What is a System?
An Ontological Framework

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Abstract

Over the past decades, the definition of *system* has eluded researchers and practitioners. We reviewed over 100 definitions of *system* to understand the variations and establish a framework for a widely acceptable *system* definition or a family of *system* definitions. There is much common ground in different families of definitions of *system*, but there are also important and significant ontological differences. Some differences stem from the variety of belief systems and worldviews, while others have risen within particular communities. Both limit the effectiveness of system communities' efforts to communicate, collaborate, and learn from others' experience. We consider three ontological elements: (1) a worldview-based **framework** for typology of different system types and categories, (2) key **system concepts** that are fundamental to the various system types and categories, and (3) appropriate **language** for the target audience. In this work, we establish the ontological framework, list key concepts associated with different types of system, and point to a direction for agreeing on an integrated set of *system* definitions in a neutral language consistent with the framework. The definitions are compatible with both the realist and constructivist worldviews, covering real (physical, concrete) and conceptual (abstract, logical, informatical) systems, which are both human-made (artificial) and naturally-occurring, using language acceptable to a wide target stakeholder audience. The contribution of this paper is setting up an ontologically founded framework of *system* typologies, providing definitions for *system*, and identifying the issues involved in achieving a widely accepted definition or family of definitions of *system*.

1 Motivation

There is a growing need to clarify the meaning and usage of the word *system*, because current differences in ontology, and therefore interpretation by individuals and communities, are leading to miscommunication. As previously separate communities start to work together to try to solve major societal problems, such miscommunication and lack of common ground in mutual understanding of this key concept can lead to potentially dire consequences. Our effort is therefore to investigate the different meanings of *system* with the objective of synthesizing a definition, or a family of definitions, which can be shared, or at least recognized, by all those who use this term.

A well-conceived definition should enable the following objectives:

- communicate more effectively across communities of research and practice to achieve common goals by using *system* as a more sharply defined term;
- learn and possibly adopt lines of thought from communities other than the Systems Engineering (SE) one;
- improve SE stakeholder communities' understanding of worldviews associated with different categories of *system* definitions; and
- relate the definition of *system* to INCOSE's current activities and scope and to the aspirations set out in and implied by INCOSE's SE Vision 2025 (INCOSE 2014B).

1.1 The Need for Change in Systems Engineering

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 or probabilistic 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.*

It is also clear from the growing interest in sustainability and resilience in infrastructure engineering, smart cities, and many other forms of complex system, as expressed for example by INCOSE (2014B), that SE can no longer restrict itself to systems that are exclusively human-made (artificial). SE can both learn from, and sometimes be called to intervene in, naturally-occurring systems, so our definition of *system* needs to encompass both human-made and naturally-occurring systems, as well as hybrid ones—systems that include both artificial and natural elements that affect each other, whether premeditatedly or not.

1.2 We, the SE community, are not alone…

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

- *many methodologies have no or weak theoretical foundations, and consequently it cannot be assessed why they sometimes fail … [issues include:]*
  - *diversity of perspectives on the meaning of the concept 'system';*
  - *variety of terminologies used across systemic specializations."*

Indeed, we found it helpful to consider the questions "why is there a diversity of perspectives?" and "why is there a variety of terminologies?"

1.3 Research goal

In this research, we elicit assumptions and lay out foundations for an integrative approach to finding or generating one or more definitions of *system* that meet the following requirements:

- They permit and encourage learning from other systems fields to improve SE theory and practice.

- They are appropriate for the wider scope of future systems engineering, as set out by INCOSE's SE Vision 2025 (INCOSE, 2014B). Under "System solutions", SE Vision 2025 (p.2) includes "*Natural Resource Management Systems, Energy and Transport Systems, Financial and Insurance Systems, Agriculture and Food Management Systems, Ecological Systems, Information Systems, etc.*" These go well beyond the classical, traditional definition of system in the INCOSE Systems Engineering Handbook, 4th Edition (INCOSE, 2014A) cited later, which is restricted to human-made systems, creating the need to update, or at least critically review, the definition of *system* used within INCOSE. Our aspiration is that this investigation and its outcomes will serve not just the SE community, but researchers and practitioners in many domains, perhaps even any domain, of human endeavor.

The kinds of systems we seek to adequately cover include the following:

  - both systems that exist in the real world and those that are constructs of the human mind, which we will call "real" and "conceptual" systems respectively;
  - very large scale emergent systems, working in complex non-deterministic environments, such as the Internet, worldwide automated financial services, the global air transportation system, and the Internet of Things;
  - systems occurring in nature, which we will refer to as "naturally-occurring systems", as well as human-made ones;
  - systems with both naturally-occurring and human-made elements, which we will refer to as "hybrid systems", including

- "intended" hybrid systems, such as deliberate human interventions to mitigate natural disasters such as flooding, fire, earthquake, etc.;
- "unintended" hybrid systems, such as systems comprising human activities unintentionally interacting with the natural environment and ecosystem.

The current paper is concerned with establishing an integrative ontological framework for classification and mapping of current *system* definitions and, if necessary, developing new definitions, along with their underpinning assumptions.

