System of Systems – the meaning of *of*

Dr. John Boardman
Stevens Institute of Technology
Castle Point on Hudson
Hoboken, NJ 07030, USA
boardman@stevens.edu

Dr. Brian Sauser
Stevens Institute of Technology
Castle Point on Hudson
Hoboken, NJ 07030, USA
bsauser@stevens.edu

Abstract - *We present distinguishing characteristics (i.e. autonomy, belonging, connectivity, diversity, and emergence), that can help us to recognize or to realize a System of Systems (SoS). The principle differentiation that we make between a thing being either a 'system' or a SoS focuses on the nature of a system's composition. We will distinctly define this set of distinguishing characteristics which will include a set of cross references from our literature research where we believe others are articulating our chosen differentiating characteristics. We conclude by summarizing the difference in these terms in a fundamental sense, one that impacts their structure, behavior and realization, and the distinction comes from the manner in which parts and relationships are gathered together and therefore in the nature of the emergent whole.*

Keywords: Systems engineering, system of systems, autonomy, belonging, connectivity, diversity, emergence

1 The Meaning of *of*

It is asserted that "a system is a collection of entities and their interrelationships gathered together to form a whole greater than the sum of the parts". Thus our attention is directed to parts (the entities), relationships (between the parts) and the whole itself which we understand in some sense to be better than the collection of parts and relationships; a something for nothing deal, except the gathering together, which is not nothing, is what gives us that extra something. It is only recently that we have come to understand the whole in its own right with terms such as architecture. This term seeks to express the gathering together operation. Alternatively the term network is being used, with parts being represented as nodes or vertices, and relationships as links or edges. But it is the network itself, measured by its topology and dimensions, e.g. diameter and clustering factor, that captures the whole. If we are to think as well as to act in systems terms, we are obliged to respect the whole as a whole which is not just about its dynamic uniqueness, relative to parts and relationships, but also its structure and how that structure is achieved (by whom, how and why) and how it is re-shaped. We must also, relative to reshaping the whole, respect the fact that forces such as innovation and competition apply not only to the parts and to the relationships but to the whole in its own right [1].

Systems thinking for too long has been preoccupied with interior design, with the parts and their relationships. Meanwhile, exterior design, the context for the whole and all that this means in terms of influences, ownership, and adaptation has been sadly neglected or reduced to statements that determine the system's interior design [2]. Anyone, military commander or CEO, will typically make this remark concerning the system they lead, "I care less about the make-up of the system, as an objective per se, but more about its ability to survive and prosper in uncertain environments perpetually changing in unknowable ways that increasingly appear to be more actively lethal with purposeful intent to secure my system's demise".

So what we are finding is that systems people are overlooking a key part of the general definition. Focus can be on parts, or on relationships, or even on the whole – especially it's inherent 'more than the sum of' quality; but they tragically overlook the 'gathered together to form' content, and it is this we wish to re-state. Put simply, 'What do we mean by *of*?'. Is the system a thing of parts presciently designed or procured by the system builder along with their relationships, the whole collection being gathered together for the sole purpose of realizing the system's designed intent? Or might there be another way of looking at this little word, *of*? A way in which a higher level system, the SoS, is specified or adumbrated with an opportunistic eye being cast over some of the existing (prospectively legacy) systems that will initially constitute its parts, and whose involvement will be by the design, not of a prescient outsider, but by these and future constituents, who, or which, will also collaboratively determine their inter-relationships, the future constitution and therefore the emergent qualities of the SoS in diverse ways that thereby contribute to its capabilities, which were 'specified'? A SoS is a system, but *of* matters, and it forms an antithetical stance to the gathering together for the type of system that subordinates its parts and relationships to meet its purpose.

