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What's in a System-of-Systems?

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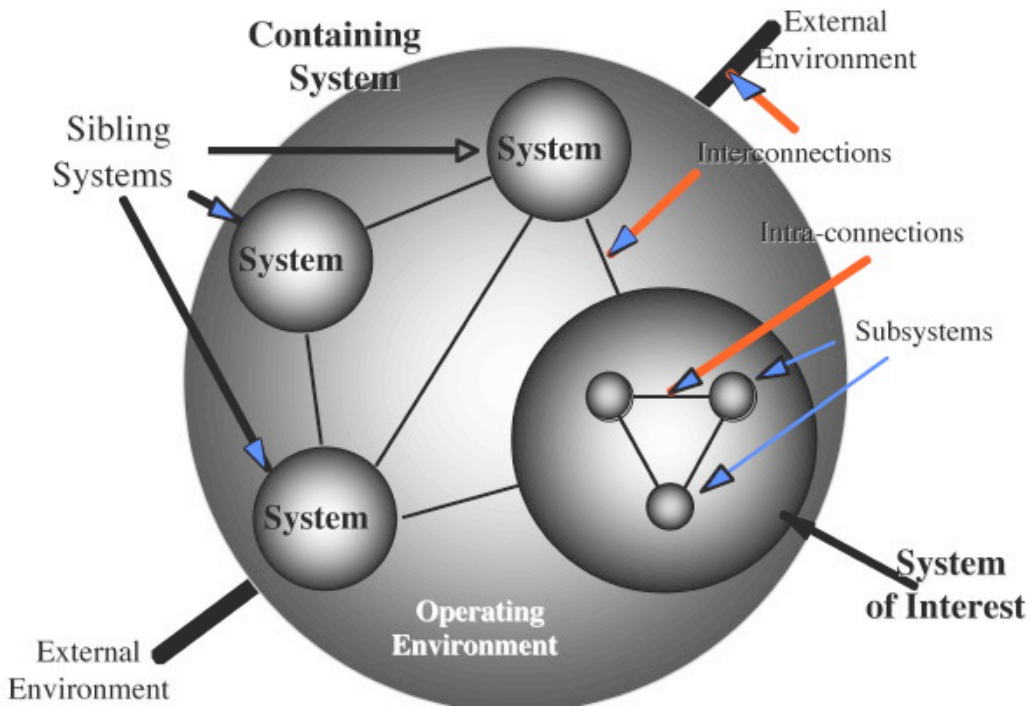
Preamble Contemporary definitions of a System of Systems still include the criterion: ***"systems with operational and managerial independence."*** *These may 'disconnect' themselves from the operational SoS, and act independently. Were this to occur, it would alter the operational SoS to the degree that it would no longer be the same SoS (sic). It would be a* ***different SoS*** *with different emergent properties and different behaviors…indicating (at the very least) a paradox in the defining criterion, with a corresponding, significant challenge to design any sensible, optimum solution…*



Hitchins' "Poached Egg"

Funny how fashions come and go. Even in something like systems engineering. Take the expression "system of systems," for example. Everyone is using it, but aren't all systems made up from other systems? It's an awkward expression, when you think about it. Suppose we have one "system of systems," and suppose we connect it to two or three others; are we creating "a system of systems of systems"? And so, *ad infinitum*, like the one about the fleas. And who cares anyway – what difference does it make? Well, it could matter if it misleads people into misunderstandings, mistakes and down right disasters. What, from a name? Well, let's see…

Ad fontes… What is a system? Well, there are lots of definitions: I expect you've got yours – I've certainly got mine:

> *A system is an open set of complementary, interacting parts with properties, capabilities and behaviors emerging both from the parts and from their interactions to synthesize a complex, organized whole of material and/or immaterial things*

Complicated? Well, it's a challenging thing to define. Notice that a system is made up from interacting parts. Using that notion, we can draw out a typical system diagram. See above...this is the student-named Poached Egg diagram, a rather static—but nonetheless invaluable—view of systems hierarchy. Our typical system, the System of Interest in the figure, is represented by a shaded circle at lower right within a wider, Containing System, along with three sibling systems; all four sibling systems are "contained," all four are interconnected, so that they may interact – in line with the definition of "system" above.

