ON INTERPRETING SCALE (OR VIEW) AND EMERGENCE IN COMPLEX SYSTEMS ENGINEERING

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Abstract - A human-centric treatment of the concepts of multi-scale analysis and emergence in complex systems engineering (CSE) is offered. This includes an attempt to characterize what an individual might do in conceptualizing a given systems engineering situation s/he is facing. The goal is to suggest fresh interpretations of the terms scale and emergence that will contribute to a more collaborative approach to improving the CSE practice. Because other authors use "scale" in several different ways, potentially causing confusion, this author proposes "view" instead. Here a given view is defined as a combination of "scope", "granularity", "mindset", and "timeframe". Although "emergence" has a rich spectrum of definitions in the literature, this author prefers to emphasize the unexpected, especially "surprising", flavor of emergence.

INTRODUCTION

It is important to bring a degree of humility to the complex systems engineering (CSE) problems to be solved or at least mitigated. To help facilitate progress, particularly in addressing the influences of human nature, one must recognize that each person, as a consequence of finite human brains, sees a different perception of any underlying reality. People should deal with ambiguous barriers of terminology before real progress can be made in exchanging, correctly interpreting, and acting on each other's ideas.

Ryan [1] explains that ontology is about "the study of being or reality or existence", and that epistemology is about "the study of knowledge". Thus, an epistemic "property depends on how reality is conceptualized, and that is always relative to an observer and subjective". Because of its psychological theme, this paper focuses on epistemic aspects of CSE and deemphasizes the more scientific ontological counterparts.

SCALE OR VIEW

Kuras and White [2] [3] assert that multi-scale (multi-view) analysis is crucial to the more effective CSE. It should not be unexpected that a number of carefully chosen perspectives can reveal, albeit sometimes surprising, patterns that help one better understand complex systems. These different views, together, may elicit ideas for influencing or shaping the environment of a complex system to help guide or shape it towards more useful capabilities.

Definition of View

A specific instance of **View** is defined as any (four-tuple) combination of **Scope**, **Granularity**, **Mindset**, and **Timeframe**. Each of these latter terms is defined as follows.

Scope: What is included in an individual's conceptualization.
Notes: Conceptualization is akin to perception (e.g., visualization). Specific analogies of Scope are the field of view (FoV) of a camera, or more appropriately here, the "mind's eye". When one sets or determines Scope, by definition, this means that everything else, <u>not</u> in Scope, is "abstracted out", e.g., not "seen" by that individual, at least in that View, because those things are not relevant to the person's intended present state of being, e.g., purpose.

Granularity: The ability of a person to discern and discriminate individual items of a conceptualization.
Notes: **Granularity** is akin to a capability to observe details, e.g., it's like resolution. Subsets of detailed items will likely include arrangements or patterns, some of which may not be discernable in other **View**s.

Mindset: What currently captures an individual's attention in a conceptualization.
Note: **Mindset** is akin to one's cognitive focus that may observe or contemplate, e.g., within his/her **Scope** and with the associated **Granularity**, a single object, pattern, notion, or idea, or collection of such elements.

Timeframe: The time interval of an individual's conceptualization.
Note: **Timeframe** is akin to temporal component of one's conceptualization, e.g., the timescale over which it occurs.

These four dimensions of View are illustrated in Figure 1. Scope goes from small to large, and Granularity goes from coarse to fine. The Mindset axis is more general in that it cannot be characterized by such a qualitative descriptor, as indicated by the "…"s at each end of the double-sided arrows. Timeframe is envisioned as the {Scope, Granularity, Mindset} three-tuple moving within the 4th dimension of time. Each of these four axes can represent an infinite, or at least unbounded, number of possibilities from which an individual might select in forming a conceptualization.