2 The problem space: different definitions of system

2.1 General linguistic usage

Figure 1 presents the origin and evolution of *system* – a highly overloaded word, and its usage frequency over time (Google, 2016). The usage of *system* steadily increased from 1800, peaking in the 1980-1990's, and then somewhat decreasing towards 2010.

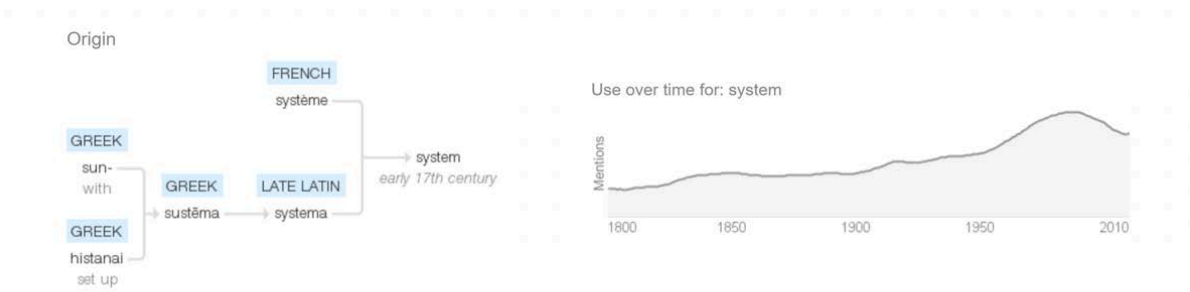


Figure 1. Left: Origin and evolution of the word system. Right: Use frequency of system since 1800

In English, *system* first appeared during the early 17th Century, coming from French système or late Latin systema. The latter word, in turn, originated from the Greek combination of the words sustēma, from *sun*, meaning *with*, and *histanai*, meaning *set up* or *cause to stand*. Together, the resulting semantics of *standing together*, *standing in relation*, or *togetherness* seems to be the essence of the original etymological root. In turn, the Greek may come from the Sanskrit *saṃsthāna*, which also means *standing together* (Sanskrit Dictionary, 2016). The Online Etymological Dictionary (2016) sheds some more light on the evolution of using *system*:

> *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 [the] 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 [as] "prevailing social order" is from 1806.*

2.2 Early uses of systems in science

Aristotle (384–322 B.C.) stated that "the whole is something over and above its parts, and not just the sum of them all" (Aristotle, 1946). Aristotelean views dominated science until the 17th century, when Descarte's new philosophy of "reductionism" became the dominant paradigm because of its success in fostering rapid progress in various areas of experimental physics, and later in biology and medicine. An early modern use of *system* in the natural sciences was by Nicolas Carnot (1824), early on during the development of thermodynamics. His systemic concept was extended in 1850 by Rudolf Clausius, who included also the surroundings – the environment as part of this concept.

2.3 General Systems Theory and cybernetics

Drawing originally from biology, Ludwig von Bertalanffy (1945) pioneered Allgemeine Systemtheorie, which was translated from German to General Systems Theory (GST). GST has introduced models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relation or 'forces' between them.

Wiener (1948), who was influenced by Bertalanffy among others, introduced the term "cybernetics" to refer to self-regulating mechanisms, providing foundation for the areas of artificial intelligence, neuroscience, and reliable communications. Ashby (1956) defined cybernetics as "*the* *study of systems that are open to energy but closed to information and control—systems that are "information-tight*". In other words, cybernetics focuses on information and control, and takes the availability of energy and matter for granted.

In his 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 sets of systems:

- *real systems*, such as galaxy, dog, cell, and atom,
- *conceptual systems*, such as logic, mathematics, music, and
- a subset of the latter group, to which he referred as *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 will propose in the paper: The major dividing line between kinds of systems is between real and conceptual systems, rather than between naturally-occurring and human-made ones, as one may be tempted to think, because both are real systems. The latter distinction is also very important, but as our conceptual model of system will establish, it is done at the next, second level. Where applicable or useful, we might add *recognized systems* as the subset of all real systems recognized as being of interest by human observers and are therefore represented by abstracted systems in the conceptual world.

2.4 Living Systems and Complex Adaptive Systems

Drawing on Bertalanffy, Miller (1978) used a classification similar to that of GST as a basis for a comprehensive theory of "Living Systems". The key elements of this theory (Miller 1978a) contain important, profound discussions on the nature of material, energy and information, and satisfactorily tackle philosophical issues concerning the independence of "real" systems from an observer. Miller changed Bertalanffy's classification and language 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*.

Allen (1986) noted that social, economic, and biological systems cannot be analyzed using only physical principles like Newtonian mechanics, because unpredictable events, human choice and innovations mandate a different approach to such complex systems. Following a similar line of thought, Holland (1995) and others at the interdisciplinary Santa Fe Institute defined a complex adaptive system as a complex macroscopic collection of relatively similar, partially connected micro-structures that increase its survivability by adapting to a changing environment. The complexity of such systems is manifested in the dynamic networks of interactions of the micro-structures, whose relationships are not mere aggregations of the individual entities. Such systems adapt through their mutating and self-organizing response to micro-events that initiate change, rendering the behavior of the ensemble unpredictable by the behavior of the components.