We can go further. The System of Interest, lower right, contains three complementary subsystems that are intra-connected, again in line with the definition. And the Containing System is also connected to other systems, indicated, but not shown, so it, too, may interact in line with the definition.

So, in this representation we have systems within systems within systems…but do we show any system of systems? The SOI is a system of interconnected sub-subsystems; the containing system is a system of interconnected sibling systems; and there is a higher level still, which we cannot see but can guess at, a system of interconnected containing systems……

None of which really helps us to understand "systems of systems."

A trawl of the 'Net helps – a bit. Following definitions were taken from the IEEE's SMC 2005 Conference, held in Hawaii. (Very nice, too!)

"Systems of systems exist when there is a presence of a majority of the following five characteristics:

- operational and managerial independence,
- geographic distribution,
- emergent behavior, and
- evolutionary development.

Primary focus: Evolutionary acquisition of complex
adaptive systems. Application: Military." [1]

To me, that's as clear as mud. There is no mention of interaction between independent systems, which nonetheless exhibit emergent behavior: curious; emerging from what? And, since only a majority of the characteristics need be present, are we free to choose any three? Can *geographically distributed* systems with *operational and managerial independence* really constitute a system?

(Although, of course, there is nothing in the definition of "system" to require that constituent systems be *continuously* connected to the SoS—'when required' would do…)

Let's try another definition:

> *Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems.*
> *Primary focus: Information systems. Application: Private Enterprise.* [2]

Reads like a description of just about any industrial organization, supermarket, High Street chain store…the definition does not seem to add much. Note again that there is no evidence of interactions, co-operation and co-ordination between the parts, no emergent behavior: curiouser and curiouser.

> *In relation to joint war-fighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems. Primary focus: Information superiority. Application: Military.* [3]

Ah, *"synergy"* – implying co-operation and co-ordination. This definition refers to a singular system of systems, and it makes sense, although…we have been concerned with interoperability and synergy in C2, C2I, C3I, C4I, C4ISR etc., for many decades. So what is new that requires, or is implied by, the term "system of systems?"

As usual, however, the military bring a little light to the subject. This is from the US Institute of Defense Analysis (IDA):

> *"A system (system of systems) is a group of interdependent, interactive entities (systems) working together to produce an output…Readiness is a measure of the ability of a system (system of systems) to produce the desired output, i.e., its capability…A system (system of systems) represents a capability to perform a*

mission/task…A tank, ship, or airplane are systems…Squads, platoons, companies, battalions, divisions are systems… A Joint Task Force is a system…A supply chain is a system…The Defense Transportation System (DTS) is a system… DoD systems provide the department's capabilities" [4]

Now there's a person who understands what a system is. A system of systems is, after all, simply a system. Here is another definition again from the US DoD, which is even more explicit:

The Future Combat Systems (FCS) is a joint (across all the military services) networked (connected via advanced communications) systems of systems (one large system made up of 18 individual systems plus the network and Soldier- often referred to as 18 plus one). A Soldier, linked to these platforms and sensors, has access to data that can provide a much more accurate picture of what's going on around him. [5]

That seems pretty clear; the network and the Soldier are systems within a family of systems. And, although not mentioned, the FCS will have a variety of whole system functions, properties, capabilities and behaviors beside the presentation of multi-sensor battle-space situation pictures.

You now see the term used, e.g., by the...

"NASA Exploration Initiative (EI), a multimillion, multi-decade, human and robotic effort to explore the Moon, Mars and beyond using a spiral development process to introduce important new technologies as they mature…The EI architecture is a System of Systems (SoS) made up of elements such as the Crew Exploration Vehicle (CEV), Earth Departure Stage (EDS), Lunar Surface Access Module (LSAM), and launch vehicles."

Similarly, the Environmental Protection Agency proposes a Global Earth Observation System of Systems (GEOSS). I wonder – was *Apollo* a system of

systems? Strange, no one mentioned it at the time. Could that have been because a) it was obvious, and b) it added nothing of any value?

Purdue University enlightens us with:

> *"All of travel—from the time you leave your home until you arrive at your destination—can be considered a system of systems as you use a car, a taxi, a shuttle bus, the airplane, etc."* [6].