2 Differentiating Characteristics

In thinking about a SoS we are faced from the outset with two inescapable verities. First that some parts of the envisaged SoS, constituent systems, already exist; these are commonly known as legacy systems. Secondly, there is some new system in view, to which these legacy systems will contribute, and in envisioning this new system there is both a commonality of purposes – of existing systems' purposes and of the to-be SoS purpose; but there is also a differentiation of purpose; in other words the existing purposes can help bring about the new SoS purpose simply because of this commonality. Translating the SoS concept into reality requires a different approach to the one currently used to engineer systems. We shall find that we are able to borrow from that approach, what we call systems engineering. But we suggest that some new key compositional elements are needed, what become differentiating characteristics to distinguish between system and SoS. It is of these we now speak.

2.1 Autonomy

The reason a system exists is to be free to pursue its purpose. That freedom always comes with constraints, of course. But those constraints cannot be permitted to overwhelm or violate its nature to perform. Were this to be the case, the system of necessity would be abandoned and another found to take its place. True, any given system may fail to fulfill its purpose, but not for reasons of autonomy. More likely it is ineffectiveness, efficiency, or even unethical behavior. The same cannot be said of a part that is integral to a system. That part is chosen – designed or procured – for a given purpose, just as a system is, but it is deliberately chosen for the reason of serving the purpose of the whole system. Thus a brake in an automobile performs the function of deceleration and finally bringing to rest the vehicle of which it is a part. But that is because the automobile designer sees the advantage for speed control, for collision avoidance or having a stationary vehicle from which to exit. Thus the vehicle has a need and in part the brake serves that need. It serves no purpose of its own. The notion of autonomy appears to have been lost in the systems approach, which is why some systems are known as such when in fact they may in truth be merely parts. Is a payroll system truly a system or merely a part of an enterprise system? Clearly some will regard it as a system, because it has parts and relationships and these were brought together to form the whole. But it was always intended, as a system, to be a part, and for that reason its autonomy is questionable and therefore in determining whether it be a system or a part, we prefer to call it a part.

2.2 Belonging

The envisioner of the SoS foresees it partly by seeing how existing systems can play a part in a new adventure; parts but yet systems. Perhaps these systems need to change, but not beyond recognition. Each will form new relationships, with other autonomous systems. Each will have to be persuaded of the value of all this – to change, to render service, and to collaborate with other systems. These are all easily viewed by the autonomous systems, putative constituents of a SoS, as costs. Why should these costs be paid? What is the RoI, the overall benefit? What is the value proposition? Do I lose my autonomy? Shall I cease to be a system, and become merely a part? If my original purpose is still valid, and I am not delinquent in fulfilling it, how can I ethically decide not to be a system? These are essential questions and the SoS envisioner has no right and must not be permitted to ignore them.

Part of the persuasion comes from the argument that the achievement of the SoS purpose is exactly why the system was brought into being but constraints at the time of its origination required a lesser target to be set. In other words the new 'supra' purpose enfolds the system's original purpose. And what is more, the existence of the SoS will enhance the value of the system's purpose, exalt the role of the system, whose belonging makes achievement of the supra purpose more likely and more effective. But that belonging does mean partness for the autonomous system. This autonomous legacy system now exhibits both partness and wholeness.

2.3 Connectivity

We observe that in the design of a system connections are considered simultaneously with parts, or subsystems. Who in the gathering together can overlook the connectivity of the parts? Moreover, it has become a golden rule [3, 4] of systems engineering that when connectivity, among part, elements or subsystems are huge, they should be hidden away, encapsulated as it were by that system element. This then makes it much more straightforward to manage the discrete interconnectivity between these elements, of which the actual number of interfaces between major subsystem elements should not exceed 15% of the total number actually possible. How can this be said of a SoS? It cannot, for reasons of legacy.

Now we are faced with the need to create connectivity, or in other words achieve interoperability, amongst the legacy systems and possibly additions of new systems to the SoS. To some extent this must call for the unraveling of the encapsulated system, giving us access to some of its inner connectivity that does not normally appear at its surface, or system boundary. Added to this is the fact that the systems themselves have an important role to play in determining the connectivity they wish to form to one another, and to new additions. This is consistent with constituent system autonomy and its choosing to belong, composing as it were from the ground up the rules of engagement by constituent systems in the unfolding design of the SoS, always towards the fulfillment of its mission, the supra purpose for constituent systems. This determination is not confined to a priori design, requiring the degree of prescience normally associated with systems engineering. *Au contraire*, it calls for a dynamic determination of connectivity, with interfaces and links forming and vanishing as the need arises. Thus the ability of constituent systems to remain autonomous proves essential, for only then can they hope to make real-time connections on behalf of the SoS to enable it achieve and sustain its capabilities.

