32nd Annual INCOSE international symposium
hybrid event
Detroit, MI, USA
June 25 - 30, 2022

What Systems Engineers Should Know About Emergence

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Abstract. The concept of emergence refers to phenomena that occur on a system level without being present at the level of elements in the system. Since a system is created to achieve certain emergent system-level behavior, while avoiding other emergent properties, a deeper understanding of emergence is crucial to further the field of systems engineering. It has also been identified as one of the key aspects of systems-of-systems. However, the concept has been the topic of much debate in philosophy, systems science, and complexity science for a long time, and there is yet no precise characterization on which there is general agreement. In this paper, a selection of the literature on emergence is reviewed to identify some key characteristics and disputes. The various philosophical points of view are analyzed from the perspective of systems engineering, to sort out what characteristics have practical implications, and which philosophical quiddities are merely of theoretical interest. The paper also relates emergence to systems engineering practices and suggests some tactics for dealing with emergence. Key results are that the inclusion of an explicit observer is essential for understanding and handling emergence, and that emergence is closely related to the amount of information required to describe the system which is also a defining characteristic of complexity.

Introduction

The idea of a *system* is deceptively simple and intuitive: it is a set of *elements* arranged in a particular way. Both the elements and the relations between them can have various *properties*, which can be thought of as variables that can take different values. The values can vary either between different elements or for the same element over time. A variation of a property over time can be seen as a *behavior* of the element, i.e., a process. Sometimes, the term *phenomena* is used to refer collectively to both properties and behaviors. The definition of systems is also recursive, in that elements can be systems themselves with their proper parts, and hence an element can also have properties and behavior. Practical systems also exist in a broader *environment*, to which it is open for interactions.

Since a system only consists of its elements, the system-level phenomena must be a consequence of the phenomena of those elements, and how they are arranged. Sometimes, this correspondence between system-level and element-level phenomena is straightforward, such as in the case of the weight of a system which is just the sum of the weight of its parts, independently of how they are arranged. In other cases, the relation between the levels is less evident, such as why mixing the two gases oxygen and hydrogen results in the fluid water, or why the apparently random movements of individual starlings appear coordinated when locking at the entire flock.

The term *emergence* is used to describe how element-level phenomena lead to system-level phenomena. In particular, it is used when this causation is non-obvious. It is a crucial notion for *systems engineering (SE)* since the reason for engineering a system is to create a certain effect that does not exist in the individual elements. Yet, it is a difficult and often misunderstood concept where debate is still ongoing on how it should be defined. In this essay, I will try to shed some light on what emergence can mean in relation to SE, and what the practical consequences are.

A Brief History of Emergence

Many accounts exist on the historical development of the emergence notion (see e.g., Goldstein, 1999), and most of them start with Aristotle's observation that can be paraphrased as "the system is something over and above its elements, and not just the sum of them all." Many of his ideas lived through medieval times but were dismantled by the scientific revolution starting in the 16th century, with its emphasis on reductionism and a mechanistic worldview (O'Connor, 2020).

It was not until the 19th century that the ideas were resurrected, in connection to the debate around Darwin's evolutionary theory and its emphasis on the gradual development of species in nature. Many theorists at the time found this unsatisfactory and tried to advance ways of reconciling Darwin's gradualism with what appeared to be larger qualitative leaps in evolution (Corning, 2002). The term "emergence" was first used in this context by Lewes (1874), and there was both interest and considerable debate throughout the 1920s about whether emergence really exists. However, the interest subsequently waned with scientific developments in quantum physics and biochemistry.

The third and current wave of investigating emergent phenomena started with developments in complexity theory and complex adaptive systems in the latter decades of the 20th century (Goldstein, 1999). Developments such as chaos theory, fractals, etc. showed that unexpected system behavior could be found in systems built on simple element-level rules, as exemplified by Conway's Game of Life (Bedau, 1997). Nonlinearity, self-organization, equilibria, and attractors are important in explaining such phenomena in terms of complexity theory. However, despite having been discussed for some 2,500 years, general agreement on key characteristics of emergence is still lacking.

Emergence in Systems Engineering

The roots and scientific underpinnings of SE are found in systems science and cybernetics, which are firmly based on the Aristotelean concepts of whole-part relations. Many scholars in systems science also emphasize non-reductionism, which strongly relates to emergence.

The International Council on Systems Engineering's (INCOSE) SE Handbook (Walden et al., 2015) is an authoritative source of knowledge in the field. It makes several attempts to describe emergence: "behavior of the system that cannot be understood exclusively in terms of the behavior of the individual system elements" (p. 6); "properties that depend on the structure (…) of the whole system and on its interactions with the environment" (p. 34); and "the principle that whole entities exhibit properties, which are meaningful only when attributed to the whole, not to its parts" (p. 82).

