Abstract. Over the past decades, a common definition of the term *system* has eluded researchers and practitioners alike. We reviewed over 100 current and historical definitions of *system* in an effort to understand perspectives and to propose the most comprehensive definition of this term. There is much common ground in different families of definition of system, but there are also important and significant differences. Some stem from different belief systems and worldviews, while others are due to a pragmatic desire to establish a clear definition for *system* within a particular community, disregarding wider considerations. In either case, it limits the effectiveness of various system communities’ efforts to communicate, collaborate, and learn from the experience of other communities. We discovered that by considering a wide typology of systems, Bertalanffy’s General Systems Theory provides a basis for a general, self-consistent sensible framework, capable of accommodating and showing the relationships amongst the variety of different definitions of and belief systems pertaining to *system*. Emergence, the appearance of a new phenomenon or capability as a result of relation or interaction between objects, is key in differentiating between objects that are systems and those that are not. Hence we propose a family of definitions, related by the common theme of emergence, which is in line with both the realist and constructivist worldviews, and covers real and conceptual systems. We believe this better reflects the current scope of systems engineering and is required to support the aspirations expressed in INCOSE SE Vision 2025.

Motivation

There is a need to clarify the meaning and usage of the word system, because current differences in interpretation by individuals and communities are leading to miscommunication. As this term serves different and important purposes, misinterpretations should be avoided, because they can lead to potentially adverse consequences. Our effort is to synthesize a definition, or a family of definitions, which can be shared by all those who use the term system. A well-conceived definition should enable the following objectives:

- communicate the meaning of *system* more effectively across communities of research and practice to achieve common goals,

- learn and adopt techniques from other communities,
- Improve systems engineering (SE) stakeholder communities' understanding of worldviews associated with different categories of definition of *system*, relevant to INCOSE's current activities and scope and to the aspirations set out in and implied by Vision 2025 (INCOSE 2014).

Researchers and practitioners express a need for a broader definition. In the special Insight article on "systems of the third kind", Dove et al. (2012) stated:

…the current INCOSE view of systems and systems engineering does not cope with the kinds of problematic situations with which society wants our help. Specifically, although the systems engineering community is reasonably successful in devising solutions for problematic situations that behave as state-determined systems or as probabilistic (but ergodic) systems, the systems engineering community has not established a record of success in devising **systems that can cope with non-deterministic situations***. Meanwhile, the number of non-deterministic situations is increasing rapidly.*

Rousseau et al. (2016) observed that "*the [systems] field continues to face many significant challenges, especially:*

1. *The presence of the systems field as a distinct enterprise within academia is often questioned …;*
2. *The systemic nature and scientific integrity of many of the systems methodologies have not been adequately demonstrated…;*
3. *Many methodologies have no or weak theoretical foundations, and consequently it cannot be assessed why they sometimes fail, and they cannot be migrated to new kinds of use-cases;*
4. *The systems field cannot assess its own completeness and articulate its potential future value in a principled way, making the credibility and growth of the field a hostage to fortune.*

… In our view, the root causes of all these challenges are:

a. *diversity of perspectives on the meaning of the concept "system";*
b. *slowness of progress towards establishing a general theory of systems;*
c. *variety of terminologies used across systemic specializations, and*
d. *lack of a model of the systems domain conceived as an academic discipline."*

Recognizing these issues in the Systems Engineering field, this work is motivated particularly by challenge 3 above, and addresses the first and third causes. We maintain that the real root causes can be found by answering the question of why is there a diversity of perspectives and why is there a variety of terminologies.

SEBoK (2016) claims that "*…any particular identification of a system is a human construct used to help make better sense of a set of things and to share that understanding with others if needed.*" We will try to address this claim and assert that for a certain class of systems there is an objective identification of the system and its boundary.

Research Problem and Methodology

Our research problem is to formulate one or more encompassing definitions of *system* that will be accepted by as many communities of theory and practice as possible. We recognize the magnitude of the challenge involved in answering this problem and realize that there may not be a single accepted definition. We set out with the following research objectives:

- Review currently accepted *system* definitions, from both INCOSE and other communities, as well as usage of *system* in everyday language;

- Identify stakeholder communities and worldviews associated with different categories of *system* definition that are relevant to INCOSE's current activities and scope, and to the aspirations set out in, and implied by, SE Vision 2025 (2014);
- In light of the above, form a view on the adequacy of current *system* definition(s) used in SE; and,
- If necessary, propose one or more new *system* definitions, consistent with the envisaged scope of SE, which will guide future development of SE and facilitate engagement with stakeholders and potential collaborators from other communities.

Prior empirical experience. Our approach was strongly influenced by the following two factors.

1. Prior attempts at converging on an agreed single definition of *system* within the INCOSE community, using an approach based on concept mapping (Novak, see http://cmap.ihmc.us), have failed. Ring (2016) reports that "*In 2012-2014 some of us experimented with concept maps as a way of revealing our respective understandings of selected words regarding SE. [The results] revealed a very low coherence coefficient.*"
2. Wilkinson et al. (2010) and Henshaw et al. (2011) successfully used a "belief systems methodology", based on the principles of Soft Systems Methodology (SSM), to explore and understand why and how different actors use what appear to be the same concepts in different but overlapping ways.

Wilkinson et al. (2010) built a conceptual model that spanned the totality of the partial and differing usages of the term *systems architecture*. From this model, they developed a simple and straightforward framework that accommodated all architecting belief systems. All the belief systems they identified fit within the two basic concepts of "forward architecting" and "reverse architecting", described by Rechtin (1991).

Henshaw et al. (2011) concluded that the different definitions and usages of *capability* within the SE community could be explained in terms of different belief systems or assumptions that stem from the use of the same word in different ways by different communities of practice. Cataloguing the different definitions and associated belief systems using Checkland's CATWOE formalism allowed different actors to recognize the perspectives of each other and understand the different usages.