2.4 Diversity

Ross Ashby eloquently argued his law of requisite variety [5] by which he asserted that in order for a system to maintain stability in an operating environment it must possess at least the same number of degrees of freedom or dimensionality of that environment, possibly represented by the number of types of external force that could apply to the system. Put a different way, the larger the variety of actions available to a control system, the larger the variety of perturbations it is able to compensate [6]. John Von Neumann [7], said: "The object of the game is to go on playing it!". The law of requisite variety is important because it implies that for Life to survive for a long time, it must conserve or generate a great deal of species diversity. Liberty is justified as being necessary for individual & cultural diversity which is requisite to sustain both the desire and the ability to survive.

The other side of this coin is the principle of parsimony [8]. This states that one should not make more assumptions than the minimum needed. It underlies all scientific modeling and theory building. It urges us to choose from a set of otherwise equivalent models of a given phenomenon the simplest one. In any given model, Occam's razor helps us to "shave off" those concepts, variables or constructs that are not really needed to explain the phenomenon. By doing that, developing the model will become much easier, and there is less chance of introducing inconsistencies, ambiguities and redundancies. So we are hemmed in between nature's preference for simplicity and life's need for variety. What does this mean for a SoS?

First we must confirm that diversity is an issue: variety wants to add to diversity; parsimony or the yen for simplicity wants to reduce it. In complexity we find precisely this. The simplest systems can produce complex behavior that is totally aperiodic, an endless variety of trajectories which eventually convey simple patterns, e.g. the Lorenz attractor [9]. Second we must be astute in applying diversity. Does it apply to the parts, as for example the hugely diverse states that make up the nation of India? Or does it apply to the relationships, for example where you would need a variety of communications systems to integrate the emergency management services to handle Hurricane Katrina's aftermath? Or does it apply to the whole, and what might this mean? In the case of the brain, the parts – neurons – are largely identical. Not much variety there. Relationships, effected by myriad chemical interactions are also limited in scope. And the brain? Well that is just a simple whole! All brains look alike and vary only slightly in weight, shape and appearance. But when the brain is put to work, by the firing of neurons and the activity of chemical interactions, what incredible variety of thought, of consciousness, of perspective?

This then is our assertion – that a SoS should, out of necessity, be incredibly diverse in its capability as a system compared to the rather limited functionality of a constituent system, limited by design. It seems to us that there is a fundamental distinction to be made between requirements-driven design for a conventional system based on its defined scope, and a capabilities-based SoS that must exhibit a huge variety of functions, on an as-needed basis, in order to respond to rampant uncertainty, persistent surprise, and disruptive innovation.

2.5 Emergence

The definition of system holds good for both system and SoS, and why not, a SoS is a system. But we assert that a SoS is also not a system. In what sense? In the sense of being gathered together. And to articulate this we need to access the concept of emergence. What is it, we ask, that appears which makes the whole greater than the sum of the parts? Not where does it come from, we can discuss that endlessly, but what actually is the difference between the 'whole sum' and the sum of the parts? If you put a number of weights onto a scale, the total weight would be the sum of the individual weights. This is simple linear addition. Nothing new. And that is because putting weights onto a scale does not constitute gathered together, not as we use the terms in defining the concept system.

Suppose a jury, asked to judge the innocence or guilt of a person accused of a felony, simply cast individual votes and left it at that. The jury in this case does not gather together. The jurors simply vote and the vote of the jury is the sum of the votes. But juries discuss and debate. In *12 Angry Men* they even hold the trial all over again! In this case an initial 11-1 for guilty (is this 10?) is turned over to 12-0 for innocent, thanks to the eloquent Hank Fonda, but more especially to the exercising of interdependent critical thinking, something that affects all of us, and maybe our votes. Juries are systems and their behavior systemic, and their final verdict is more than the sum of the parts, in this case because parts change, because votes swing.