Recently, a group of INCOSE fellows revised certain core definitions underlying the discipline (Sillito et al., 2019). They define a system as "an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not," thus emphasizing behavior that could be emergent (although the group has deliberately avoided using the term emergence). Further, they defined SE as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." As for engineered systems, they view it as "a system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints." In summary, SE is thus seen as a goal-driven and purposeful activity which is integrating many disciplines and has an emphasis on the holistic level. The goals are typically expressed as emergent phenomena.

Several of the most influential characterizations of *systems-of-systems (SoS)* also emphasize emergence, such as Maier (1996) who describes emergent behaviors as properties of the SoS that cannot be localized to any component systems. In his view, the principal purposes of the SoS are fulfilled by emergent behaviors. Boardman & Sauser (2006) see emergence as a key SoS feature, but one that cannot be completely foreseen. In a survey on SoS "pain points", Dahmann (2013) concluded that methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors are needed.

Purpose and Overview of the Paper

It should by now be clear that the notion of emergence is fundamental in SE. Yet, it is often dealt with very shallowly, and many of the finer distinctions between emergent and other phenomena that philosophers have been investigating throughout a few millennia are lost. A likely reason for this is that the writing style of much of the philosophical literature makes it relatively inaccessible to non-specialists. The lack of clear definitions and conclusions adds to this. However, the consequence is unfortunately a lack of proper guidance for systems engineers in how to deal with emergence.

The main purpose of this paper is to introduce some of the key elements of emergence to an audience of practitioners. I will prioritize intuitive and understandable explanations over completeness and formal precision, and hence only selected references are included which I have found to be particularly valuable. A minimum of philosophical nomenclature is used, and when possible, terms from SE are selected instead.

In the remainder of the paper, I will first present some tacit assumptions that are often made when discussing emergence and introduce some major disagreements that exist on the nature of emergence. I will also explain to what extent the assumptions and disagreements are relevant to SE. One key finding is the role of observers, and this leads to a discussion on how modeling and complexity relate to emergence. Then, several tactics are suggested for how to deal with emergence in SE activities. The final section summarizes the conclusions of the paper.

Tacit Assumptions

In many accounts of emergence, two underlying assumptions exist, that are rarely made explicit. It is important to be aware of these since they have a large influence on the field of emergence theory.

Tacit assumption 1. The same concept of emergence applies to any kind of system, from the subatomic level to society. The concept of systems is abstract and thus applicable to anything that can be seen as consisting of an arrangement of parts. Consequently, the literature on emergence frequently uses examples ranging from quantum physics up to the whole society to underpin various theories, even in the same paper. Although it would be elegant to have a single all-encompassing theory that is applicable or meaningful in the same way across such a broad scale, it is far from evident that this tacit assumption is valid. The leap from the domain of the physical reality to that of cognitive and social agents is particularly breathtaking.

SE is by definition concerned with multidisciplinary systems which are positioned towards the higher levels of the abstraction hierarchy and often involve human elements. Therefore, peculiarities of emergence theories that are mainly motivated by examples from fundamental disciplines such as physics, have limited bearing on SE.

Tacit assumption 2. The levels of system and element are given (Kim, 2002). When basing a discussion on examples from natural science, this might not be so controversial since many years of research have contributed by defining abstraction levels that offer powerful explanations up to the level of a single human. However, the division into certain discrete levels is essentially a result of history and to some extent culture, and this becomes more pronounced the higher one moves up the abstraction hierarchy.

For SE in general, and SoS in particular, this assumption does not necessarily apply. There are usually many stakeholders with divergent views of the system, and they use different abstractions in their analysis. There are also many types of connections between the elements, and it is not obvious how to divide the system into elements, or even separate the system levels (Boulding, 1956). Typical rules of thumb for decomposition, such as maximizing coupling within a subsystem and minimizing it between subsystems, is difficult when the strengths of different connection types are incomparable. In systems architecting, this problem is handled by working with several views that provide alternative abstractions and hence may identify different emergent phenomena. The choice of abstractions to use is however ultimately made by the systems engineer to support the goal of the SE activity and is not given by nature.

Philosophical Controversies

In the philosophical debate on emergence, some key questions are: What phenomena should be called emergent? Are emergent phenomena predictable, or do they always come as a surprise? Apart from the causal relation from element-level phenomena to system-level phenomena, should we also consider causation in the opposite direction? And finally, must there be an observer for an emergent phenomenon to exist? For each of these questions, some alternative points of view are reviewed, and their relevance to SE is discussed.

What Phenomena Should Be Called Emergent?

One of the main difficulties in the field of emergence is to find a clear definition of the term itself, and many variations have been proposed (Kalantari et al., 2020). In general, there is agreement on the basics, namely that emergent phenomena appear on the system level and are different from the phenomena of the individual elements. Also, there is agreement that not all such system-level phenomena merit to be called emergent, but that the term should be reserved for non-trivial relations between the two levels. In this way, system phenomena are excluded if they are explicable by simple aggregation of element phenomena while disregarding the way elements are arranged.