Doh! And here was me thinking that was a transport system. Since most so-called *transport systems* are comprised of independent, uncoordinated, even uncooperative businesses, I doubt whether the transport in my area even meets the definition of "system."

There is clear concern in the literature, too, evidently generated by the term system(s) of systems (SoS). Folks suggest that we are going to need a new form of systems engineering to cope with this new phenomenon. Risk management will have to be re-thought. Academics are seeing dollar signs at the thought of new research budgets to explore this 'new' phenomenon. And there is a new subject to be developed and taught: system(s) of systems engineering. And here is where we ought, perhaps, to be a little concerned.

If the term SoS encourages people to view the world in systems terms, that is all to the good. However, it is also true that SoS are systems, like any other. Those who have been concerned with programs such as Polaris, Trident, Strategic Defense Initiative (SDI), national defense systems, nuclear power generation, global disaster relief, etc., etc., can testify to the ability of systems engineering to cope with extremes of complexity and complication. It is, after all, the purpose for which the systems approach, systems science, systems thinking and systems engineering were conceived and developed.

And those who have been concerned with disasters such as the following, can testify to what happens when systems engineering is either not applied or is, perhaps misapplied:

> *"…the chemical plant leakage in Bhopal (1986); the explosion of the NASA Challenger space shuttle (1986) and the Apollo fire (1967); the sinking of the Titanic (1912); the nuclear explosion in Chernobyl (1986), and the disaster at the Three Mile Island power plant (1979)…the capture of markets by Japan from the U.S., the decline in U.S. productivity, and the failure of the U.S. secondary school system…the millions of people dying of starvation every year while other nations stockpile surplus food; medical disasters such as heart disease, while governments subsidize grains used to produce high cholesterol meat, milk, and eggs; and many more. One implication is clear. Systems engineering faces challenges well beyond the sphere of engineering."* [7].

So, while we may need to continue developing and evolving systems engineering, the idea that there is a new subject called "systems of systems engineering" seems to me to be self-evident nonsense: a "system of systems" is a system, so SoS engineering simply reverts to Systems Engineering – shades of Gödel's Incompleteness Theorem!

O.K., I feel better now…

If you go back through the records, you will find that systems engineering was introduced specifically to overcome reductionist practices, by using what has come to be known as "the systems approach." And systems engineering is supposed to embody the systems approach. Recently, it seems, people have been making systems engineering up as they went along. In particular, engineers have been making systems engineering up. And they have used their engineering knowledge and experiences to help them – what else

would they do? The trouble is that engineers traditionally use reductionist methods to create solutions, and reductionist methods do not accommodate complexity – they exacerbate it!

We might call this recent, engineers' metamorphosis of systems engineering "the engineering of systems," and it embodies what you might call a Lego building block approach to systems. Join the blocks together in the right way, it proposes, and you can construct whatever you want from the bottom up. Of course, you cannot use that approach to construct systems with people in, because people insist on being flexible, adaptable and all that, so they don't make very good Lego bricks…I once heard an engineer demand of the "ergo-gnomes" that they provide him with a transfer function for a human operator (sic!) – without such a transfer function, how was he supposed to design anything? So, the engineering of systems (EoS) is unable to address teams, operators, users, etc: they are considered to be "outside" of the system; Engineering of Systems (EoS) makes artifacts for people to use.

Peter Checkland once described the engineers' view of systems as like a bag of pool balls: you can put your hand in, take a ball out, examine it, put it back, and nothing is changed. In reality, systems are more like a privet hedge from which you may try to extract one branch. In tearing out the branch, you destroy the branch, damage the hedge and – at the end – you are unable either to replace the branch, or restore the hedge.

Let's look at another definition:

> *SoSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure. Primary focus: Education of engineers to appreciate systems and interaction of systems. Application: Education.* [8]

SoSE is "systems of systems engineering," of course. This definition seems to be describing, *not* systems engineering, but the *"engineering of systems,"* Lego

brick building style. And if that does not worry you, it should – it really should. It used to be called bottom-up integration, and it has a checkered past – see the quote above listing disasters…

What is "bottom-up integration"? It is an attempt to create a system by joining various parts together to form bigger parts, then joining bigger parts together to make even bigger assemblies, and finally – for instance – hooking up various platforms to make a defense capability. In effect, it proceeds *up* the hierarchy shown on the poached-egg diagram. What's wrong with that? Plenty is wrong with that.