Steven Johnson reports emergence to be 'the movement from low-level rules to higher-level sophistication' [10]. This is more articulate than most definitions since it clearly implies synergy but goes further in attributing it to a change of scale and scope. Our neurons, precious little things that they are, have no idea what we are thinking. Ants follow pheromone trails but it is colonial enterprise that discovers and collects food, that disposes of garbage - including dead ants, and that protects the Queen ant – evidently no commander [11]. This is true value added, and the 'greater than' measures smartness, about which James Surowiecki writes compellingly [12].

How does emergence give us differentiation between a system and a SoS? In one crucial sense: in a system, emergence is deliberately and intentionally designed in. What's more unintended consequences, i.e. unpleasant or painful emergent behavior is tested out, as far as possible. With a SoS, emergent behavior dare not be restricted to what can be foreseen or deliberately designed in, even if this risks greater unintended consequences, though of course these can still be tested for. A SoS must be rich in emergence because it may not be obvious what tactical functionality is required to achieve broad capability. Instead, a SoS has *emergent capability* designed into it by virtue of the other factors: preservation of constituent systems autonomy, choosing to belong, enriched connectivity, and commitment to diversity of SoS manifestations and behavior. The challenge for the SoS designer is to know, or learn how, as the SoS progresses through its series of stable states, to create a climate in which emergence can flourish, and an agility to quickly detect and destroy unintended behaviors, much like the human body deals with unwanted invasions.

3 Systems vs System of Systems

To define a living cell or a computer we use differing and diverse definitions, but to describe them as systems, we use equivalent distinguishing characteristics. When Ludwig von Bertalanffy wrote about systems in the 1940s, he described fundamental constructs that provide for a unification of all systems across domains. Therefore, in our pursuit to understand what distinguishes a SoS from a system, we concentrated on distinguishing characteristics and not definitions. In the expanding study of complex networks, this advance has become a fundamental approach in understanding networks as they may apply to terrorists, the World Wide Web, or genetics. Our understanding of SoS, just like our understanding of system, must transcend domains.

The distinction between a system and SoS lies in the meaning and significance of 'gathering together', teasingly hidden in the meaning of *of*. What the two have in common is being gathered together which is why it is proper to refer to a SoS as a system. However a SoS is much more because its parts, acting as autonomous systems, forming their own connections and rejoicing in their diversity, lead to enhanced emergence, something that fulfills capability demands that set a SoS apart. We summarize our thinking in Table 1 which also includes a set of cross references from our literature research where we believe others are articulating our chosen differentiating characteristics.

Table 1 : Differentiating a System from a System of Systems

Element	System	System of Systems	Cross References
Autonomy	Autonomy is ceded by parts in order to grant autonomy to the system	Autonomy is exercised by constituent systems in order to fulfill the purpose of the SoS	Directed [13], Planned [13, 14], Embedded [15], Autonomy [4, 15-17]
Belonging	Parts are akin to family members; they did not choose themselves but came from parents. Belonging of parts is in their nature.	Constituent systems choose to belong on a cost/benefits basis; also in order to cause greater fulfillment of their own purposes, and because of belief in the SoS supra purpose.	Enterprise [14, 18, 19], Shared Mission [20-22], Sharing [14]
Connectivity	Prescient design, along with parts, with high connectivity hidden in elements, and minimum connectivity among major subsystems.	Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possibly via a net-centric architecture, to enhance SoS capability.	Interdependence [23, 24], Distributed [13-15, 21, 25-27], Networked [14, 21, 25], Multiple Solutions [24], Loose Coupling [16], Integration [27-29], Interoperability [29-31], Synergism [4, 30]
Diversity	Managed i.e. reduced or minimized by modular hierarchy; parts' diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of the hierarchy	Increased diversity in SoS capability achieved by released autonomy, committed belonging, and open connectivity	Independence [22, 24-27], Diversity [15, 22, 32], Heterogeneous [25, 33]
Emergence	Foreseen, both good and bad behavior, and designed in or tested out as appropriate	Enhanced by deliberately not being foreseen, though its crucial importance is, and by creating an emergence capability climate, that will support early detection and elimination of bad behaviors.	Evolving [14, 16, 23, 25-28], Intelligence [14], Sum is Greater than Parts [24], Behaviors [34], Emergence [4, 14, 16, 25-27], Dynamic [14], Adaptive [19, 31]