2.5 "System" in current and daily usage

Modern definitions and usage tend to be couched in some combination of parts, relations, interactions, function and purpose. Systems may be thought of as real (concrete), imaginary, or both, corresponding to realist, constructivist or pragmatic worldviews. Figure 2 shows a word cloud compiled from approximately 100 definitions of *system* comprising 2665 words extracted from systems engineering and wider literature.

Figure 2: Word cloud of approximately 100 *system* definitions using 2665 words

Google (2016) provides two main definitions for *system*:

1) *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;*
2) *an organized scheme or method. "a multiparty system of government".*

There are also many domain-specific definitions. For example, Business Dictionary (2016) also provides two main definitions:

1) *A set of detailed methods, procedures and routines created to carry out a specific activity, perform a duty, or solve a problem.*
2) *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.

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.

We see in this definition several important features that fit with most Systems Engineers' concepts of "systemness".

The INCOSE Systems Engineering Handbook, 4th Edition (INCOSE, 2014A) states that *the systems considered in … this handbook are man-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 [and are as follows]:*

- *…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).*

[These are] an elaboration of the fundamental idea that a system is a purposeful whole that consists of interacting parts.

On careful examination, it is clear that these definitions only apply (and are indeed only claimed to apply) to purposeful human-made (artificial) systems. Since not every system is human-made and not all purposeful systemic human interventions involve only human-made systems, we clearly need a broader definition for *system*.

2.6 A basis for system definitions: ontological commitment

Very often, definitions of *system* occur in isolation, without a corresponding statement of assumptions, which, in philosophy, are called *ontological commitments*. One notable example is the fundamental difference between real and conceptual systems: A real system consists of interacting physical entities or agents exchanging material and energy, while a conceptual system is a mental construct, consisting purely of information. Parts of a conceptual system can be related, but they cannot interact unless hosted by a real system. Hence, by implication, any definition referring to "interacting" parts, refers to a real system, whereas a definition containing the term *relationship* can refer to both real and conceptual systems. In general, inconsistencies among different definitions of system are likely to be caused by different implicit, undeclared ontological commitments - assumptions that must be accepted for the definition to be "true" - on the part of the definers. Examples in which such commitments are explicitly spelt out include Hybertson (2009) and Sillitto (2014), but such examples are not frequent.

2.7 Common key concepts in system definitions

Many of the definitions share some common concepts:

1. Systems have *structure* – they are comprised of parts and relationships among them.

2. Systems exhibit *holism*, *togetherness*, *unity*, or *systemness*—the extent to which something is a system.

3. Systems exhibit *emergence* – the property, function, or phenomenon that can be attributed only to the system as a whole and not to any of its components acting alone.

4. Systems occur at multiple levels of organization (e.g., cell, organ, organism, and flock or herd in living systems), with new types of emergence manifested at each level or organization.

5. Systems exist within their *environment*, with which they interact, exchanging material, energy and information.

6. Some systems have a *goal*, *purpose*, *mission*, or *objective* that they are expected to achieve or for which they are designed. AS we argue below, a goal, purpose, mission, or objective only apply to human-made systems.

2.8 Purpose of living systems

The purpose of biological and geophysical systems is not premeditated; rather, it is retroactively inferred by humans examining the current function and its evolution. This is eloquently expressed by Ruse (2013): "*There's no sense for most scientists [to say] that a star is* ***for*** *anything, or that a molecule serves an end. But when we come to talk about living things, it seems very hard to shake off the idea that they have purposes and goals, which are served by the ways they have evolved.*"

Yet we do need to shake off this idea, because the purposes and goals of living organisms are only deducible by humans *a-posteriori* by inspecting the organisms that survived because a very long sequence of genetic changes made them fit for the changing environment, not because these creatures had any premeditated gaol in mind which they worked to achieve. Free will, goal-orientation and desires are all human traits that we should avoid attributing to non-human objects. An exception may be software agents that are endowed with human-like goal oriented behavior, a trend that seems to grow with the development of intelligent robots.

Feedback, homeostasis and viability are also system characteristics that are frequently noted in definitions of systems, but they also apply mostly to biological or advanced human-made systems.

2.9 Is system a real entity or a mental construct?

As we discuss in the next section, there are two major worldviews on the *system* concept: the *realist* and the *constructivist*. According to the realist worldview, systems *actually exist* in nature, independently of human observation and thought. Almost conversely, in the constructivist worldview, a system is a purely *mental construct*.

Hybertson (2009) defines *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 an entity can correspond to a number of systems, which are modes of description, depending on what aspect of the entity we are interested in, such as cost, reliability, or performance: "*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 interaction 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. 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.*"

2.10 "System Boundaries": a human construct, naturally-occurring, or both?

Taking a constructivist approach, 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.*" Yet, referring to living systems, Miller (1978) has clarified that they do have clearly defined boundaries, which can be identified objectively by the difference in entropy and organization between the "system" inside the boundary and the "environment" outside. He argues that "*evolution has provided human observers with remarkable skill in distinguishing* *systems. Their boundaries are discovered by* ***empirical operations*** *available to the general scientific community rather than set conceptually by a single observer.*" We explore this proposition that, at least for a certain class of systems, there is an objective way to identify the system and its boundary.