Selected approach. The basis of the approach taken includes the following steps:

1. Collect definitions of *system* from within the community, surveying the SE literature and a wider common language definitions, and probing the use of this word by other communities.
2. Scan these definitions for similarities and differences, and try to understand the worldviews underlying the differences, again with reference to the wider systems and philosophical literature, as well as the SE literature.

   In this we blend work by Lloyd (2016) and Popper (1978). Popper's "Three Worlds Model" distinguishes between

   - World 1, the real physical world (where our "real systems" exist);
   - World 2, the world of individual thought, which is how each one of us perceived the world – our "mental models" are in World 2;
   - World 3, the world of shared (and by implication, documented) knowledge; both our "informal shared models" and "formal shared models" belong in World 3.

   Lloyd (2016) adds a fourth "world" or "domain", which he calls "the platonic world of forms", after Plato's notion of formal knowledge. We have borrowed (and possibly bowdlerized) this concept for our "formal shared models".
3. Build a conceptual framework that captures and ideally integrates the essence of the different worldviews, types and natures of *system* described in the literature, emphasizing those that are of particular interest to SE stakeholders.
4. Test the following twin hypotheses:

    a) It is possible to construct a conceptual framework that has wide coverage of the systems field and the different worldviews of *system*.
    b) The conceptual framework constructed in the previous step can be used to map a range of system types of interest. This can be done by finding examples to test the key distinctions in the framework, and if necessary, adapting the framework to accommodate the various examples.

5. Construct a family of definitions that can be mapped directly to the conceptual framework, capturing the essential features of the precursor definitions. While doing this, we need to ensure that consistency across the family of definitions is maintained and avoid a language that has substantially different semantics for the different stakeholder communities.

Definitions and Observations

INCOSE Definition. The INCOSE Systems Engineering Handbook, 4th Edition (INCOSE 2015) states that *the systems considered in … this handbook are human-made, created and utilized to provide products or services* ***in defined environments*** *for the benefit of users and other stakeholders. The definitions cited here … refer to systems in the real world. A system concept should be regarded as a shared "mental representation" of the actual system. The systems engineer must continually distinguish between systems in the real world and system representations. The INCOSE and ISO/IEC/IEEE definitions draw from this view of a system:*

- *…an integrated set of elements, subsystems and assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (INCOSE)*
- *…combination of interacting elements organised to achieve one or more stated purposes (ISO/IEC/IEEE 15288).*

Thus, the usage of terminology throughout this handbook is clearly an elaboration of the fundamental idea that a system is a purposeful whole that consists of interacting parts.

As we shall see, these definitions are reasonably consistent with other definitions that apply to their declared scope of purposeful artificial (human-made) systems. Indeed, we argue that any artificial system has a purpose, but since not every system is artificial, we seek a broader definition.

The issue we address in this research is whether these definitions meet the following requirements:

- They adequately cover
    - systems that are not real, but rather conceptual, logical, abstract, or informatical;
    - very large scale emergent systems, working in complex non-deterministic environments, such as the Internet, worldwide automated financial services, and the Internet of Things, and
    - naturally occuring and hybrid (artificial/natural) systems, including
        - unintended systems, such as systems created by human activities that unintentionally affect the natural environment and ecosystem, and
        - intended systems, such as interventions to mitigate climate change or natural disasters of flooding, fire, earthquake, etc.;
- They permit and encourage learning from other systems fields to improve SE theory and practice; and
- They are still appropriate for the wider scope of future systems engineering as set out by INCOSE's SE Vision 2025.

Etymology of the word *system*. The following is an excerpt from the online etymological dictionary:

1610s, "the whole creation, the universe," from Late Latin systema "an arrangement, system," from Greek systema "organized whole, a whole compounded of parts," from stem of synistanai "to place together, organize, form in order," from syn- "together" (see ***syn-****) + root of histanai "cause to stand" from PIE root *stā- "to stand" (see* ***stet****).*

Meaning "set of correlated principles, facts, ideas, etc." first recorded 1630s. Meaning "animal body as an organized whole, sum of the vital processes in an organism" is recorded from 1680s; hence figurative phrase to get (something) out of one's system (1900). Computer sense of "group of related programs" is recorded from 1963. All systems go (1962) is from U.S. space program. The system "prevailing social order" is from 1806.

General Systems Theory. In his General Systems Theory (GST), Bertalanffy (1968) stated that *a system can be defined as a set of elements standing in inter-relations*. In the preface to the revised edition, p. *xxi*, he describes the scope of "systems" as including the following:

- *real systems*, such as galaxy, dog, cell, and atom,
- *conceptual systems*, such as logic, mathematics, music, and
- a subset of the latter group, which he called *abstracted systems* to denote conceptual systems that correspond with portions of reality.

This is the (necessary but not sufficient) basis of the overall framework for system definitions that we propose here. We add a fourth element, *recognized systems*, as the subset of all real systems recognized as being of interest by human observers. Thus, recognized systems in the real world are mirrored by abstracted systems in the conceptual world. More importantly, we add the somewhat overloaded term of *emergence* as another required element in the definition of *system*.

Drawing on Bertalanffy, Miller (1978; 1978a) used a very similar classification and built on it to develop a comprehensive theory of "Living Systems" (Miller, 1978). The key elements of this theory, summarised by Miller (1978a), contain some very important and profound discussion on the nature of material, energy and information, which satisfactorily tackles important philosophical issues about observer independence of "real" systems. This is a most valuable reference, particularly since it addresses a large number of the issues we discussed in a way that is closely aligned with the point our discussions had reached prior to finding and studying this reference.

Miller adapted Bertalanffy's classification slightly in that he used the term *concrete systems* instead of *real systems*, and asserted that *abstracted systems* are distinct from, rather than a subset of, *conceptual systems*. He provided a set of definitions with characterizations for "all systems" and his three major classes of system, as summarized in Table 1.