Two characteristics are often associated with emergent phenomena (O'Connor, 2020):

- *Dependence*: The emergent phenomenon is caused by element-level structures and processes, and there must be a change at the element level if the emergent phenomenon is to change.
- *Autonomy*: Many different arrangements of elements may give rise to the same emergent phenomenon, making the phenomenon autonomous from a particular element-level structure. This includes having more or fewer elements of a certain kind (to some limit) or substituting some elements for similar ones.

As indicated by the autonomy characteristic, emergence is to some extent a matter of multiplicity, resulting from several elements of some similarity. If there were only two elements involved in creating the emergent phenomenon, and one of them was removed, emergence cannot persist. This is because the emergent phenomenon does not reside in any individual element, but if there is only one element left, it must come from that element. Yet, I have not been able to find any clear description of how large numbers of elements are needed to create emergence.

However, the autonomy characteristic is by some researchers seen as being against the principles of science. How can a phenomenon of a system be explained by anything else than its elements and their arrangement? Any theory of emergence must explain away this problem (Bedau, 1997).

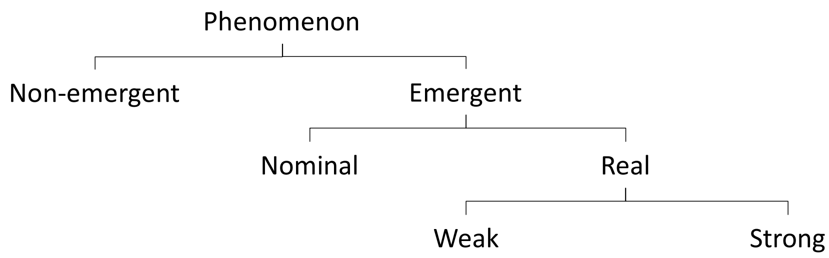

Figure 1. Classes of emergent phenomena.

Goldstein (1999) discusses how emergence has sometimes been seen as a provisional construct used when there is a lack of element-level scientific explanation of the system-level phenomenon. In that view, the need for emergence would eventually disappear as science progresses and plausible explanations are found, and the autonomy characteristic is just indicating a lack of knowledge.

For SE, the key point is to identify which system-level phenomena matter for the system to be successful. Whether a phenomenon is emergent by one of the stricter definitions, or even not emergent at all, is a question that mainly concerns how difficult it will be to deal with it. Since SE is usually a time and budget constraint activity, waiting for science to explain away autonomy is usually not an option but SE needs to be carried out at the current state of knowledge.

Are Emergent Phenomena Predictable?

A lot of the literature presents emergence as a surprising and unpredictable phenomenon (Kalantari et al., 2020). However, this is a bit problematic since surprise is a subjective notion and depends on the prior knowledge of the person observing the world. So even if the phenomenon is surprising the first time it is seen, it may not be so the second time. Also, once detected, it can be described and included in the human knowledge base and shared with others. Hence, even someone who has not experienced the phenomenon firsthand may still be able to anticipate it.

The notion of surprise is tied to events resulting from dynamic processes. This dynamic nature of the phenomena is also implied by the word "emergence" itself, denoting in everyday language something that *becomes* visible. There are however two different interpretations of that dynamic process (Bonabeau & Dessalles, 1997): Either the phenomenon appears after some time as nature has its course, or it appears as a result of shifting perspectives of an observer by using new instruments improving perception, or by constructing new abstractions onto which observations can be mapped.

The discussion about predictability has given rise to a subdivision of phenomena into different classes, as illustrated in Figure 1:

- The set of all phenomena forms a superset that includes *non-emergent* and nominally emergent phenomena as subclasses. Non-emergent phenomena include those where the same phenomenon is present both at the element and system levels, and where the correspondence is described through an aggregation.

- *Nominally emergent phenomena* are system-level phenomena that are not meaningful at the level of elements. Nominal emergence does not explain how the emergent phenomena come about, it just identifies them (Bedau, 2002). However, it requires at least a transformation that goes beyond a simple aggregation.

- *Weakly emergent phenomena* are system-level phenomena that require at least a simulation to be deduced from the element-level phenomena, and this is computationally more difficult since it requires an undecidable amount of time to complete (Bedau, 1997). In contrast, the aggregations and transformations associated with phenomena that are only nominally emergent could be computed based on the static structure of the elements, and thus not be dependent on time.

- *Strong emergence* refers to system-level phenomena that are not even in principle deducible from the element-level phenomena and structures.

The above division into distinct categories is very common but given that they are based on the possibility or difficulty of deduction, I find it more natural to instead think of this as a continuum. The question then turns from whether a phenomenon is emergent or not, to how emergent it is.