4 Conclusions

For us the difference between system and SoS lies in composition. Both terms conform to the accepted definition of *system* in that each consists of parts, relationships and a whole that is greater than the sum of the parts, and therefore in that sense they are the same. But these terms differ in a fundamental sense, one that impacts their structure, behavior and realization, and the distinction comes from the manner in which parts and relationships are gathered together and therefore in the nature of the emergent whole. This distinction in gathering together comes about by two opposing forces, present in a SoS but entirely lacking for a system. These are the forces of legacy and mystery. Legacy is a driving force from the parts perspective and mystery acts upon the whole.

The a priori existence of systems, prospective constituents of a SoS, fundamentally influences the character of a SoS, leading quite possibly to this having multiple personalities the collection of which enhances its capabilities. The uncertain and unknowable environment in which the SoS must operate presents a mystery of endless proportions, the only proper response to which is to have increasing variety, of a continually emerging nature, to deal with unforeseeable reality that eventually becomes clear and present danger.

Whereas the monstrous events at Pearl Harbor on December 7th, 1941 presented the specter of suicide pilots of fighter airplanes targeting military assets, the enigma of that phenomenon persisted six decades later in the unthinkable evil of suicide pilots converting Boeings into bombs targeting buildings that housed unsuspecting civilian workers.

Mystery defies extrapolation, and its appearance in present events is explained only through historical perspectives. Enigma assails prescience. But the wisdom of crowds, exemplified by a SoS that exhibits unforeseeable emergence via the autonomous behavior, interoperability and diversity of its constituent systems, might be a sufficient response. Right now, it certainly is necessary.

References

[1] R. M. Henderson and K. Clark, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, vol. 35, pp. 9-30, 1990.

[2] H. H. Goode and R. E. Machol, *System Engineering*. New York: McGraw-Hill, 1957.

[3] E. Rechtin, *Systems Architecting*. Upper Saddle River, NJ: Prentice Hall, 1990.

[4] Y. Bar-Yam, "The Characteristics and Emerging Behaviors of System of Systems," in *NECSI: Complex Physical, Biological and Social Systems Project*, 2004, pp. 1-16.

[5] W. R. Ashby, *Introduction to Cybernetics*. London: Routledge and Kegan Paul, 1964.

[6] "The Law of Requisite Variety," Principia Cybernetica, http://pespmc1.vub.ac.be/REQVAR.html, January 10, 2006, 2001

[7] JOC/EFR, "John von Neumann," School of Mathematics and Statistics University of St Andrews, Scotland, http://www-groups.dcs.st-and.ac.uk/~history/Mathematicians/Von_Neumann.html, January 10, 2006, 2003

[8] D. Becket, "William of Ockham," University of Kent at Canterbury, http://wotug.ukc.ac.uk/parallel/www/occam/occam-bio.html, January 10, 2006, 1994

[9] P. Bourke and D. v. Berkel, "The Lorenz Attractor in 3D," http://astronomy.swin.edu.au/~pbourke/fractals/lorenz/, January 10, 2006, 1997

[10] S. Johnson, *Emergence - The connected lives of ants, brains, cities, and software*. New York: Touchstone, 2002.

[11] "The Book of Proverbs," in *Holy Bible*, Chapter 6, Verse 6.

[12] J. Surowiecki, *The wisdom of crowds*. New York: Doubleday, 2004.