Table 1: Miller's Definitions of Classes of System

Class	Miller's Definition	Miller's Characterisation, in his own words, *and our comments*
All systems	A system is a set of interacting units with relationships among them [Ludwig von Bertalanffy]	The word "set" implies that the units have some common properties. These common properties are essential if the units are to interact or have relationships. The state of each unit is constrained by, conditioned by, or dependent on the state of other units. The units are coupled. Moreover, there is at least one measure of the sum of its units which is larger than the sum of that measure of its units. [This wording is obscure; it refers to what some would call "emergent properties".] *This would be better phrased as: "…there is at least one measurable aspect, for which the system as a whole is larger than the sum of the aspects of each of its units measured separately."*

Class	Miller's Definition	Miller's Characterisation, in his own words, *and our comments*
Conceptual systems	Miller does not define conceptual systems explicitly, but his discussion implies that he means the same as Bertalanffy (1968)	A conceptual system may be purely logical or mathematical, or its terms and relationships may be intended to have some sort of formal identity or isomorphism with units and relationships empirically determinable by some operation carried out by an observer, which are selected observable variables in a concrete system or an abstracted system. The observer selects the variables of his conceptual system.
Concrete systems	A concrete, real, or veridical system is a non-random accumulation of matter-energy, in a region in physical space-time, which is organized into interacting interrelated subsystems or components. We call these real systems.	The observer [of a concrete system] … distinguishes a concrete system from unorganized entities in its environment by the following criteria: (a) physical proximity of its units; (b) similarity of its units; (c) common fate of its units; and (d) distinct or recognizable patterning of its units. … evolution has provided human observers with remarkable skill in using such criteria for rapidly distinguishing concrete systems. **Their boundaries are discovered by empirical operations available to the general scientific community rather than set conceptually by a single observer.** *Concrete systems are a superset of the 'classical' SE systems, which are concrete, human-made systems.*
Abstracted systems	Miller does not define abstracted systems explicitly, but his discussion shows that he means the same as Bertalanffy (1968)	Because some of the relationships in abstracted systems are selected by scientific observers, theorists, and/or experimentalists, it is possible that they might be confused with conceptual systems, since both units and relationships of conceptual systems are so selected. The two kinds of systems differ in that some units and/or relationships of every abstracted system are empirically determined and this is not true of any conceptual system. *We do not find this an adequate exclusion criterion, and prefer to regard abstracted systems as a subset of, rather than distinct from, conceptual systems.*

The one significant respect in which we disagreed with Miller's position is that we were not persuaded that we could satisfactorily differentiate *abstracted systems* from all other *conceptual systems*. The reason for this may be that with recent advances in computer science and complexity theory we have access to richer understanding of conceptual systems than the one that existed in 1978. In our proposed framework, we follow Bertalanffy (1968) in suggesting that *abstracted systems* are a subset of, rather than distinct from, *conceptual systems*.

Other definitions in current use. Several hundred definitions of the word "system" can readily be identified. A collated list of those we collected has been made available on the INCOSE Website. Examples of definitions of system include:

1. *A constraint on variety* (Heylighen, 1994).
2. *A model of a whole entity* (Checkland, 1999).
3. *A function-carrying object* OPM definition, (Dori, 2002). This definition pertains to concrete, human-made systems, where function is the process that the system enables (is instrument for), and from which value is extracted by the system's beneficiaries.
4. *A combination of interacting elements organised to achieve a given purpose (*ISO/IEC 15288).

5. *An open set of complementary interacting parts, with properties, capabilities and behaviours emerging, both from the parts and their interactions, to synthesise a unified whole* (Hitchins, 2007).
6. *Relationships mapped over a set of objects* (Simpson, 2006).
7. *That which is fit for purpose* (Ring, 2016).
8. Searching Google (2016) for "system" yielded about 4.13 billion hits and two primary definitions:
    - *a set of connected things or parts forming a complex whole, in particular. a set of principles or procedures according to which something is done;*
    - *an organized scheme or method. "a multiparty system of government"*

    For each of the two definitions above, "*a set of connected things*", a set of domain-specific definitions is given. For the first one these include:

    - **Physiology**: a set of organs in the body with a common structure or function, "*the digestive system*"; the human or animal body as a whole, "*you need to get the cholesterol out of your system*"
    - **Computing**: a group of related hardware units or programs or both, especially when dedicated to a single application
    - **Astronomy**: a group of celestial objects connected by their mutual attractive forces, especially moving in orbits about a center, "*the system of bright stars known as the Gould Belt*"
    - **Chemistry**: short for crystal system – each of seven categories of crystals (cubic, tetragonal, orthorhombic, trigonal, hexagonal, monoclinic, and triclinic) classified according to the possible relations of the crystal axes

    For the second one, "*an organized scheme or method*" we find:

    - orderliness; method "*there was no system at all in the company*". synonyms: orderliness, systematization, planning, logic, routine "*there was no system in his work*"
    - a method of choosing one's procedure in gambling
    - a set of rules used in measurement or classification "*the metric system*"
    - the prevailing political or social order, especially when regarded as oppressive and intransigent. "*don't try bucking the system*" the establishment, the administration, the authorities, the powers, bureaucracy, officialdom, the status quo "*youngsters have no faith in the system*"
9. Business Dictionary (2016), like Google (2016) provides two main definitions:
    - *A set of detailed methods, procedures, and routines created to carry out a specific activity, perform a duty, or solve a problem.*
    - *An organized, purposeful structure that consists of interrelated and interdependent elements (components, entities, factors, members, parts etc.). These elements continually influence one another (directly or indirectly) to maintain their activity and the existence of the system, in order to achieve the goal of the system.*

    These two definitions are analogous, albeit in reverse order, to the two in Google: the first is similar to "*an organized scheme or method*" and the second—to "*a set of connected things*".