Crutchfield (1994) relates emergent phenomena to computational complexity theory which deals with the resources (primarily time) needed for an algorithm to perform computation as a function of input size. This appears to be a suitable basis for formalizing such a scale in principle. However, the classes of computational complexity disregard the exact values of constants in that function, and those constants could be very different for different observers, depending on their prior knowledge, what abstractions they choose, and their computational resources. When analyzing emergent properties, the size of the input to that analysis would correspond to the number of elements and relations between them. However, for weak emergence, the starting state also matters since it can take a different amount of time to reach the event where the phenomenon becomes visible.

A lot of debate on emergence is related to the question of whether strong emergence exists in nature at all. As an example, Chalmers (2006) claims that it does indeed exist, but that there is only one example of it, namely how consciousness emerges in the brain.

In the context of SE, a similar argument as in the previous subsection applies. Given the time and resources available, waiting for an undecidable simulation of a weakly emergent phenomenon may not be an option. Alternatively, even if the phenomenon is merely nominally emergent, determining the complete simultaneous state of a very large number of elements may be technically and practically infeasible. In both these cases, the phenomenon needs to be treated as strongly emergent and has to be analyzed by modeling the relations to other system-level phenomena without reference to the elements.

Can System-Level Phenomena Affect Element-Level Phenomena?

Emergence is usually described in terms of how element-level phenomena cause system-level phenomena. However, in some situations, one may also consider *downward causation*, i.e., that system-level phenomena affect element-level phenomena. It is difficult to come up with solid examples of this in the natural sciences, but for cognitive and social systems, it seems more natural.

Take an organization as an example. It is a system whose elements are the humans working in it. Those elements will perform various activities, among those jointly defining objectives of the organization, which can be seen as emergent system-level properties. The elements will then let those objectives guide their future actions, and downward causation is thus taking place.

Downward causation may thus play a role in SE and particularly in SoS. In an SoS situation, each element (commonly referred to as a constituent system, CS) is, by definition, independent and makes decisions based on its priorities. Hence, a CS exhibits all the features of a cognitive agent.

The interesting question then becomes whether the element can observe the system-level phenomena. Typically, an element would only be able to observe other elements to which it is related, and in most large systems, an element would only relate to a few other elements, at least at the same time. The possibility of downward causation thus depends on whether the elements have information about a sufficiently large part of the system for the emergent phenomenon to be visible. In SoS engineering, providing mechanisms for downward causation is a key part of the design. This improves situation awareness of the CS and thereby increases the chances that the desired emergent phenomena are realized. The same applies in systems where humans play important roles as system elements.

Must There Be an Observer for an Emergent Phenomenon to Exist?

To reason about emergent phenomena, there must be a cognitive agent present (e.g., a human). However, the question then arises whether the phenomenon exists in nature at all even if the agent is not present, or if it is only relevant to discuss emergence relative to an observer. Corning (2002) insists that emergent phenomena are real and measurable, and thus present even without an observer. Bonabeau & Dessallles (1997) take the opposite point and argue that the presence of objective measures of emergence is illusionary and that concepts of emergence are much better captured and analyzed by accepting the observer's role. Ryan (2007) also discusses the presence of observers in relation to emergence and notes that there is an important connection between emergence and scope, i.e., the location of the border between the system-of-interest and the environment.

Regardless of your position in this philosophical discussion, it is worth noting that in an SE context there are always observers. SE is a purposeful activity, and the purpose is given by different stakeholders. It is only the effects that those stakeholders observe that matter, and hence there is not so much to gain from an SE perspective by ignoring the observer. It is also worth noting that many of the previous points raised in this section of the paper are easier to explain if the observer is included, as Bonabeau & Dessalles (1997) suggests:

- The tacit assumption that levels and elements are given is no longer needed, but it is the observer that decides what level of abstraction the system should be placed on and how the system should be divided into elements.
- The degree of surprise can be related to whether the observer has previously encountered the phenomenon or not.
- The difficulty of deducing the phenomenon becomes relative to the computational power and current knowledge of the observer, instead of being seen as an absolute fact.
- Downward causation, where the behavior of an element is dependent on emergent phenomena, can be analyzed by thinking of the element as an observer internal to the system.

There is thus not much to lose by assuming the presence of observers when reasoning about emergence and SE, and I will in the remainder of this essay make that assumption. The presence of the observer also implies that emergence is to a large extent a question of information representation and processing.

The idea that knowledge is created by an observer trying to formulate models of the natural world from its observations is sometimes referred to as *constructivism*. Although I have above discussed this in the relation between emergence and observers, it has a broader bearing on SE. Questions such as if systems exist in reality or only in the minds of observers, or if system boundaries are designated by observers or are intrinsic, can be debated, and Dori et al. (2020) formulate a few different world views that are possible. However, it is beyond doubt that constructing models of the world is a defining characteristic of SE, regardless of whether it is mental models in the mind of individual systems engineers, or if it is also supported by external models such as in the model-based or digital engineering approaches now popular. Another key aspect, which is particularly important in SoS and other socio-technical systems, is that different stakeholders may choose different abstractions for their world models depending on what they value (Checkland, 2000). This is difficult to explain if assuming that systems are given by nature.