In the realist worldview, systems exist in nature, independently of human observation and thought. Indeed, the implication of a system being "two or more parts interacting to create emergent properties" is that systems are widespread in nature, or even one of its primary organizing principles. Some of these systems are recognized, identified and explained by humans. Our conceptual models of these *recognized systems* are approximations of the corresponding real systems. The fidelity of the model's representation of the real system can be determined by our ability to use the model to predict or anticipate system properties that have not yet been observed or reported. The scientific method is used to constantly improve our models of real systems over time. A series of hypotheses and their tests allows us to refute, confirm or improve our models so that they become progressively better representations of the real system over a wider range of conditions and generalizations.

Some systems have obvious physical boundaries, such as living cells, organs and animals. Others, such as the atmosphere or the earth's climate system, are more diffuse and spread out. These diffuse systems are not identified by their physical appearance, but by effects they induce, which cannot be attributed to a single entity that comprises them. The occurrence or existence of such effects drive us to conclude that they are caused by underlying systems—assemblages of objects, entities, component or parts whose interactions give rise to processes that trigger and generate the observed effects. The system is identified and understood when these processes have been identified, and mapped to the parts and interactions that cause them. Sillitto (2016) has suggested that to identify this sort of system, we start with the observed effect and work back through the processes causing the effects, to discover the physical *system*.

2.11 Language as a facilitator and barrier to defining system

System is a word, a label used to communicate a concept between people. The correct and appropriate use of the word *system* is a matter of opinion or belief, not of scientific proof. This means that rather than being subject to scientific judgement, the quality of the definition can only be assessed by the extent to which that definition allows for the most effective communication. What is a matter of scientific proof, is whether a particular entity satisfies a particular definition of *system*. Sillitto (2011) pointed out that in systems engineering, *different stakeholders use the same word to mean different things, and different words to mean the same thing*. This is not unique to systems engineering and is especially true and critical for *system*. Our broad survey of over 100 collected definitions of *system* suggests the following observations.

1. Many *system* definitions relate to each other through a generalization-specialization relationship: some definitions specialize a wider definition to be more precise, but over a narrower scope or area of applicability. In general, the longer the definition, the more specialized and narrow it is.

2. Some sets of *system* definitions are mutually exclusive. Notable examples include realist definitions, appropriate to systems that exist in the real world, as opposed to constructivist definitions, which are mental constructs.

3. Many definitions describe the same *system* concept using different language.

4. Many definitions describe the same *system* concept, or closely related concepts, from different perspectives.

5. Some *system* definitions are explicitly formulated in mathematical language, while others are informally couched in natural language, with varying degrees of rigour and explicitness.

6. Some *system* definitions apply to a limited field, such as human-made (and hence purposeful) systems, or living systems, but they are expressed or used in ways implying that they are universal, thereby excluding many potential *system* candidates.

3 Understanding the problem situation

3.1 Diversity of perspectives: Worldviews, Communities and Contexts of Practice

The issue of *system* definition is well situated within the philosophy of science, of which constructivist epistemology, or **constructivism**, is a branch. Conceived primarily by Piaget (1954), it concerns ways in which humans make meaning in relation to the interaction between their experiences and their ideas. Constructivists maintains that the world is independent of human minds, but knowledge of the world is a human and social construction (Crotty, 1998). Thus, science consists of mental constructs aiming to explain sensory experiences or measurements of the natural world by construct models of the natural world. At the other extreme of the philosophy of science or metaphysics is philosophical **realism**, which claims that there is only one correct description of reality, making most aspects of reality ontologically independent of our beliefs, conceptual schemes, perceptions, or linguistic practices. Along these lines, the constructivist worldview of *system* might hold that systems are fruits of our imagination, whereas the realist worldview maintains that systems are out there, no matter what humans think.

In email correspondence reproduced with permission, David Rousseau writes that "*Worldviews related to 'systems' are highly varied. Most current metaphysicians of science subscribe to Scientific Realism, which encompasses three commitments:*

- *The world has a definite and mind-independent structure;*
- *Scientific theories are true or not because of the way the world is; and*
- *Our best scientific theories are approximately true of the world.*

But even this is not a uniform position … some Scientific Realists 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). 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)."

He goes on to note that if Scientific Realism is on the right track, then progress is possible in understanding the world and our relation to it. Scientific Realism has indeed become the dominant view amongst metaphysicians of science. To successfully engage in "traditional" Systems Engineering, it is sufficient to be a Pragmatic Compositional Pluralist, i.e., act "as-if" Scientific Realism is true (subject to hedges) and not be preoccupied with whether it is actually true. However, if one wishes to contribute to the development of a foundational science of systems and strengthen SE, then it is helpful to contemplate these philosophical worldviews.

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. However, empirical observations show 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) has observed that systems engineers holding opposing constructivist and realist worldviews seem to be perfectly able to work together on practical system projects, showing that effective collaboration is possible between participants holding opposing worldviews.

3.2 Variety of Language

One of the issues that makes definitions difficult to agree is the specialized meaning of words in particular communities. For example, when systemists refer to "a set of parts", do they mean exactly what pure mathematicians means when they talk about *sets*? Are *parts*, *elements*, *objects*, *entities* and *constituents* all synonymous? Are all people in all system communities comfortable with the use of the word *object* to include abstract information elements or the diffuse constituents of continuous *systems*, such as the atmosphere or climate system? Or do some find it impossible to get past the natural language use of "object", as a bounded physical entity? Is "emergence" well enough understood that we can use it in a definition of "system"? Different definitions refer to properties, functions, capabilities, and behaviors – are these all distinct, are they overlapping concepts, or can we regard them as synonyms? We would like to be able to use words with their natural language definitions to construct our proposed definition of *system*, but is this possible, given the degree to which the meanings of these words are overloaded within and across the communities we are trying to work with?