    The definition goes on to state that:

    All systems have (a) inputs, outputs and feedback mechanisms, (b) maintain an internal steady-state (called homeostasis) despite a changing external environment, (c) display properties that are different than the whole (called emergent properties) but are not possessed by any of the individual elements, and (d) have boundaries that are usually defined by the system observer.

Although this is not indicated, clearly this paragraph pertains to the second definition, "*organized, purposeful structure*", and not to "*a set of detailed methods*".

10. Oxford English Dictionary (OED, 2016) place system in Frequency Band 7 of 8, which contains words that occur between 100 and 1000 times per million words in typical modern English usage. In 11,995 words, OED provides no less than 16 groups of (mostly domain-specific) definitions, including the following:
    - *a group or set of related or associated things perceived or thought of as a unity or complex whole*
    - *a set of things working together as parts of a mechanism or an interconnecting network – a complex whole*
    - *a set of principles or procedures according to which something is done*
    - *a collection of natural objects, features, or phenomena considered as or forming a connected or complex whole*
    - *an organized scheme or method*
    - *the prevailing political or social order, ("the system") especially when regarded as oppressive and intransigent*
11. Hybertson (2009) offers an explicit "ontological commitment" to go with his informal and formal definitions of *system*:
    - A "preliminary informal concept": *A system is an entity that is of interest as a whole and as a set of two or more connected parts, where connection can be due to structural relations or dynamic interactions*;
    - A set of formal commitments that can be summarised as follows: *a designation by an observer of a group of entities that exist in some world, with logical boundary, known or uncertain, with at least two related or interacting parts - closed or open...*

    While the "preliminary informal concept" could be applied to both real and conceptual systems, the formal definition and associated commitments declare a **constructivist worldview**, which we discuss in a later section. Many of the definitions we found are compatible with either this constructivist worldview or with a **realist worldview**. Indeed, many system definitions seem to imply, but not explicitly state, a realist worldview. Some definitions are specific about the nature of parts of a system, e.g., "hardware, software, people, process…".
12. Rechtin (1991), Dickerson (2008), and Sillitto (2014) propose a common definition along the following line.
    - *[A system is comprised of] parts interacting to create properties of the whole not possessed or exhibited by any of the parts on its own*.
13. Crawley et al. (2016, p.9) define system as follows.
    - *A system is a set of entities and their relationships, whose functionality is greater than the sum of the individual entities.*

    In the discussion just following this definition, they emphasize the two important parts of this definition:

    1. *A system is made up of parts that interact or are interrelated.*
    2. *When the entities interact, there appears a function that is greater than, or other than, the functions of the individual entities.*

    The second part is the system's *emergence*. Notably, the system's function is not always just greater than the sum of the parts – it can be, and usually is, totally *different* from the function of any of the parts. Thus, a system's part functions combine in *non-linear*, often unexpected ways, to give rise to a newly emergent function!
14. ProofWiki (2016) defines a *mathematical system*:
    - A **mathematical system** is a set S=(E, O, A) where:

E is a non-empty set of elements,

O is a set of relations and operations on the elements of *E*, and

A is a set of axioms concerning the elements of *E* and *O*.

15. Urmantsev (1978) defined an object-system mathematically:

    The object-system, OS, is a unity constructed in accordance with relations (in particular, interactions) r which are elements of a set {Ros} combined with conditions z which are elements of a set {Zos} and restrict the relations. The unity is built of primary elements m from a set {M~} selected from the universal set U according to criteria a, which are elements of a set {A~}. The sets {Zos}, {Ros} and {M~} may be empty, or consist of any number of elements, from one to infinity, and the elements may be identical or different.

16. Boardman and Sauser (2008) have characterized system as follows:

> *We believe that the essence of a system is 'togetherness', the drawing together of various parts and the relationships they form in order to produce a new whole…*

Commonalities between definitions. Many of the definitions share some common elements:

1. Composition: Systems are comprised of (at least two) parts or components in relationship.
2. Holism: Systems exhibit holism (from whole), togetherness, unity, or systemness.
3. Function: There is a goal that the system is expected to achieve or a purpose for which it was is designed (true almost exclusively for human-made systems).
4. Emergence: Systems exhibit emergence – the property, function, or phenomenon that can be attributed only to the system as a whole, but not to any of its components acting alone.
5. Environment: Systems have boundaries that distinguish them from their environment.

The following elements are also indicated as system characteristics, but they are less common:

6. Feedback: Systems have correction mechanisms to keep them balanced over time.
7. Homeostasis: Systems have tendency toward maintaining a relatively stable equilibrium between interdependent elements.

Differences Between Definitions. Sillitto (2016) points out that one of the current problems with systems engineering is that *different stakeholders use the same word to mean different things, and different words to mean the same thing*. This is especially true and critical for *system*. Our broad survey of the collected definitions suggests the following observations.

1. Some definitions relate to each other through a “generalization-specialization” relationship, i.e., some definitions specialize a wider definition to be more precise, but over a narrower area of applicability.
2. Some sets of definitions are mutually exclusive relative to others, notably where there is a split between the worldviews characterised as “realist”, for which systems are those that exist in the real world, and “constructivist”, for which systems are purely mental constructs.
3. Many of the definitions describe the same concept using different language.
4. Many definitions describe the same concept, or closely related concepts, from different perspectives.
5. Some definitions are formal, explicit, couched in mathematical language, while others are informally couched in natural language, with varying degrees of rigor and explicitness.
6. Some definitions apply to a limited field, such as human-made purposeful systems, or living systems, but are expressed or used in a way that they are understood to be the only correct meaning of “system” in any domain, such that anything excluded by the definition in question is not a system.