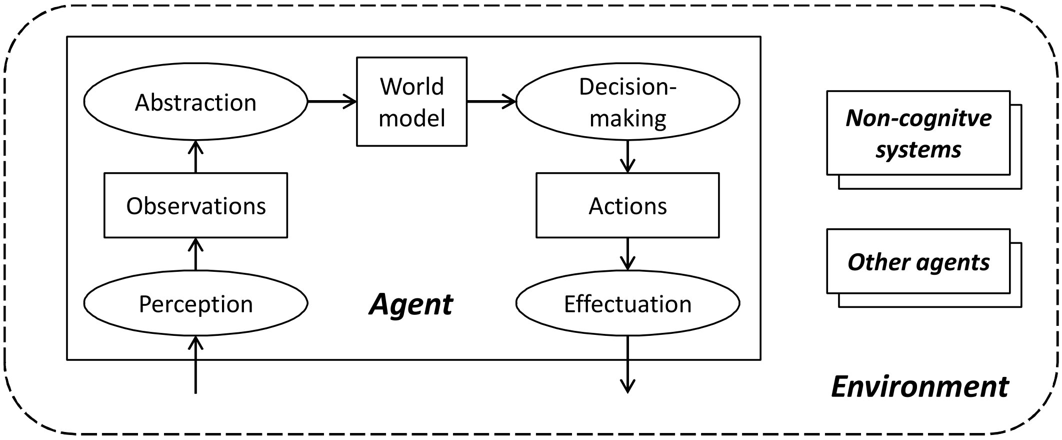

Figure 2. Conceptual model of a cognitive agent.

Fundamentally, SE is an information processing activity carried out by a set of human agents using different tools and resulting in some decisions about the system (Axelsson, 2002). Information models are essential in that processing, and information also plays a key role in explaining emergence if assuming the presence of an observer.

Cognitive Agents, Abstractions, and Complexity

To further explain the role and characteristics of observers, this section will introduce a model of a cognitive agent. I will first describe how the information processing activities of an observer may be conceptualized through some of the key elements of such an agent. Then, the questions of how observers choose abstractions and models are discussed, and finally, a few remarks regarding complexity are provided.

Conceptualizing Observers

To frame the discussion on the role of observers in the understanding of emergence, I will now introduce a simple conceptual model of a cognitive agent. It is similar to the one used by Crutchfield (1994), and consists of the following elements (see Figure 2):

- The agent exists in an *environment* consisting of physical entities as well as other agents.
- The agent has a capability of *perception* allowing it to make *observations* of the environment.
- The agent can use its capability of *abstraction* to find and label various phenomena in the observations and use those to structure the information in its *world model*.
- Based on the world model, the agent can utilize its capability of *decision-making* to select what *actions* it should take through its capability of *effectuation* of the environment. These actions also include communicating with other agents in the environment.

This model is in itself an abstraction by a certain cognitive agent (namely the author of this paper!) trying to make sense of the world, and many other alternative abstractions could be used instead. For instance, alternative models could better highlight the dynamic nature of cognition and show explicitly the many feedback loops that occur, allowing the agent to learn.

The purely cognitive and conscious processes are abstraction and decision-making, whereas perception and effectuation bridge the cognitive and physical worlds. In the following two subsections, I will discuss how abstraction and decision-making relate to emergence and SE in more detail, and this is followed by a brief note on the relation to complexity theory.

Choosing Abstractions

Abstraction is the process of removing information from observable phenomena and retaining only information that is valuable for a specific purpose. Abstraction is essential in any discussion on emergence since reasoning on the system level removes information about the elements, but emergence also requires the introduction of new concepts not present at the element level, as discussed above related to the nominal form of emergence.

The concepts resulting from abstraction can be concrete, such as when identifying a car in a picture but ignoring the color of it, or it can be more abstract, such as identifying a means of transportation. Words or other symbols are associated with the concepts selected through abstraction, to allow reasoning about them. There is thus a linguistic or semiotic aspect of abstraction. Removing information is a way of focusing attention on what is perceived to be important, and it also makes analysis and explanation tractable.

A given set of information can be reduced in many different ways, and abstractions are thus not given by nature but may be chosen freely by the cognitive agent. Still, not all abstractions are of equal value, but they should ultimately serve as the basis for efficient decision-making leading to actions whose results the agent subjectively perceives as valuable. Efficient decision-making means reducing the computational effort of deducing what actions to take, and if including a certain abstract concept can achieve that, it should be used. Discovering new abstractions can be seen as a process of innovation (Crutchfield, 1994).