As an exercise, we could construct a reasonable and quite general definition of *system* using any combination of the following groups of words [the numbers in brackets are the various options for each set of words]:

> *A system is a <set, combination, group, collection, configuration, arrangement, organization, assemblage, assembly, ensemble [10]> of <parts, components, elements, objects, subsystems, entities [6]> <combined, integrated, organised, configured, arranged [5]> in a way that <creates, enables, motivates [3]> <properties, functions, processes, capabilities, behaviors, dimensions [6]> not <possessed, exhibited, presented [3]> by the <separate, individual, single [3]> <parts, components, elements, objects, subsystems, entities [6]>.*

Multiplying the options for all the word sets yields no less than 291,600 combinations! Which of these well over quarter million definitions are universally understood and acceptable? Which ones would trigger unexpected objections from particular stakeholders?

3.3 Concept of "Systemness"

We define *systemness* as the degree to which an entity or concept is considered or conceived of as a system. So while we struggle with defining *system*, it is relatively easier to gauge the subjective feeling of systemness that specific words raise among various people.

Different definitions of system range from the most general and non-committing definition of "parts in relation" (Bertalanffy) at one extreme, to the specialized detailed definition of *an open set of complementary interacting parts, with properties, capabilities and behaviors emerging, both from the parts and their interactions, to synthesise a unified whole* (Hitchins, 2014) at the other. As argued, the longer the definition, the more restrictive it is, so obviously, systems according to the latter definition are a small subset of the former. For example, not all sets of "*parts in relation*" have "*properties, capabilities and behaviors emerging, both from the parts and their interactions, to synthesise a unified whole*".

During our team's discussions, it became clear that different members had a different intuitive feel for systemness and what they believed to be the threshold for "a proper system". This was explored with reference first to a nutcracker, and then to other potential systems, including a refrigerator, an aeroplane, a surf board, a flock of geese, and the climate. Perspectives (sometimes contradictory) advocated for defining a system (extracted from a much longer discussion) included:

- "The usual scientific way, that is to say define abstractly the concept of abstract system and then say that a concrete system is anything that can be modelled by an abstract system.
- "The notion of emergence has to involve the creation of new property dimensions or attributes, not merely a different value of the same attribute.

- “I regard a nutcracker or a hammer as a tool, a fridge and a plane as technical systems, whereas Hitchins holds that even the plane only becomes a system when the pilot steps in.”

- “Every tool is a system.” [Which elicited disagreement, including this response:] “The nutcracker (and a hammer) cannot credibly or usefully be considered a system. It is merely a tool that in its normal embodiment has several parts. It can do nothing and has no intelligence or decision-making process independent of the operator.

- “The refrigerator, once provided with power, can exercise internal decision processes, control, and state behavior, so is qualitatively different from a nutcracker, or a hammer.

- “So the level of control and internal decision processes makes the difference? If so, is a refrigerator a system but a cooling box supplied with ice not a system?”

Examining the discourse that ensued, we note the following observations about systemness:

a) The boundaries of systemness as expressed by experienced practitioners are narrower than the those offered by the wider, but more rigorous and measurable “academic” definitions.

b) The criteria for systemness do not cleanly fall out of the definitions examined.

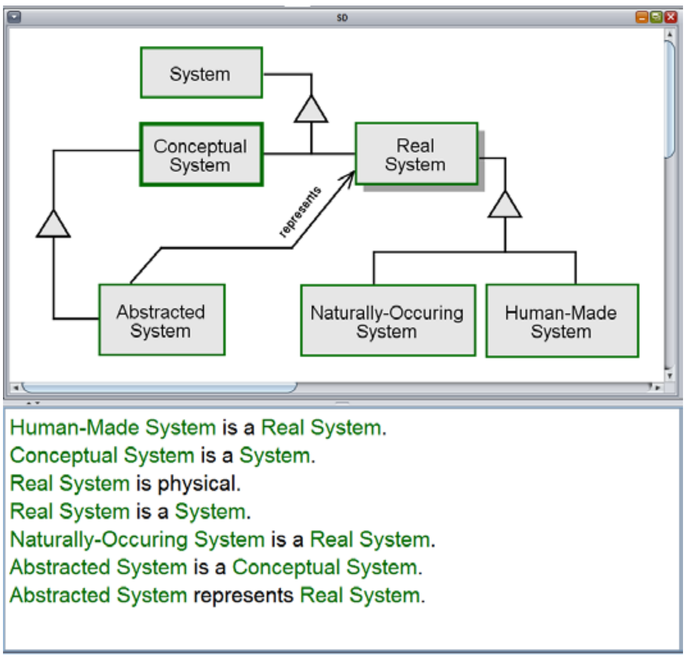
c) The intuitive arguments that certain configurations are not “proper systems” are strongly driven by factors that include the level of autonomous decision making or adaptation to the environment within the system. This is consistent with definitions that emphasise properties such as homeostasis and maintenance of viability, which are appropriate mostly to living systems and emerging human-made systems that try to mimic them.