System is a word, a label used to communicate a concept across people, so rather than being a scientific artefact, its most "correct", "right", or "best" definition can be judged by what allows for the most effective communication. This communication is especially critical both within and between the science and engineering communities, so members can coherently share ideas and pursue joint endeavours. Thus, the correct and appropriate use of the word *system* is a matter of opinion and belief, not of scientific proof. What is a matter of scientific proof, is whether a particular real world entity or formal conceptual entity has properties that we choose to associate with our definition of *system*.

Stakeholders and Worldviews of "System"

Members of different stakeholder groups might be expected to hold worldviews that are similar to others in their group, and different from those of other groups. Of the many complementary and opposed or contradictory worldviews in the systems field, perhaps the most important is the opposed pair of "constructivist" and "realist" (Sillitto 2016), followed closely by whether artificial or human-made systems are similar to or fundamentally different from naturally occurring systems.

Despite the above expectation, it is a matter of empirical observation that members of the same stakeholder group may hold different or even contradictory worldviews about systems. For example, many practicing systems engineers are realists, and many are constructivists, so identifying different worldviews with different stakeholder groups, or vice versa, is an over-simplification. Sillitto (2016) makes the empirical observation that systems engineers holding opposing constructivist and realist worldviews seem to be perfectly able to work together on practical system projects, demonstrating that effective collaboration is possible even if participants hold opposing worldviews.

Stakeholders. The Vision 2025 identified, and we added, several relevant stakeholders for Systems Engineering and future systems including:

- *System Users: The general public, public and private corporations, trained system operators*
- *System Sponsors: Funding organizations, investors, industrial leaders and politicians*
- *Policy Makers: politicians, public/private administrators, governments / governing bodies, policy analyst / think tanks, non-governmental agencies*
- *Engineering executives*
- *Academics & researchers: including for various disciplines and domains*
- *Practitioners*
- *Tool Vendors*

Each of these stakeholder groups have different viewpoints for what is relevant and important about a system, none of these viewpoints is complete, and all are likely to be important to various degrees. However, the worldviews that each brings vary widely.

Worldview summary. In email correspondence reproduced with permission, David Rousseau writes:

> *"Worldviews related to 'Systems' are highly varied given how young the scientific enterprise and even younger the metaphysics of science is. A majority of current metaphysicians of science subscribe to Scientific Realism, which (briefly) encompasses three commitments: that the world has a definite and mind-independent structure, that scientific theories are true or not because of the way the world is, and that our best scientific theories are approximately true of the world. But even this is not a uniform position, for example, when thinking about 'structure', some Scientific Realist are Atomists (who think that only fundamental particles are really "things"), or Priority Monists (who think that only one thing exists, namely the whole universe) or Compositional Pluralists (who think parts can make up new kinds of things and things can have some properties not determined by their contexts).*

> *There are further divisions within these views, and Scientific Realists also differ from each other about other issues, such as the nature of laws, causation, necessity, etc. And all these positions can be reformulated in terms of thinking primarily about things, or processes, or interplays of things and processes. Of course, there are also other views to Scientific Realism, e.g., Philosophical Idealism (roughly, the view that consciousness is the ultimate reality), Social Constructivism (many versions, but roughly, the view that we cannot know the truth about anything, and hence whether there are mind-independent truths, because of our cultural conditioning), and Postmodernism (many versions, but roughly, the view that there are no absolutes, everything is relative and contingent).*
>
> *If Scientific Realism is on the right track, then progress is possible in understanding the world and our relation to it. It probably counts for something that has become the dominant view amongst metaphysicians of science. I think in order to be successful at SE, it is sufficient to be a Pragmatic Compositional Pluralist, i.e., act "as-if" it is true (subject to hedges) and not engage with whether it is actually true (subject to hedges) or not. However, if one wishes to contribute to the development of a foundational science of systems (e.g., to strengthen SE), then, I think, it is helpful to take an interest in these philosophical trade-offs."*

The constructivist worldview. In the constructivist worldview, a system is purely a mental construct. We already noted that Hybertson (2009) has defined system in terms of a formal model corresponding to a part of the real world, with an observer-designated boundary. Aslaksen, in email correspondence reproduced with permission, argues along similar lines that "system is a mode of description":

> The **system concept** is a *mode of description*; any aspect of an entity can be described in terms of three sets:
>
> - a set of elements;
> - a set of interactions between these element; and
> - a set of interactions with the outside world (which may be simply an observer).
>
> [In this worldview] nothing *is* a system, and everything can be *described* as a system; ontologically, a system is not a thing, descriptions are a separate ontological class. The purpose of describing something as a system is to handle its complexity, and in order to fulfil this purpose, the elements (i.e., the partitioning) must be chosen so that the complexity of the interactions is considerably less than the complexity of the elements (which remains hidden). The application of the concept takes place in a step-by-step, top-down fashion, each step revealing more of the complexity of the entity in the form of sub-system, sub-sub-systems, etc.
>
> To an entity there can correspond a number of systems (i.e., descriptions), depending on what aspect of the entity we are interested in, such as cost, reliability, performance, etc.

The realist worldview. In the realist worldview, "system" is a label applied to entities or groups of entities in the real world, comprising a complex whole, where interactions between parts generate real-world behavior that is not attributable in whole to any one of the individual parts. Most of the definitions identified or summarized above implicitly accept, and some of them only make sense in, the realist worldview. Few of them are explicitly realist, and of those, some exclude the possibility of systems being purely conceptual or imaginary. In the context of this paper, the word *complex* pertains to systems "with many interacting parts" as defined by Holland (2014, p. 1).

The widespread informal understanding is that a system is two or more elements interacting to create emergent properties of the whole not attributable to any of the parts acting in isolation. The scientific realism, or realist worldview, taken along with this understanding, implies that systems are widespread in nature, or, as phrased by Dori (2002, p. x), "*Systems are all around us.*" Indeed, it seems that systems are a primary organizing principle in nature.