In SE, as in many other aspects of life, agents need to collaborate which requires communication. Therefore, it is valuable to agree on which abstractions to use. Through culture and education, humans share a rich set of abstractions in the form of language that is often a sufficient basis for world models. However, in the development of new systems or when applying SE in new situations, the current abstractions may not be sufficient or efficient. Also, different stakeholders will choose abstractions that best capture their needs, and this is particularly apparent in soft systems and SoS where a multitude of world views needs to coexist (Checkland, 2000). In general, the larger the system considered, the more information is needed to describe it, and hence the more alternative abstractions exist to choose from.

World Models as Sources for Decision-Making

The abstractions used in the world model should serve the purpose of decision-making regarding which actions to take. The essential role of the world model is to be able to accurately predict what the next observation will be given a certain action. If this can be done, the next observation after that will also be predictable, and so forth, leading to a possibility to reason about alternative futures and plan for sequences of actions. The predictive power of the world model is then the probability distribution of how well its predictions match the states of the real world. Apart from this quality characteristic, there is also an economical perspective, namely how much information it contains (less is better for the same predictive power) and the computational expense of the calculations.

When creating abstractions, it is not sufficient to only identify separate concepts, but also to clarify the relations between them. This is what gives the ability to reason about the information in the world model. If the concepts represent emergent phenomena, there needs to be a cohesive theory on the system level without referring to the element level, to allow systems engineers to predict if the system will fulfill its purpose or not. This also means that when selecting a level of abstraction to use, the concepts on that level should relate more strongly to one another than they do to concepts on other levels (Goldstein, 1999). There should be intra-ordinal laws (Kopetz et al., 2015) that provide explanatory and predictive power within a selected level, making it self-contained.

The structure of world models also relates to its use as a basis for simulation, and as noted above, this is particularly important for phenomena that can be viewed as weakly emergent. Two forms of simulation are particularly interesting, namely system dynamic and agent-based simulations (Schieritz & Milling, 2003). The former works solely on the system level, and thus requires identification of both the phenomena (emergent or not) and the intra-ordinal laws that connect their dynamics. The latter describes dynamics on the element level but allows emergent phenomena to be observed.

Emergence and Complexity

As a final note on the nature of emergence in SE, the relation to complexity will now be briefly touched upon. The reason is that there are some striking similarities between the contemporary theories of emergence and complexity, in that they both relate to observers and information processing.

The complexity of a system is associated with the amount of information required to describe it in sufficient detail. As Gell-Mann (1995) points out, the maximum complexity should be attributed to information somewhere between randomness and complete order. Various ways of compressing the description are plausible, e.g., by finding repeated patterns that can be included as new concepts through abstraction. One way of doing that is to reason about system-level patterns, which, from a practical perspective, are emergent phenomena if the details of the correspondence between system and element levels do not matter.

The importance of an observer is also as relevant in complexity theory, although this is often overlooked (Axelsson, 2002). Depending on the a priori world model of a person describing the system, the description needs to include different amounts of detail, and thus be of different length, and the length of description is associated with the level of complexity.

This view is also acknowledged by Sillitto et al. (2019) in their effort to define complex systems in the scope of SE. Although they highlight aspects such as “non-trivial” relationships between cause and effect in an attempt to provide an objective definition, what is non-trivial is of course dependent on who the observer is. Also, they state that a major goal of SE is to reduce perceived (i.e., subjective) complexity by establishing shared models of a system among the stakeholders.

Tactics for Dealing with Emergent Phenomena

The model of a cognitive agent presented in the previous section is abstract and primarily based on the characteristics of a human being. However, the principal ideas may be applied to other entities such as a technical system that performs information processing (although a technical system does not have an intrinsic notion of value on which to base its decisions but inherits the values of its maker, owner, or user). It can also be applied to an organization.

The latter case is particularly relevant to SE since complex systems are by necessity developed by organizations (Axelsson, 2002), but it must then be acknowledged that the organization as such is an abstraction. A particular agent may belong to many organizations and different agents may have different views on the nature of an organization they both belong to. It thus makes sense to think of organizational phenomena as being emergent, and there is a strong element of downward causation. The notion of the organization is not physical, but it only exists in the world models of the agents participating in it, or tangibly in different documents. This affects how those agents act as discussed in the section on downward causation above. If the agents have a sufficiently common model of the organization, based on shared abstractions, it will create the desired emergence of coordinating the agents’ actions.

In this section, I will discuss some tactics for better dealing with emergence that can be applied by an organizational system. The organization is viewed as a cognitive agent and the tactics relate to the capabilities for perception, abstraction, decision-making, and effectuation of the systems engineering organization. Some benefits but also drawbacks of these tactics are presented, to give some ground for finding suitable management trade-offs regarding the extent to which resources should be spent on various activities.

Perception: Awareness of Emergent Phenomena

The first step for an organization to deal with an emergent phenomenon is to become aware of it, and this is the role of organizational perception. If this is not done properly, there is a risk that important phenomena are disregarded.