4 An integrated framework for system definitions

We conclude that there is little possibility of coming up with a single definition of system that will be simultaneously precise enough to be useful, and general enough to meet the agreement of all – or even many – parts of the systems community and its stakeholders. Therefore, we set out to construct a framework of system types to which different related system definitions could be mapped.

In reviewing the plethora of different definitions of *system* and related worldviews, and searching for common ground among them, we decided that Bertalanffy's view of the different types of system provides the basis for a framework within which at least most system definitions can fit. Importantly, by acknowledging *real* and *conceptual* systems, it accommodates both the *realist* and *constructivist* worldviews; and with the concept of "abstracted system" (a conceptual system corresponding to a real one), it accommodates the relationship between systems and models of those systems.

Figure 3 is a preliminary OPM (Dori, 2002) model of *System* based on Bertalanffy's framework, created using OPCAT[1] (Dori et al., 2010). Like any OPM model, it comprises the graphical part – the Object-Process Diagram (OPD) at the top, followed by the automatically-generated Object-Process Language (OPL) paragraph – a collection of sentences in a simple subset of English that textually specify what the OPD specifies graphically.



[1] OPCAT is freely downloadable from http://esml.iem.technion.ac.il/?page_id=1849

Figure 3. OPM model of System based on Bertalanffy's GST

The OPM model expresses the following frame of reference:

- **Real System** and **Conceptual System** are **Systems;**
- **Real Systems** may be **Naturally-Occurring Systems** or **Artificial Systems** (human-made);
- **Abstracted Systems** are **Conceptual Systems** which are intended to represent **Real Systems**.

Examining the model, we see that at the highest level, specialization into two kinds of systems is not between natural and artificial systems, as one might be tempted to think, but between *real* and *conceptual* ones. Building on this basic set of relationships, we propose the classification for systems set out in the following paragraphs. So far we have found that all identified definitions of *system* can be sensibly mapped to one or more areas of the "system space" mapped out by this classification.

4.1 Primary classification of systems: real vs. conceptual

Based on the discussion above, Table 1 presents primary classification of systems with descriptions and examples.

Table 1. Primary classification of systems with definitions and examples

System Type	Definition	Examples
System	a group of parts combined in a way that creates one or more emergent property or capability not possessed by the separate parts	*Everything listed below*
Real System	two or more elements interacting in physical space-time to create emergent properties, capabilities, functions or effects that the elements in isolation cannot achieve	*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…*

System Type	Definition	Examples
Conceptual System	a model, a product of human thought, with emergence through new meaning not conveyed by the individual elements and boundary designated by the conceiver	*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 program, a matrix of numbers or mathematical expressions, a topological map, a model of a real system, a machine drawing, an electric circuit scheme, a UML or OPM conceptual model, relationship between elements of belief in religion, politics, philosophy, etc.*
A particular class of conceptual system:		
Abstracted System	conceptual system that abstracts a corresponding real system	*a system architecture, an organization chart, design information for manufacturing a product, a mental or mathematical model of an observed or postulated physical phenomenon, a diagram or sketch of a real-world system*

In choice of language we follow Bertalanffy. We chose to stay with Bertalanffy's *conceptual system* rather than the synonymous *abstract system*, to avoid potential confusion between the overall class of conceptual or abstract systems and the important subclass of *abstract**ed** systems*, discussed below, in which the conceptual system is "abstracted from" or is "an abstraction of" a corresponding real system. We prefer Bertalanffy's *real system* to the widely used alternative, *concrete system*, because the term "concrete" is unfit and counterintuitive when applied to biological and other naturally-occurring systems, and in an engineering context this term might be restrictively associated with civil engineering.

4.2 Classification of conceptual systems

We classify conceptual systems, which are essentially models (products of human thoughts) into mental models, informal shared models, and formal shared models (see Table 2).

Table 2. primary classification of systems with definitions and examples

System Type	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)*

4.3 Classification of real systems

We classify real systems by their origin as naturally-occurring or artificial. As described and exemplified in Table 2, real systems may be naturally-occurring, human-made (artificial), or hybrid – those containing both artificial and naturally-occurring elements. Hybrid systems may be artificially modified or artificially influenced.

Table 3. Classification of real systems with definitions and examples

System Type	Definition	Examples
Naturally-occurring System	a real system that exists in nature	*the universe, the solar system, planet earth, human being, ant, ant colony, atoms, systems in nature that we have not yet recognised.*
Human-made (Artificial) System	a real system created by human (or other sentient) beings	*aeroplane, airline, air defence system, city, car, military, factory, ship, procurement system, camera, computer, transportation system, communication system*
Hybrid System	a system that combines natural and artificial sources, modifications, or influences	*See below.*
Two types of Hybrid System:		
Artificially Modified naturally-occurring systems	Hybrid systems created by modifying elements of naturally-occurring systems	*genetically modified crops and animals, engineered biological tissue, result of bypass surgery, agriculture*
Artificially 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*

Both hybrid and artificial systems may be *intended* systems—systems created, modified or influenced by sentient beings for a purpose, or *unintended* systems—accidental systems, created by unintended coupling between one intended system and other intended or naturally-occurring systems. Examples include electrical noise due to unintended interference due to unforeseen interaction between two systems that were supposed to be isolated from each other, eco system degradation due to the unforeseen effects of pollution by artificial systems – in which case the artificial system has an unintended interaction with a natural one.