In the realist worldview, systems exist in nature independent of human observation and thought. Some of the realist systems are recognized, identified and explained by humans. Our conceptual models of these systems are approximations of the corresponding real physical system with some degree of fidelity. The model's fidelity corresponds primarily with our ability to predict or anticipate system properties and behaviors that have not yet been observed and reported. The scientific method is used to improve our models of real world systems over time by a series of hypotheses and tests that allow us to refute, confirm, or improve our conceptual models so that they progressively become better representations of the real system over a wider range of conditions.

A Conceptual Framework for "System"

In reviewing the plethora of different definitions of "system" and related worldviews, and searching for common ground between them, we were naturally drawn to Bertalanffy's work on general system theory. We formed and decided to test the following hypothesis: Bertalanffy's view of the different types of system offers the basis for a framework within which at least most system definitions can fit, and would therefore provide a suitable conceptual framework for organizing a family of definitions of *system*. As such, we determined that at the highest level there are two kinds of systems: real and conceptual, as shown in Figure 1.

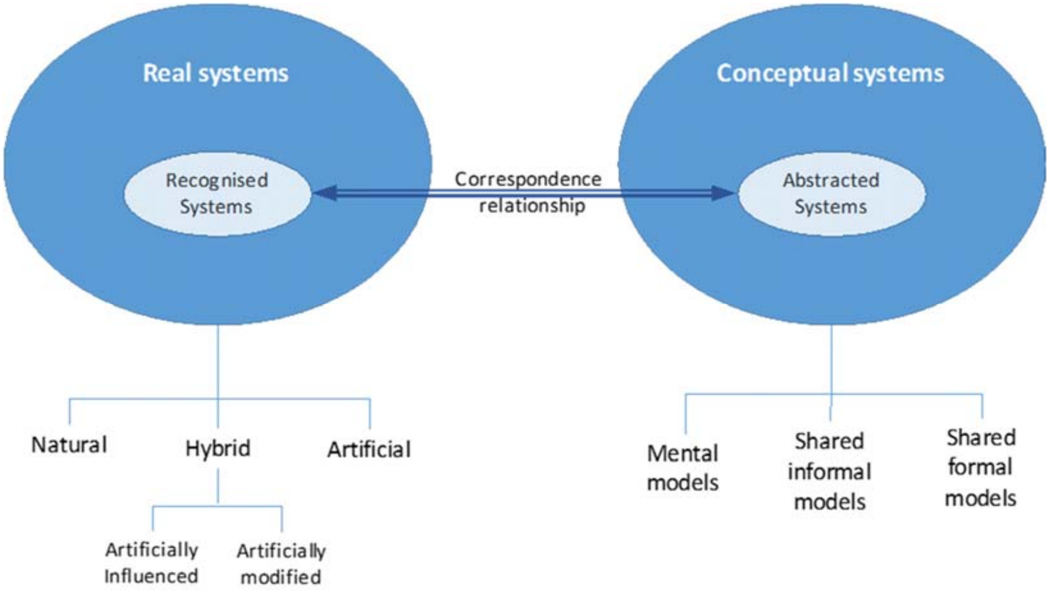

Figure 1. Conceptual Framework for "System"

Real vs. conceptual systems. A *real system* consists of parts interacting in space-time, exchanging material, energy, or information with each other and with the environment, creating physically-measurable effects not attributable to actions of individual parts or to interactions of any proper subset of the parts. Real systems inhabit the material world, and involve flows of material and energy. In addition to their material effects, these flows enable the creation and transmission of information in real systems.

A *conceptual system* is a set of inter-related informatical elements, which, taken together, can be processed by and external processor to synthesize higher-level members in the informatics hierarchy. Note that in this case the external processor can be a human, a group of humans, or something other than a human-made computing device.

The definitions of *system*, *real system*, and *conceptual system* are elaborated in Table 2 with examples and explanation for the rationale.

System definition refined through emergence. If real and conceptual systems are so different, why do we call both kinds systems? In order for real and conceptual systems to be specializations of a generic *system*, they must have something fundamental in common, justifying their labelling as systems. What is that common thing?

Careful examination of our real and conceptual system definitions above reveals that what they have in common is the following feature: both real and conceptual systems exhibit **emergence**, induced by the integration of their parts – *physical* parts in real systems and *informatical* parts in conceptual systems. Emergence is the appearance of a new phenomenon or capability as a result of relation or interaction between objects, and is key in differentiating between entities that are systems and those that are not. In *real* systems, emergence is exhibited as new properties or behavior that are due to interactions between the parts of the system. In *conceptual* systems,a higher level of meaning emerges from the relationships between the parts. In terms of Dori's (2002) Informatics Hierarchy, this can be described as the generation (by a processor such as a brain or computer) of higher-level informatic objects from lower-level ones.

While conceptual systems themselves are static and do not perform any activity, they can provide the basis for action in the physical world – ideas in the brains of humans or other animals, or computer programs, when placed in a suitable computing and communication environment, can have powerful real-world effects.

Table 2. Definitions for System and Two Primary Types

All systems: Def. 1: A complex whole, whose properties are due to its constituent parts, as well as to relationships among the parts. Def. 2: A collection of possibly interacting, related components that exhibits emergence. Comment: *Bertalanffy's core definition,* "Parts in relation", *is a good root definition for a mathematical systems theory, but seems too wide to be sensible for real systems, in that it does not exclude a table on a floor, or a pebble on a beach.*
Real systems: Def. 1: Two or more elements interacting in physical space-time to create properties and effects not achievable by the elements in isolation. Def. 2: A collection of interacting parts that exhibit emergence. Examples: *Plane, planet, solar system, universe, atom, climate system, weather, flock of geese, bridge over an estuary, cat, herd of wildebeest, bacterium, mammal's cardiovascular system, an ant colony* Comment: *The boundaries of real systems are discovered by "empirical operations available to the general scientific community rather than set conceptually by a single observer" (Miller, 1978). Real systems exist in Popper's "World 1".* Subtype Definitions in **Table 3**.
Conceptual systems: Def. 1: Two or more related informatical objects, which, taken together, have meaning not conveyed by the individual elements. Def. 2: A collection of related informatical objects that exhibit emergence by enabling the creation of new informatical objects. Examples: *Relationships between letters to form words. Relationships between axioms to form a theory. Relationships between equations to form a mathematical model. Relationships between lines of code to form a computer programme. A matrix of numbers or mathematical expressions. Relationship between elements of belief to form a belief system (religion, politics, philosophy, etc). A model of a real system.* Comment: *A conceptual system is the product of thought (by humans or other sentient beings); the*

boundary of a conceptual system is designated by the conceiver of the system.