A prerequisite for organizational awareness is individual awareness, so there must be at least someone on the SE team who has sufficient knowledge to understand that a certain phenomenon exists, and to cover more phenomena, a diversity of staff is needed. By working truly multidisciplinary, a broader spectrum of detection mechanisms is introduced, and with it a richer language of abstractions, which increases the chances that phenomena will be identified and predicted. On the other hand, some of the disciplines may in the end not contribute so much, and there can be a cost of excessive staff.

However, it is not enough that one single individual knows, but the knowledge must be spread to others and acknowledged as being relevant to SE. Here, there is a risk that diversity fires back because people with different backgrounds often use different language and abstractions due to various world views, which can make communication more difficult (Axelsson, 2002).

Most organizations engage repeatedly in SE activities in similar domains, and perception could be enhanced through organizational learning. This includes improving skills at creating, acquiring, and transferring knowledge, and modifying its behavior to reflect new knowledge and insights (Garvin, 1993). It will ensure that there is a rich world model present in the organization based on previous projects, capturing experiences of which phenomena have mattered in the past. The drawback of this is that it can create a false sense of certainty, by ignoring novel aspects of the new situation which reduces the perceptive capability. There is thus a feedback loop from the world model back to perception, that can be both positive and negative.

Abstraction: Understanding the Nature and Importance of Phenomena

Once a system-level phenomenon has been recognized, its nature needs to be understood. This includes both the relations with other system-level phenomena and its relations to stakeholders. Is the phenomenon beneficial or not, and to which stakeholders? Failure to understand the nature of phenomena carries risks related to missing phenomena that matter to stakeholders and handling trade-offs between conflicting phenomena improperly. In the worst case, it could even mean embarking on an expensive development effort that never had a chance to fulfill its purpose, due to the interplay between different phenomena.

To handle this, organizations need to model the system level. This can include commonly used conceptual models expressed in, e.g., UML, SysML, or OPM. However, often the dynamics matter, and therefore system dynamic models and simulation should also be explored.

Many organizations tend to regard the *system-of-interest (SoI)* as being composed of those elements and relations over which it has power, control, ownership, or mandate to change. Although this may seem natural given that the objective of SE is to design a system, it can lead to a too shallow analysis of those elements that are in the environment of that SoI. This is because the SoI may contribute to emergent behavior in the larger system of which the SoI is an element. If there is downward causation on the SoI, this emergence becomes very important but will be ignored. Similarly, feedback loops that are closed through the environment may affect the SoI considerably. Therefore, systems engineers need to think in three levels, not two: the environment system, the elements of the environment system (including the SoI), and the elements of the SoI.

A challenge to this approach is that there may be many possible environment systems that need to be considered. Often, the environment systems will be soft systems and hence a multitude of world views will co-exist (Checkland, 2000). As described by Martin (2004), even an ordinary integrated product will have a complex environment, and for SoS, this is even more apparent.

Decision-Making: Analyzing Causation of Emergent Phenomena

Having identified the system-level emergent phenomena, the task of SE becomes to select elements and relations between them that create the desired phenomena and avoid the undesired ones. A key activity in this is to suggest alternative solutions and evaluate these. In doing so, it is useful to understand the strength of emergence. As noted above, emergence has a strong relation to complexity, given that both can be seen as measurements of the amount of information in a system description. Excessive complexity is a cost driver and can also negatively influence many qualities such as reliability.

What can systems engineers then do to reduce the strength of emergence, and hence reduce complexity? The decision-making done by the SE organization is about selecting elements and relations. Since the strength of emergence is a result of how difficult it is to describe in what way element-level phenomena cause system-level phenomena, it seems plausible that different design alternatives could result in emergence of different strengths. A tactic of SE would then be to consciously evaluate the strength of relevant emergent phenomena and consider this as part of trade studies.

The strength of emergence does not only depend on the arrangement of elements in the system but is also subjective based on the combined world model of the organization. The more an observer knows and understands, the less strong the emergent properties are. Systematic organizational learning is hence a useful tactic also for decision-making.

Model-based SE is important since the digital models become explicit and accessible representations that complement the individual world models distributed in the minds of the people in the organization. However, there is a risk that for economic reasons the diversity of these models is reduced, or that the relations between different sub-models are not appropriate, and hence that certain abstractions are downplayed. This increases the risk of missing relevant emergence when analyzing or simulating the models. To remedy this, the organization should ensure that many views are included in the model. Frameworks such as UAF acknowledge this and can be starting points, but flexibility is also needed. It must be possible to include models on many levels of abstraction. Trying to enforce one “truth” may lead to ignoring important abstractions that could allow more efficient analysis.