[13] H. Eisner, "RCASSE: Rapid Computer-Aided Systems of Systems Engineering," *Proceedings of the 3rd International Symposium of the National Council of Systems Engineering*, vol. 1, pp. 267-273, 1993.

[14] J. A. Lane and R. Valerdi, "Synthesizing SoS Concepts for Use in Cost Estimation," *IEEE Transactions on Systems, Man, and Cybernetics*, pp. Forthcoming, 2005.

[15] C. Keating, R. Rogers, R. Unal, D. Dryer, A. Sousa-Poza, R. Safford, W. Peterson, and G. Rabadi, "System of systems engineering," *EMJ - Engineering Management Journal*, vol. 15, pp. 36, 2003.

[16] I. A. Monarch and J. Wessel, "Autonomy and Interoperability in System of Systems Requirements Development," presented at 16th IEEE International Symposium on Software Reliability Engineering, Chicago, IL, 2005.

[17] SoSECE, "System of Systems Management - Adapted from Glossary, Defense Acquisition Acronyms and Terms, Eleventh Edition," System of Systems Engineering Center of Excellence, September 2003.

[18] P. G. Carlock and R. E. Fenton, "System of systems (SoS) enterprise systems engineering for information-intensive organizations," *Systems Engineering*, vol. 4, pp. 242, 2001.

[19] SoSECE, "What is System of Systems (SoS)," System of Systems Engineering Center of Excellence, November 9, 2005.

[20] J. H. Holland, *Hidden Order How Adaptation Builds Complexity*: Helix Books, 1995.

[21] A. J. Shenhar, "One Size Does Not Fit All Projects: Exploring Classical Contingency Domains," *Management Science*, vol. 47, pp. 394-414, 2001.

[22] W. A. Crossley, "System of Systems: An Introduction of Purdue University Schools of Engineering's Signature Area," presented at Engineering Systems Symposium, Cambridge, MA, March 31, 2004.

[23] S. C. Cook, "On the Acquisition of Systems of Systems," presented at 11th Annual Symposium of the INCOSE, Melbourne, Australia, 2001.

[24] H. Eisner, J. Marciniak, and R. McMillan, "Computer-Aided System of Systems (S2) Engineering," presented at IEEE International Conference on Systems, Man and Cybernetics, Charlottesville, VA, 1991.

[25] D. DeLaurentis, "Understanding Transportation as a System of Systems Design Problem," presented at 43rd AIAA Aerospace Sciences Meeting, Reno, NV, 2005.

[26] A. Sage and C. D. Cuppan, "On the Systems Engineering and Management of Systems of Systems and Federations of Systems," *Information, Knowledge, Systems Management*, vol. 2, pp. 325-345, 2001.

[27] M. Maier, "Architecting Principles for System-of-Systems," *Systems Engineering*, vol. 1, pp. 267-284, 1998.

[28] S. J. Luskasik, "Systems, Systems of Systems, and the Education of Engineers," *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, vol. 12, pp. 55-60, 1998.

[29] R. Pei, "Systems of Systems Integration (SoSI) - A Smart Way of Acquiring Army C412WS Systems," presented at Summer Computer Simulation Conference, 2000.

[30] W. H. J. Manthorpe Jr, "The emerging joint system of systems: A systems engineering challenge and opportunity for APL," *Johns Hopkins APL Technical Digest (Applied Physics Laboratory)*, vol. 17, pp. 305, 1996.

[31] D. Carney, D. Fisher, and P. Place, "Topics in Interoperability: System-of-Systems Evolution," Software Engineering Institute, Carnegie Mellon University, Pittsburgh, PA March 2005.

[32] A. P. Sage, "Conflict and risk management in complex system of systems issues," presented at Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2003.

[33] Purdue, "System of Systems Research Report." West Lafayette, IN: Purdue University, 2005.

[34] R. C. Parks, R. A. Jung, and K. O. Ramotowski, "Attacking agent-based systems," presented at 2004 IEEE 1st Symposium on Multi-Agent Security and Survivability, 2004.