{View} = {Scope, Granularity, Mindset, Timeframe}

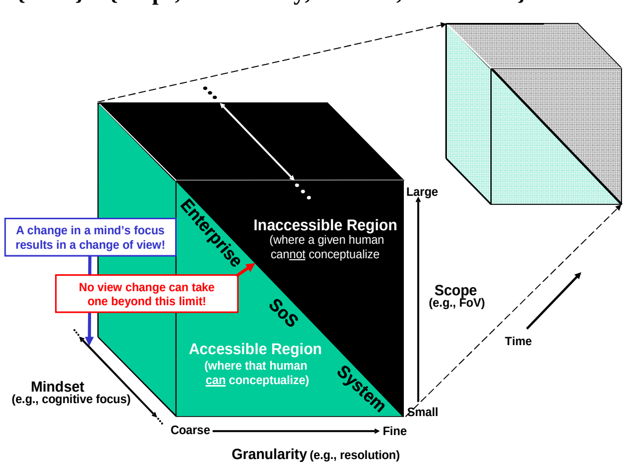

Figure 1. Conceptual Definition of Human Perceptions of View

However, following Kuras [2] no one has a true perception of the underlying reality of any situation. Mike says the brain has a finite number of neurons, and therefore, is ultimately of limited capacity to observe everything accurately. For example, imagine actually trying to locate the proverbial needle in a haystack, or to list all outcomes of an organization's current endeavors. This implies, for example, that everyone has limits to the ranges of Scope, Granularity, and Timeframe that can be perceived. This region of space within which one cannot conceptualize is depicted by the inaccessible ***black*** region of Figure 1. The ***green*** region is the space in which a person can perceive or visualize. Along the Mindset axis (see ***MIndset Range***) the range of these regions is depicted as infinite, or at least unbounded.

Furthermore, each person has a different, or at least distinct, perception of that reality. As Ryan [4] says (see ***Definition of Emergence***), "When practical limitations are the cause, [a] property [of a macrostate] may appear to be emergent to one observer, but is not emergent to an observer with a deeper understanding of the microstate." Sheard [5] uses the analogy of the Grand Canyon and where the sub-canyons correspond to distinct realities of people. Sarah suggests that understanding one's own viewpoint is limited and the existence of other competing points of view is necessary (in this author's terms) for accelerating the evolution of CSE. This is a fundamental point meant for people who might be a little more humble and less dogmatic when discussing and working with complex systems!

Mindset Range: Finite or Infinite?

Consider whether a person's Mindset has a finite or infinite range. The author believes that the range of the Mindset axis of is infinite, or at least unbounded, because of analog properties of the brain's physiology and because of the emergent properties of the mind (see ***Emergence and Surprise***). Various references in the literature [6] [7] [8] are quite convincing in this regard. For example:

> C. W. Johnson [9] "… it makes little sense to talk of human cognition in terms of individual neurons. Consciousness is intrinsically a systems level property quite distinct from the underlying physiology of lower level components."

> Ryan [4] states: "Even though formal and social systems must both ultimately have physical instantiations, they do not have obvious bounds ... on possibilities. For instance, although the number of distinct thoughts a human mind will have in its lifetime is finite, we apparently cannot specify in advance any finite set containing every possible thought, nor determine the finest possible distinction between two thoughts the mind is capable of making."

Although any individual can have only a finite number of distinct thoughts in a lifetime, the <u>set</u>, and by implication the <u>range</u>, from which those thoughts can be selected is unbounded, i.e., "infinite"!

> McCarter [10] "… [the mind's] potential is unlimited. … the mind is the emergent phenomenon of the brain … consciousness is a prime example... the individual neurons and parts of the brain by themselves cannot account for consciousness... and the actions of consciousness are much more than the biology of the parts of the brain.... the very definition of emergence is one [that] implies infinity.... and just as the universe is infinite on a macro scale.... the mind is infinite on the micro scale... or, perhaps, on a different plane in reality."

Clearly, this is a philosophical question that goes beyond an analytical approach considering only the number of neurons (or synapses) involved; counting the number of brain parts and their interconnections in upper-bounding the number of conceptualizations possible by is too simplistic. Much larger questions have been raised in terms of what is computable in the universe [11] [12].