Subtype definitions for real and conceptual system appear in **Table 3** and **Table 4**, respectively. Thus, a conceptual system may be considered as a "mode of description" (Aslaksen).

Table 3. Subtype Definitions for *Real System*

Real System Subtype	Definition	Examples
Naturally occurring systems	A real system occurring in nature	*The universe, the solar system, our planet, human beings, ants, ant colony, atoms;* *systems that exist in nature that we have not yet recognised.*
Artificial systems	A real system created by sentient beings	*Aeroplanes, airlines, air defence systems, cities, cars, ships, cameras, computers, a beaver dam*
Hybrid systems (HS); two subtypes	A system that has attained its current form through a combination of natural and artificial influences	*See below.*
HS1: Modified naturally occurring systems	Hybrid systems created by modifying elements of naturally occurring systems	*genetically modified crops and animals*
HS2: Influenced naturally occurring systems	Naturally occurring systems **influenced** by actions of sentient beings and/or systems made by them.	*selectively bred crops and animals;* *the water flow downstream of a dam or flood prevention system*

Table 4. Subtype Definitions for *Conceptual System*

Conceptual System Subtype	Definition	Examples
Mental models	Concepts and ideas existing in the mind of an individual sentient being	*How we think a computer or a car works, perception of how other people see us, an initial concept of a system design.*
Informal shared models	Concepts and ideas shared with other sentient beings.	*A book, drawings or sketches, photographs, a speech, a video recording, minutes of a meeting, a song or ballad or story or legend, a system of beliefs (religious or political).*
Formal shared models	Concepts and ideas shared with others as a set of formally related informatic objects.	*Computer programme, mathematical proof, 3-D solid model of a physical artefact, executable simulation of an electronic circuit or a physical system, a system of equations (e.g. Maxwell's Equations).*
Abstracted systems (special subtype	Conceptual systems that correspond to (i.e. are an abstraction of) recognized	*A system architecture, an organisation chart, the set of design information for a product, a mental or mathematical model of an observed or*

Conceptual System Subtype	**Definition**	**Examples**
that relates to recognized system)	systems	*postulated physical phenomenon, a diagram or sketch of a real world system (e.g. exploded view of a spacecraft or jet aircraft).*

Summary and Future Work

We set out to begin tackling the challenge of defining the elusive concept of *system.* We laid down foundations for a framework that accommodates different worldviews, as well as real and conceptual systems, human-made and natural systems. There is still a long way ahead of us before we can be satisfied with the result. Indeed, we are continuing this effort to establish a framework that will cater to as large a stakeholder audience as possible, both within and outside the SE community.

References

Adams, K.M., Hester, P.T., Bradley, J.M., Meyers, T.J., and Keating, C.B., 2014, *Systems Theory as the Foundation for Understanding Systems*. Systems Engineering 17(1), pp. 112–123.

Bertalanffy, L.,1968, *General Systems Theory - Foundation, Development, Applications - Revised Edition*, Baziller Press

Boardman, J. and B. Sauser, 2008, *Systems Thinking: Coping with 21st Century Problems*. Boca Raton, FL, USA: Taylor & Francis.

Business Dictionary, 2016, System definition http://www.businessdictionary.com/definition/system.html Accessed Nov. 14, 2016.

Checkland P., 1999, *Systems Thinking*, Systems Practice, Wiley

Checkland, P., 1986, *Systems Thinking*, Systems Practice, Wiley

Crawley, E., Cameron, B., and Selva, D., 2016, *System Architecture: Strategy and Product Development*. Pearson, Hoboken, NJ.

Dickerson, C., 2008, "Towards a logical and scientific foundation for system concepts, principles and terminology"

Dori, D., 2002, *Object-Process Methodology – A Holistic Systems Paradigm*, Springer Verlag

Dove, R., Ring, J., and Tenorio, T., 2012, "Systems of the Third Kind: Distinctions, Principles, and Examples". Insight 15 (2):6-8. International Council on Systems Engineering, pp.1-5.

Google, 2016, System search https://www.google.com/search?q=system&rct=j Accessed Nov. 14, 2016.

Hensha, M., Kemp D., Lister, P., Daw, A., Harding, A., Farncombe, A., and Touchin, M., 2011, "Capability Engineering – An Analysis of Perspectives"

Heylighen, F., 1994, "(Meta)Systems as Constraints on Variation—A classification and natural history of metasystem transitions"

Hybertson, D., 2009, *Model oriented Systems Engineering Science - a unified framework for traditional and complex systems*, CRC Press

rt Introductions. Oxford: Oxford University Press.

Holland, John H. 2014. *Complexity: A Very Short Introduction*. Oxford: Oxford University Press

INCOSE, 2014, *A World in Motion: Systems Engineering Vision 2025*

INCOSE, 2015, *Systems Engineering Handbook, A guide for system life cycle processes and activities*, INCOSE (4th edition)

ISO/IEC/IEEE, ISO/IEC/IEEE 15288, 2015, *Systems and software engineering - System life cycle processes*

Jackson, 2003. *Systems Thinking: Creative Holism for Managers*, Wiley.