4.4 Recognized real systems: a subclass of real systems

- **Recognized Real Systems** are recognized to exist in the real world.
- Their recognition can be through one or more of the three universal system aspects: **structure**, **behavior**, **function**.

Scientific realists realize that not all systems in the real world have been identified by humans. It is therefore useful to distinguish between those that have been identified and those that have not. Further, as we have already noted, systems may be recognized directly as a physical structure, or indirectly through study of systemic function or behavior. As we present in Table 4, which describes recognized systems, structure is listed as the first indicator, as it is relatively stable and time-independent. Behavior is next, as its perception requires following change over time; and function is the last, as it requires understanding how the system's structure-behavior combination—its architecture—benefits some beneficiary. Each system has at least structure and behavior, and all human-made ones also have function. For example, while an aeroplane is primarily recognized by its structure, its behavior (flying) and function (carrying people and cargo over long distances) are well known and understood.

Table 4. Classification of recognized real systems with definitions and examples

System type	Definition	Examples
Recognized Real Systems	systems that are known, recognized, intended, or perceived to exist in the real world	*the universe, the solar system, planet Earth, human being, ant, ant colony, atom, the USA Federal highway system*
The boundary of a recognized system is proposed by the observer and refined through successive approximations by empirical observation.		
Three basic types of recognized system according to the primary aspect that enables their recognition:		
Structurally-recognized Real Systems	systems that have a well-defined and easily agreed-on physical boundary	*an ant, an aeroplane, a car, a bird, a ship, the Mediterranean Sea*
Behaviorally-recognized Real Systems	systems that may be fleeting or transient, recognized by correlated or synchronised behavior of the parts	*a flock of geese, a crowd of soccer supporters, a dance group, The Red Army Choir, the Earth climate system*
Functionally-recognized Real Systems	systems that are embedded in and distributed throughout other systems or their environment, but have a clear effect or function	*a mammal’s cardio vascular system, a road through a landscape, the global air-traffic control system*

4.5 Correspondence with Popper’s three worlds

Popper (1978) has suggested dividing the world into three worlds based on categories that bear similarity to our system typology:

- World 1, which is compatible with real systems, is the world of physical objects, including biological entities, and events or processes that transform them.
- World 2, which is compatible with conceptual systems, is the world of mental objects and events.
- World 3, which is partially compatible with recognized systems, is objective knowledge—scientific knowledge, cognitive tools, human social organizations, stories and beliefs.

Worlds 1 and 2 interact in ways similar to the interaction between software and the hardware it runs on, or between ideas and the physical human brain required to conceive, digest, communicate and comprehend them, as we explain in Section 5 below.

4.6 Systems with different autonomy and control levels

Many systems experts are uncomfortable with the consequences if we push the definition of "system" towards the logical limit of "parts in relation". From discussion within our group and extensive review of literature and correspondence, we think that an important aspect of systemness, namely the degree to which a thing is considered "system", relates to the capacity of the system to manage itself and react in the face of changing, unstable environment.

In order to explore whether there are specific thresholds on the spectrum from "parts in relation" to Hitchin's more restrictive definition, we considered three reference models from the literature: Miller's Living Systems Theory (Miller, 1978); Beer's Viable System Model (VSM, Beer 1972); and the generic system reference model of Hitchins (2007). The systems in these reference models have internal capacity for communication, decision making and adaptive control, and characteristics that include homeostasis, resilience, and ability to cope with unforeseen circumstances. Considering these attributes, it is possible to identify thresholds on the spectrum from the broad, almost all-encompassing system definition of "parts in relation" to the one requiring "emergent properties, capabilities, and behaviors". Determining whether a system has these attributes may not answer the question "is this a system?", but it does answer the question "what kind of system is this?"

Importantly, decision-making behavior of a certain type at one level of the system does not necessarily imply the same type of behavior at the next level up. Moreover, non-deterministic behavior at a subsystem level may be associated with deterministic behavior at the system level, possibly through feedback and goal-seeking control mechanism. The converse may also be true: systems with deterministic behavior at some subsystem level may exhibit non-deterministic behavior at the system level, for example emergent self-organization of cellular automata, or hysteresis in physical systems.

5 Encoding and Communicating Information in Real Systems

While real-world systems are made of physical elementary particles that make up atoms, and exchange energy and material, ideal conceptual systems are constructed only of items in the informatics hierarchy (Dori, 2002): data, information, knowledge, expertise, and seldom even ingenuity. The matter-mind dualism has occupied many generations of philosophers. Information systems span the gap and create a bridge between conceptual systems and real-world systems.

High levels of emergence, such as feedback, control, and goal seeking, occur in real-world systems through interaction between system parts and the environment by the exchange of material, energy, and information. In order for information to be recorded and transmitted, it must be somehow encoded in matter or as matter-energy states, such as marks engraved in stone, ink marks on paper, aligned magnetic domains in a magnetic storage medium, energy levels or spin states in an atom or molecule, charge distribution in a semiconductor memory, molecular changes in the brain synapses, or encoding of protein molecules in DNA. Information transmission in the real world involves electric, electromagnetic, or mechanical energy, and sometimes materials – the physical transport of an information-bearing object, such as a letter in the mail.