Multi-View Analysis

Kuras argues that scale (this author's View) is tied to Mindset mainly, i.e., {View} ≡ {Mindset}, although Kuras admits that Scope and/or Granularity often change with one's change in Mindset [13]. In the author's opinion this interpretation with its emphasis on Mindset is too restrictive. However, as indicated by the note in ***blue*** font in Figure 1, a change in Mindset does lead to a change of View. See Figure 2 for two rather famous examples of this [14]. Again, according to this author's definition, one's View can change if any of the four components, viz., Scope, Granularity, Mindset, or Timeframe, or any combination of these components changes.

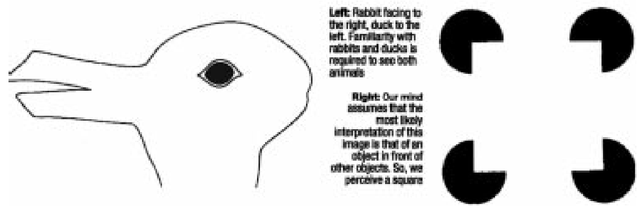

Figure 2. Changes in Mindset Result in Two Distinct Views

Referring to Figure 1, the note in ***red*** font indicates that no View change can take one from the ***green*** region into the ***black*** region. For example, suppose one is working on a System of Systems (SoS) at some combination of Scope, Granularity, Mindset, and Timeframe within the ***green*** region and in the vicinity of the ***red*** arrowhead. Assuming for now that the Mindset and Timeframe remains the same, one cannot simultaneously increase both the Granularity and the Scope; one must be content with increasing either component of View and decreasing the other component accordingly to move along the ***green*** side of the diagonal boundary between the two regions. Increasing Scope and decreasing Granularity by some amounts can be akin to viewing a larger Enterprise of which the SoS may be a part. Conversely, increasing Granularity and decreasing Scope by similar amounts corresponds to viewing a particular system that may help compose the SoS. By analyzing both these new Views, as well as the original View, one should be able to learn more about the underlying reality concerning the work thereby enhancing one's understanding of what to do. By taking advantage of changes to Mindset and Timeframe, as well, there is an increased richness to be had in solving particular problems of pressing importance. This should be better to consider different perspectives rather than continually trying to "beat a problem into submission" using only one particular View.

Thus, the usual vertical view of enterprises, SoS, and systems can be tilted to one side as in Figure 1 and interpreted in the context of conceptual multi-View analysis of a single complex-system. Typically fine-grained Granularity and narrow Scope will be more appropriate for individual systems, particularly automatons, while coarse-grained Granularity and broad Scope will be more appropriate for aggregations of autonomous agents (e.g., individual human beings) mixed with large numbers of autonomic units in social systems such as enterprises.

EMERGENCE

Definitions of Emergence

[9] and [15] both make a basic point: There is no concise, precise, and generally accepted definition of emergence. True, but this can stimulate interest and productive dialog.

The author prefers the following definition.

Emergence: Something <u>unexpected</u> in the collective behavior of an entity within its environment, not attributable to any subset of its parts, that is present in a given **View** and not present in the comparative **View**,

Notes: Some people employ a broader definition of emergence where things that emerge can be expected as well as unexpected [16]. This author prefers to consider expected things to be intentional, designed-in, known in advance, explainable with hindsight analyses, or at least not very surprising (e.g., although human evolution or cognition may not be easily explained, these general states of being are no longer surprising), and not warranting special recognition of having an emergent property. Primarily this is done to emphasize the need for very adaptable and robust management processes in CSE.

A rather comprehensive treatment of various definitions of emergence is found in Fromm [17]. S. Johnson [7, pp. 18, 21] discusses “the movement from low-level rules to higher-level sophistication ..." and “… self-organization, of disparate agents that unwittingly create a higher-level order." [15] says "… emergence has to do with qualitatively different kinds of description being appropriate to different levels of abstraction. …”

> Bar-Yam [18] defines "Emergence is...
> 1) ...what parts of a system do together that they would not do by themselves: collective behavior.
> 2) ...what a system does by virtue of its relationship to its environment that it would not do by itself: e.g. its function."