Miller G. 1978, *Living Systems Theory*, McGraw-Hill

Miller J. G., 1978a, *Living Systems - The Basic Concepts*, Panarchy.org

Oxford English Dictionary, 2016. http://www.oed.com/view/Entry/196665?redirectedFrom=system#eid Accessed Nov. 14, 2016

ProofWiki, 2016. https://proofwiki.org/wiki/Definition:Mathematical_System Accessed Nov. 13, 2016.

Rechtin E, 1991, *Systems Architecting - Creating and Building Complex Systems*, Prentice Hall

Ring, J, 2016. "Transforming to System Management for non-deterministic situations", INCOSE Webinar 90

Rousseau, D., Wolby, J., Billingham, J., and Blachfellner, S., 2016. "The Synergy Between General Systems Theory and the General Systems Worldview"

SEBoK, 2016. Systems Engineering Body of Knowledge: http://sebokwiki.org/wiki/What_is_a_System%3F Accessed Nov. 11, 2016.

Sillitto, H., 2014, Architecting Systems - Concepts, Principles and Practice, College Publications, System Series Vol 6

Sillitto, H., 2016, "Do Systems Exist in the Real World?"

Simpson, T.W., Siddique, Z., Jiao, J.R., 2006, *Product platform and product family design, Methods and applications*, Springer Verlag

Urmantsev, Y.A., 1978, "Principles of general systems theory – System Analysis and Scientific Knowledge (in Russian)", Nauka, Moscow, pp. 7-41.

Wilkinson, M., King, P., James, A., Emes, M., Bryant, P, 2010. "Belief Systems in Systems Architecting: Method and Preliminary Applications"

Biography

Hillary Sillitto, CEng, FInstP, ESEP, INCOSE Fellow studied Physics at the University of St Andrews and Applied Optics at Imperial College. He started his engineering career at Ferranti in Edinburgh, moved to Thales in 1993, and held senior positions in Thales Optronics and UK Corporate, and on secondment to MOD. He is a past president of INCOSE's UK Chapter, held visiting professorships at the Universities of Strathclyde and Bristol, and is a member of the Omega Alpha Association. His book *Architecting systems – concepts, principles and practice* was published in October 2014.

Professor Dov Dori heads the Enterprise System Modeling Laboratory at the Faculty of Industrial Engineering and Management, Technion, Israel. He is Fellow of IEEE, INCOSE, and IAPR and a visiting Professor at MIT. His research interests include model-based systems engineering, conceptual modeling of complex systems, systems architecture and design, software and systems engineering, and systems biology. Prof. Dori invented and developed Object-Process Methodology (OPM), adopted as ISO 19450. He has authored over 300 publications and has mentored over 50 graduate students.

Regina M. Griego, Ph.D. is a Distinguished R&D Systems Engineer at Sandia National Laboratories working on systems strategy. She has over 30 years of experience leading multi-agency and multidisciplinary teams in various domains to deliver systems and develop organizational capability. She is a teacher, mentor, and coach and recognized for her research and ability to elicit a common conceptual basis for realizing solutions. Regina is an INCOSE Fellow, past Technical Director, and the Enchantment Chapter Founding President.

Scott Jackson, PhD. formerly, senior systems engineer at Boeing. Currently private consulting engineer working with aircraft companies in China and Brazil to implement systems engineering. *Author of Systems Engineering for Commercial Aircraft* (2nd Ed) (2015) (Ashgate) (also available in Chinese) and *Architecting Resilient Systems* (2010) (Wiley).

Daniel Krob, Ph.D. is currently both president of the Center For Excellence on Systems Architecture, Management, Economy & Strategy (C.E.S.A.M.E.S.) and institute professor at Ecole Polytechnique.

He is an INCOSE Fellow. His research interests are currently focused on systems modeling, architecting and engineering. Daniel Krob is also training and advising in these domains major international companies in aerospace, automotive, energy and finance. He authored more than 100 papers, several patents and text books.

Patrick Godfrey FINCOSE, FREng, Deng is Emeritus Professor at the University of Bristol UK, having retired from being the Director of their Systems Centre. He is a Fellow of the Royal Academy of Engineering, Institution of Civil Engineers, Energy Institute and Honouree Fellow of the Institute of Actuaries. He spent the majority of his career in the design of offshore oil and gas installations but has more recently focuses on the application of systems engineering to the development of infrastructure. He is co-author of *Doing it Differently - Systems for Rethinking Infrastructure* (2017).

Eileen Arnold is a co-founder and Chief Systems Engineer for ConsideredThoughtfully, a career mentoring company. Eileen has over 35 years of experience as an electrical/software/systems engineer and workplace mentor in Commercial/Defense Aerospace and Defense weapons systems. She is an INCOSE Fellow and ESEP with a Department of Defense Acquisition extension, and Project Management Professional (PMP). She is an INCOSE volunteer and author since 1996 and has held a variety of international and chapter level leadership positions and a past IEEE Fallcon technical chair.

James Martin, Ph.D. is an enterprise architect and systems engineer affiliated with The Aerospace Corporation developing solutions for information systems and space systems. He previously worked for Raytheon Systems Company and at AT&T Bell Labs. He was a key author for the SE Body of Knowledge (SEBOK) and led the development of ANSI/EIA 632. His book, *Systems Engineering Guidebook*, was published by CRC Press in 1996. James is an INCOSE Fellow, a Founders Award recipient, and was leader of the Standards Technical Committee.

Dorothy McKinney currently leads a dot com start-up, ConsideredThoughtfully, Inc. which provides just-in-time information for professionals interested in career development and professional growth. Dorothy retired in 2014 from Lockheed Martin after 34-plus years with the corporation; in parallel she served as an adjunct professor for San Jose State University and then Portland State University. Other industry experience includes ARGOSystems and SRI International. She is an INCOSE Fellows and an AIAA Associate Fellow.