For weakly emergent phenomena, agent-based simulation is an important technique to use. If a system-level model including the phenomena has been developed earlier, this can now be complemented with an agent-based simulation on the element level. By observing the latter model for emergent phenomena, these can be compared to the system dynamics simulation to see if a particular element-level solution is acceptable or not.

SE may in some cases exploit downward causation, especially for SoS. Undesired emergence can be the result of limited situation awareness in constituent systems of an SoS, and a tactic is then to improve this by including more communication. In principle, for an element to observe emergent phenomena, it would need information from all other elements, creating an excessive amount of communication links. However, if the dynamic of the emergent phenomenon is sufficiently slow, the elements could gather such information over time by changing their relations to other elements more rapidly and building a model of the system over time.

Another option is if elements communicate with each other, and not only pass on the information that they have gathered themselves but also the information they have received from others. In this way, the system-level phenomena can be understood by each element through chains of peer-to-peer communication, where each element only links to a few peers.

Sometimes the solution is to include special elements, called mediators, whose role is to gather information about the system-level phenomena, process it, and share it with other CS. This then becomes a more centralized alternative to the peer-to-peer approach, and although it adds a cost to the SoS it can improve performance.

A good example of downward causation is a transport SoS, where the traffic flow on various routes is an emergent phenomenon depending on the speed and route choice of individual drivers. It is most likely a case of weak emergence, and mediators that collect information about traffic jams and use that as a basis for route guidance can affect the behavior of drivers and improve traffic flows. To the mediator, the real system can almost be seen as a simulation that is observed to understand the emergent phenomenon.

It can be debated whether the mediator or peer-to-peer approaches are valid examples of downward causation since they can be understood by looking at the element-level mechanisms. Still, in SE, what matters more is if there is a need for improved element-level situation awareness, and in that case what the appropriate design solutions are for achieving it.

Effectuation: Controlling Emergent Phenomena

Depending on the strength of emergent phenomena, different approaches may be needed for achieving what is desired. If the emergence is only nominal, but not weak, a static design solution may suffice. For weak emergence, which requires simulation to be predicted, it seems plausible that also a more active dynamic control strategy will be needed. Systems engineers then need to consider feedback control mechanisms in their design and be aware of the law of requisite variety (Ashby, 1956), which stipulates that the complexity of the controller will be at least as high as that of the controlled element. The controller will thus increase in complexity with the strength of the emergent phenomena. It may also require additional enabling systems to support it, both organizational and technical, throughout the lifecycle.

As pointed out previously, emergence sometimes occurs at a level above the narrow SoI that the organization has power over. The SoI then contributes to that emergence, but so do other elements in the environment of the SoI. There is thus an option to not only influence the emergence through the elements and relations inside the SoI, but an alternative is to effectuate the elements in the environment, which could be other agents. However, this turns the problem into a soft system or SoS problem, and a different approach may be needed. Other organizations have control of the external elements, and it becomes necessary to establish relations and partnerships with them and to ensure that they have incentives to act in a way beneficial for the desired emergence.

Conclusions

In this essay, I have tried to explain some of the key aspects of emergence and how they relate to SE. To summarize the key messages in the paper, I have, with support from the literature, advocated a subjective view on emergence and complexity, where the strength of emergence depends on prior knowledge and experiences of an observer. Emergence is thus strongly related to the representation and processing of information. Based on that, I introduced a conceptual model of the observer as a cognitive agent and discussed the roles played by abstraction and world models in how it perceives emergent phenomena. The same model of a cognitive agent was then applied at the level of an SE organization, and some tactics that organizations can use to deal with emergence were suggested.

As pointed out by Bonabeau & Dessalles (1997), emergence is foremost an intuitive phenomenon. This means that there are different ways of filling it with meaning, and this can explain the lack of consensus on a precise definition. Still, emergence plays a prominent role in most accounts of systems and SE, but it is rarely analyzed in-depth when discussed with a pragmatic audience. By studying the different aspects of emergence brought up in the literature over time, our understanding of systems can deepen. With this paper, I hope to share some insights and stimulate further research in the area, leading to a better understanding of good tactics to use.

Given its very long history, the subject must be approached with some modesty, and undoubtedly a lot more can be said. Much of the existing literature is written in a philosophical style which reduces its accessibility to practitioners without a background in that field, and I have tried to strike a balance between the philosophical arguments and practical application. With that said, I know from experience that a little philosopher is hiding in many a systems engineer. For those so inclined, some of the references may provide good starting points for further reading.

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Biography

Jakob Axelsson received an MSc in computer science in 1993, followed by a Ph.D. in computer systems in 1997, both from Linköping University, Sweden. He was in the automotive industry with Volvo Group and Volvo Cars 1997-2010. He is now a full professor of computer science at Mälardalen University, Sweden, and a senior research leader in systems-of-systems at RISE Research Institutes of Sweden. His research interests include all aspects of systems-of-systems engineering. Prof. Axelsson is a member of INCOSE and has served as chairman of the Swedish chapter.