Bar-Yam also gives good explanations of how—in terms of the two examples [see ***Examples of Emergence***]: the trees and their forest; and a key and its lock—these two pieces of his definition relate to each other.

> Ryan [4]:"Definition 1 (Emergent property). A property is emergent iff it is present in a macrostate and it is not present in the microstate." "Definition 4 (Novel Emergent Property). A property is a novel emergent property iff it is present in a macrostate but it is not present in any microstate, where the microstates differ from the macrostate only in scope." "Definition 5 (Emergence). Emergence is the process whereby the assembly, breakdown or restructuring of a system results in one or more novel emergent properties. ..."

It seems that Ryan's revelation that emergence only has to do with Scope comes from these definitions! Why can't the reverse be true also?! I.e., one can see something "emerge" when observing a View with more Granularity, even though the Scope has not changed!

Examples of Emergence

As evidenced just above the author thinks that unexpected emergence should include what might happen to an observer experiencing an increase in Granularity, perhaps accompanied by a decrease in Scope. A hypothetical but likely actual example of this corresponds to a biological researcher’s observation of previously unknown patterns in a microscope view of a cell. One sees a "pattern" not otherwise observed because of an increase in Granularity (resolution), not an increase in Scope. Nevertheless, the pattern that emerges can still be thought of as a macro-state effect from a micro-state cause.

Ryan has two good examples of emergence that are neither surprising nor unexpected, a Mobius strip [4] and;

> "The orchestra produces an emergent property, call it a symphony. It is emergent because none of the components … could produce it in isolation." [19]

Norman [19] commented:

> "[The Mobius strip] exists outside of the conceptualization of any human. …So, there exists a phenomenon which shows itself only upon closure of a specific relationship [twisting and attaching the ends of the rectangular strip of paper]. What should we call this? In the case of the Mobius strip it [is] the 'emergence' of one-sidedness."

Beneficial Emergence

Emergence can have benefits, consequences, or don't care or as yet undetermined effects.

> Mogul [20]: "Emergent behavior can be beneficial. ... But it is not always beneficial. ... I will use the term 'emergent misbehavior' to focus on problematic behavior. ..."

This author is more interested in pursuing opportunities associated with beneficial emergent behavior, although one certainly needs good heuristics to help determine when emergent behavior is "bad".

Boardman and Sauser [21] include "foreseen or deliberately designed in" emergence for SoS. However, they acknowledge that some emergent behavior (especially the undesired kind) can be unexpected.

> C. W. Johnson [9]: "… there are many systems level properties that are not directly related to system subcomponents but which might be predicted. … For example, 'risky shift' occurs when greater risks are accepted by groups than would have been taken by individual team members. … Designers can, therefore, take steps to guard against these behaviors that might otherwise compromise [CSE]."

This is interesting in its own right regarding group dynamics [22].

Emergence and Prediction

> Mogul [20]: "Emergent behavior is that which cannot be predicted through analysis at any level simpler than that of the system as a whole. Explanations of emergence, like simplifications of complexity, are inherently illusory and can only be achieved by sleight of hand. This does not mean that emergence is not real. Emergent behavior, by definition, is what's left after everything else has been explained."

The last part of the definition resonates with the emphasis this author is placing on unexpected and unexplainable emergence.

> Abbott [23]: "… we have no idea how to build simulations that can identify emergent phenomena—or even more difficult, how to identify the possibility of emergent phenomena. … I called this the difficulty of looking upward."

This is an important point to make about emergence; the school of thought this author is subscribing to has said all along that particular outcomes that emerge, i.e., specific emergent properties, are not predictable.

> S. Johnson [7]: "But it is both the promise and the peril … that the higher-level behavior is almost impossible to predict in advance. …" "… understanding emergence has always been about giving up control, letting the system govern itself as much as possible, letting it learn from the footprints. ..."

One can predict there will be emergence if the system has characteristics of a complex system but one cannot pre-specify what behaviors will emerge. Although outcomes may be surprising, the fact that they occurred is not (see ***Emergence and Surprise***).