First, it is based on an assumption that joining parts together does not affect the parts – that each part operates and behaves as it did previously. That is true for a wall made up from bricks, interfaced with mortar. It is not true, e.g., for two people who get married and live together: each is changed, and the new pairing exhibits emergent properties, new behaviors if you like, not evident in either person on their own. And similarly, it is not true for open complex systems like teams, companies, businesses, platforms, etc.

When you network a bunch of complex things together, you are very likely to inadvertently couple functions that were previously not coupled. And, since we are talking open, interacting, transitive systems, you may unwittingly be creating a complex mesh of unforeseen, unwanted couplings, the behavior of which can be both unexpected and counter-intuitive.

It can get worse: as systems engineers we are all aware of what happens when systems become closely coupled. First they interact more swiftly, and then, as the coupling gets tighter, chaotic behavior may arise. Chaotic behavior is really insidious; things appear OK, but every so often, at indeterminate intervals, there may be outbursts of erratic behavior. Subsequent test shows nothing wrong.

Can you detect bottom-up integration in the "engineering of systems?" An obvious sign is that the whole equals the sum of the parts; there is no such

thing as emergence. Look, too, for signs such as "functional decomposition," and the so-called "V-approach." Both of these reductionist paradigms are indicative of "bottom-up," and there are many others.

So, looking at the systems-of-systems phenomenon, are we seeing a resurgence of bottom up integration? Is there an idea going around that we can create a defense capability "bottom-up" by networking various military platforms (ships, tanks, planes)? I hope not, but I suspect so. We have been down that road in the past – it is full of potholes.

While folks are getting excited over systems-of-systems and 'engineering of systems' sagas, they may be missing the real trick here. None of the definitions given above has hit on the obvious factors that characterize these large-scale systems.

There seem to be at least three essentials being overlooked:

- Co-operation and co-ordination. A key feature of what folks are calling 'systems of systems' is that the various independent, viable parts—from which such systems are supposedly formed—are drawn together so that they may co-operate and co-ordinate their actions – making them no longer independent, of course, as they become "part of the system." In systems terms, we talk of synergy, co-operation and co-ordination between the parts to produce desired external effects: or emergence; or, perhaps, the whole is greater than the sum of the parts…as Aristotle would have put it…but, in ancient Greek, of course.
- Whole system features. A system of systems is a whole system – complex perhaps, but a system nonetheless. So, it will share fundamental characteristics with all systems, such as function, behavior and form. Functions of the whole system are *not* functions of the parts. Functions and behaviours of the whole are extensive/systemic. Examples of whole

system functions might include: a defense capability; battle-space situation awareness; deconfliction; self-defense; C4ISR; threat assessment; strategic planning; reconfiguration; formation management, etc., etc. None of these functions would be performed alone by individual platforms, sensors, weapons, etc:

- These whole system features indicate another major limitation with "bottom-up" integration. With bottom-up, whole system features are limited to what can be provided by, and are accessible in, the building blocks at subsystem level
- Systems engineering – the real deal, that is – identifies what is needed of the *whole system,* and then creates these *whole system functions, properties, capabilities,* etc., by incorporating appropriate subsystems and by developing *new whole-system features,* too. This way you get what you need – not just what is available
- Non-linear dynamics and behavior. When a number of complex systems interact, the result is generally non-linear behavior.
    - It is this very non-linearity that gives *biological* systems their high power densities, flexibility, adaptability and wide dynamic ranges, and all without cybernetic feedback and control.
- Non-linear systems worry engineers; they are not used to them. Straightforward engineering mathematics doesn't work: non-linear simultaneous equations do not give unique results; they may give an infinite number of solutions.

Classic systems engineering, on the other hand, has little problem with non-linear systems and their design. Non-linear systems may be best viewed using a biological, or organic metaphor, rather than the

engineers' machine metaphor. Open, non-linear dynamic systems are internally active, expending energy to maintain their status. If you were to look inside a recumbent, resting person, you would find their internal systems in a ferment of activity: heart pumping, adrenal glands on the go, central nervous system firing, all five senses active, immune system scouring the system for pathogens, new cells being created to replace those reaching the end of their life-cycle, and so on…and all of that is just to maintain the *status quo.* Not much like a manmade machine, then…

Any system can be considered as having being (form), being capable of doing (function) and of exhibiting behavior – a system of systems is no different. 'Doing' requires Function Management, which has aspects of *Mission Management, Resource Management* and *Viability Management.* But, of course, these are aspects of the *whole system, not* of its parts/subsystems.