This physical information encoding combined with the physical transmission of information as signals along communication channels constitute the interface between conceptual and real systems. This matter-information combination is what enables naturally- or artificially-intelligent systems to exercise control and respond to external stimuli so as to maintain their function.

In conceptual systems, emergence occurs in the sense that combinations of informatical elements – data encoded in symbols, information, knowledge or ideas – can create and communicate to sentient beings meaning not possessed or implied by the individual informatical elements on their own.

6 How Do Information Systems Fit into this Classification?

Information or software systems are created by humans in the conceptual world, often to reflect the past and present state of real systems, and to plan or forecast their future state. The software and the informatical objects comprising this kind of conceptual systems are stored in the physical world using storage devices. To function and produce an effect in the real world, they must be provided with a suitable physical computing environment, acting as a "thinking" infrastructure. Similarly, ideas are created by in human minds as abstract concepts and are initially recorded as electro-chemical patterns in the brain. They can be stored as certain kinds of artefact in the physical world – symbols, sketches, words, musical notes, etc. They only produce an effect in the real world when assimilated into peoples' consciousness so they can relate to it at the deep semantics level. There is thus a certain degree of analogy between *software programs* executed on general-purpose computers to control technical systems and *ideas* in human brains, influencing the way they think and act: Just as software requires a physical computer to run, so does an idea require a human brain to comprehend, digest, and act on it.

7 Proposed Framework for System Definition and Classification

- **Real System** and **Conceptual System** are **Systems.**
- **Real systems** exist in the physical world.
- **Conceptual systems** are the product of human thought.
- **Conceptual Systems** may be: **mental models, informal shared models,** or **formal shared models.**

Readers familiar with Popper's (1978) "Three World" model will recognise that Real Systems exist in Popper's World 1, Mental Models in World 2, and shared models in World 3.

- **Abstracted Systems** are **conceptual systems** which represent **real systems**.

- **Real Systems** may be **Naturally-occurring, Artificial,** or **Hybrid** (containing both naturally-occurring and artificial elements)**.**
- **Hybrid systems** may be **Artificially Modified** or **Artificially Influenced.**
- **Hybrid Systems** and **Artificial Systems** may be **intended** or **unintended.**
- **Recognised Real Systems** are recognised to exist in the real world.
    - They may be recognised by their **structure**, **function** or **behavior**.
- **Real Systems** can be characterised by their internal capacity for **communication**, **decision making**, and **adaptive control.**
- **Real Systems** that share the characteristics of “viable systems” and “living Systems” exhibit **homeostasis**, **resilience** and **ability to cope with unforeseen circumstances**.
- Information systems are conceptual systems hosted in real systems.

8 Conclusions and Future Work

Based on a classification outlined by Bertalanffy, this paper presents an ontologically-founded framework into which the diverse plethora of existing definitions of *system* can be mapped, and the worldviews they stem from can be traced. Our framework anchors the different *system* definitions in their respective worldviews and domains of system practice, enabling key system concepts to be understood and differentiated in their proper contexts.

Among other benefits, this framework resolves the problem that a commonly used definition of *system* in terms of “interacting parts” only works for real world systems, does not apply to conceptual systems, and is therefore not consistent with the constructivist worldview held by many systems engineering practitioners.

Important issues explored in this work include developing better understanding of the relationships between informatic systems, such as computer programs in the conceptual world, and the real-world technological systems they need to in order to execute and control other real-world systems, the analogous relationship between abstract ideas and human actions, and a number of explorations of *systemness* through examination of diverse examples, ranging from a nutcracker to an aeroplane. When discussing complex systems such as the latter, questions arise concerning whether it is a system in the factory or only when the pilot is flying it, and whether the crew or the passengers are part of the system.

Given that formal language would be inappropriate for the wide range of stakeholder communities, the next step is to tackle the language issue. We shall seek to identify natural, clear, non-specialized, intuitive language for a set of system definitions that match the framework, that will render the definitions both precise enough to be useful and acceptable to the widest possible range of the system community. We plan to augment a survey we have started to gauge the perceived characteristics of systemness in an attempt to propose a compound metric that might serve to quantify this system attribute. Further, we plan to elaborate the OPM conceptual model of system so it will cover the topics discussed in the paper and go beyond it, such as open vs. closed systems. Free use is made of system-related words such as attributes, characteristics, properties, capabilities, behaviors, dynamics, and function. Like system, different people apparently interpret them differently, adding to the confusion, so these and similar concepts need to be defined too. Assuming our quest for a proper framework for system definition is successful, in a parallel track, we aim to tackle the next challenge—defining Systems Engineering.

Acknowledgements

The authors wish to acknowledge and thank Regina Griego, Eileen Arnold, Dorothy McKinney, Patrick Godfrey, Scott Jackson, James Martin, and Daniel Krob. This active group of INCOSE Fellows joined the effort of defining *system* and contributed their time and intellect in email and live discussions during months since our first meeting in INCOSE IS 2016 at Edinburgh in order to clarify and highlight many relevant issues that are discussed throughout the paper.

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