> C. W. Johnson [9]: "... complexity [is] one of the most significant 'macroethical' questions ... 'the key point is that we are increasingly building engineered systems that, because of their inherent complexity, have the potential for behaviors that are impossible to predict in advance'. A recurring theme … will be the 'surprise' [see ***Emergence and Surprise***] that engineers often express following adverse events. ... incidents revealed traces of interaction between operators and their systems that arguably could not have been anticipated using current engineering techniques."

Emergence and Entropy

Weeks, *et al*., [24] illustrates the authors' concept for increasing the mutual information between the system specification, S, and the implementation ("language"), L, as development proceeds. In itself, this makes sense to this author. However, they define the amount of emergence as the mutual information, or correlation, between S and L, i.e., the entropy H(S) minus the conditional entropy, H(S|L). This author does not use this definition of emergence. Further, they characterize H(S|L) as "surprise"; agreed—that interpretation, i.e., the (unexpected) uncertainty that remains after implementing the system seems to be of greatest importance. They also say "... a system exhibits minimal emergence when everything is a surprise (zero mutual information)." This author feels, to the contrary, when everything is a surprise, there is maximal, not minimal, emergence! It is useful to equate "uncertainty" with entropy here. Further, characterizing H(S|L) as surprise (see Figure 3) supports this author's kind of emergence.

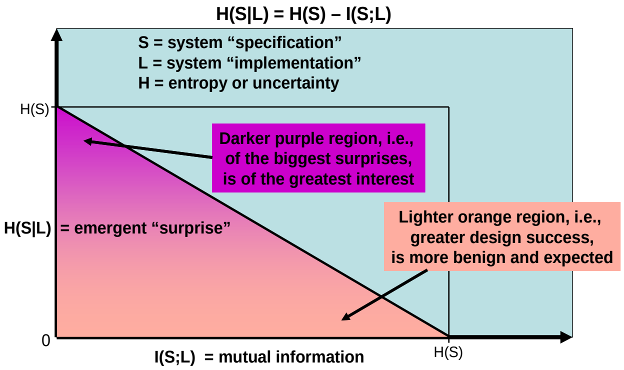

Figure 3. Emergent "Surprise" as the Conditional Entropy of an Implemented System

Emergence and Surprise

> Damper [15]: "Many authors have attempted to explain emergence in terms of surprise ...The problem here is that surprise is in the eye of the beholder." "John Holland … pointed out that von Neumann's demonstration of a self-reproducing machine 'nicely refutes the use of surprise as part of the definition of emergence'. 'It's still a great example of emergence', … And rather than feeling 'cheated' once we know the details, there should be '... no diminution in wonder....'"

Turning surprise into wonder is not a bad thing! Surprise is what is interesting, especially that different people will differ on the degree to which they are surprised.

> Ronald, *et al.*, [25]: "The description of a phenomenon as emergent is contingent, then, on the existence of an observer; being a visualization constructed in the mind of the observer, emergence can be described as a concept, like beauty or intelligence. Such concepts are slippery." "Clearly, the existence of an observer is a sine qua non for the issue of emergence to arise at all." "Our emergence test [see Ronald's paper] centers on an observer's avowed incapacity (amazement) to reconcile his perception of an experiment in terms of a global world view with his awareness of the atomic nature of the elementary interactions."

This author agrees! These concepts surrounding the inclusion of an observer are fundamental in highlighting the surprise aspect of emergence on which this author wants to focus. So the degree of surprise is important: As the observer tries to learn more about the emergence phenomena, his/her surprise may diminish. The more important emergent properties, in this author's opinion, would be those for which surprise persists despite the best efforts of the observer.

CONCLUSION

Each of us sees a distinct perception of reality. New perceptions can arise from changes in the components of a new interpretation of scale: {View} = {Scope, Granularity, Mindset, Timeframe}. To improve the practice of systems engineering, continual surprise is the most important aspect of emergence that results from multi-View analysis.

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