In addition to *whole system* features of *Function Management* there will be features of *whole system Behavior Management* and *whole System Form Management.* None of these different aspects exists in isolation; they are all contemporaneous and mutually affective. In designing the whole system, then, it is necessary to start at the top and work down, (hence systems engineering is "top-down" as opposed to engineering of systems, which is "bottom-up.")

Additionally, and importantly, there will be a whole-system *Concept of Operations,* or CONOPS, which describes how the whole system is intended to work. The CONOPS requires that the whole system possess/exhibit whole system functional capabilities (prime mission functions). It is these *prime mission functions* that are directed by *Mission Management* and resourced by *Resource Management,* while *Viability Management* ensures that the whole system continues to be able to "do its stuff."

So far, we have not mentioned the subsystems, which, in the case of a defense capability, might be platforms, teams, troops, squadrons, etc. A sensible way to look at these subsystems is as a substrate, upon which to lay the whole

system functional and behavioral management features. Whole system functions may exchange information "upwards and downwards" with subsystems, but coupling will be loose to obviate the risk of creating lateral meshes of inter-linked function between platforms. [9]

So, there are sensible ways to understand and synthesize complex systems from complex systems, and if you want to call complex systems by names such as "system(s) of systems," that's fine. But please, please, don't think, like every teenager discovering sex, that you have just found something new. If you want to create "systems of systems," for heavens sake use the tried and trusted systems approach! They are just systems, after all…

Oh! I nearly forgot; is it possible to define a "system of systems?" Looking at the definitions above, it is clear that:

1. there are some confused pundits out there;
2. some folks are using the term willy-nilly;
3. there is no consensus of what the term means;
4. some folks are seeking to capitalize on the confusion.

So, please let me offer a reasoned definition of the term:

> *A system of systems (SoS) is an open set of complementary, interacting systems with properties, capabilities and behaviors of the whole emerging both from the systems and from their interactions to synthesize a complex, organized whole of material and immaterial parts, operating with optimum effectiveness in its operational environment.*

If you look back, that is just my definition of a system, with a simple hierarchy shift… and a bit added [10]

Derek Hitchins, 2005

Critique

So, an old article, sixteen years old…does it have any relevance today? In the intervening period Systems Engineering (SE) has changed, seemingly fundamentally, and may now be regarded, de facto, *as the engineering of systems (EoS), although–confusingly–it has yet to change its title. So, the revised, not-really-'SE' seems to employs reduction, bottom-up integration, and is aimed at making artifacts—where it meets the market need well, it has to be said.*

In the intervening period, SoSE has also 'developed.' Unsurprisingly, SoSE appears to follow the same broad approach as EoS, but is experiencing difficulties when seeking to optimize the capability of a SoS where one or more constituent parties may separate off—the "operational and managerial independence" criterion. While there is no need, within any definition of "system," for a constituent party to be permanently connected, it is nonetheless necessary for all constituents to be active within the SoS when called upon operationally—else, of course, the SoS' optimized capability cannot be realized.

That issue could be resolved in a variety of ways: the "independent system" might be viewed, not as a constituent system within the SoS, but as an intermittent external source, perhaps. Alternatively, there could be two conceptual SoS's, one with *the "independent system" incorporated, and the second* without *it. Each of these SoS's could be separately optimized, capability-wise, and some form of "changeover switch" built in so that the unexpected 'disconnection' or 'reconnection' of the "independent system" would trigger the requisite pre-arranged transition, resulting in the best capability available in the circumstances. Like the mythical Peace/War Switch—messy and impractical!*

Needless to say—but nonetheless true—classic "top down" Systems Engineering would not have encountered such difficulties. But, OTOH, classic SE would probably insert coupling and additions between and within the various constituent subsystems where necessary to synthesize a comprehensive, viable capability—which would, undoubtedly incur costs. So,"you pays yer money and you takes yer choice." As ever. If you want it done properly, its going to cost…

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