Emergence and Systems Engineering:
Putting Complex Systems to Work

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Abstract. A primary objective of this paper (as well as of this symposium overall) is to examine concepts from the field of complex systems that can be applied to systems engineering. In this paper we focus primarily on the notions of emergence and entities and discuss their implications for systems engineering.

1 Introduction

Complex Systems. The study of Complex Systems (originally called Complex Adaptive Systems) as a distinct and recognizable discipline has been ongoing for more than three decades. Most trace its origins to John Holland’s work on genetic algorithms (Holland, 1975) in the 1970’s. Holland showed that a non-directive random process, which resembles biological evolution, is capable of producing useful designs.

Some trace it much farther back—to Henri Poincaré’s invention of chaos theory, approximately a century ago, when he demonstrated that it is mathematically impossible to find a closed form solution to the Newtonian equations for the trajectories of three or more interacting gravitational bodies.¹

¹ The following websites (among others) tell the story.

Systems Engineering. According to the INCOSE website,²

Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder’s needs are satisfied in a high quality, trustworthy, cost efficient

² http://www.incose.org/practice/fellowsconsensus.aspx
and schedule compliant manner throughout a system's entire life cycle.

Although not explicit in this definition, a significant aspect of systems engineering is the development of a design for the system being engineered.

Our focus in this paper will be on the relationship between emergence and design. Emergence will lead us to consider the issue of entities, what they are and what it takes for them to persist. We also examine the sorts of environments that support emergence.

Section 2 discusses the notion of design in complex systems and explores what it means to say that a system is complex.

Section 3 extends the framework developed in section 2 to define emergence. It also shows how emergence is intimately related to systems engineering.

Section 4 discusses how emergence is connected to our notion of entities. It discusses the question of whether entities are objectively real. (We conclude that they are.)

Section 5 discusses the relationship between thoughts and things—and in particular between thoughts, requirements, designs, and things. It discusses computer science's success in developing languages that help us externalize our thoughts. It attributes a significant part of that success to the fact that the languages in which we express our thoughts are also the languages we use to control computers. Systems engineering isn't so fortunate.

Section 6 discusses dissipative systems, a kind of entity intermediate between static and dynamic entities, and the kind of entities engineers tend to build. A major difference between dissipative systems and dynamic entities is that dynamic entities are designed from the core to be self-sustaining, with whatever additional functionality they have built on top of their ability to sustain themselves.

Section 7 discusses service-oriented designs. It argues that this is not a fad but a fundamental design principle used by nature.

Section 8 discusses feasibility ranges, that all emergent properties have them, and that it would serve us well to pay more attention to them.

Section 9 discusses modeling and simulation. Makes the point that we aren't nearly as good at it as we need to be. It also makes the point that even if were much better at it, we would still not necessarily know how to use it to model emergence.

Section 10 discusses innovative environments. An innovative environment is one that may be thought of as emergence-friendly. This section suggests some properties that innovative environments may be expected to have and that seem likely to foster emergence.

2 Design in complex systems
Before discussing design in the constructive sense as used in systems engineering, we examine what we mean by design in general.

A primary goal of science is to compress phenomenological descriptions into concise abstractions. One wants to formulate a statement about nature that (a) captures a wide range of phenomena but (b) is more abstract and concise than a simple enumeration of the phenomena described. If successful, one will have achieved a reduction in the al-
algorithmic complexity of one’s description of nature.

Chaitin, one of the developers of the theory of algorithmic complexity, credits Leibniz with being one of the first to formulate the goals of science in this way. (Chaitin, 2003)

What is a law of nature?

According to Leibniz, a theory must be simpler than the data it explains!

Because if a physical law can be as complicated as the experimental data that it explains, then there is always a law, and the notion of “law” becomes meaningless!

Understanding is compression! A theory as complicated as the data it explains is NO theory!

All of this is stated very clearly (in French) in 1686 by the mathematical genius and philosopher Leibniz!

2.1 Upward predictability

When applied to a relatively well-bounded region of interest (here for convenience called a system) one is looking for what we would not call the design of the system.

Science often proceeds by examining a system’s components and their interrelationships in the hope that in doing so one will be able to formulate a simpler description of the system as a whole.

Newton’s law of gravity is a good example. It offers a description of how two bodies will move with respect to each other—a description which is much simpler than an enumeration of the relative positions of the bodies in time. Furthermore, given Newton’s law of gravity, it is possible to construct closed form equations that characterize the position of the two bodies when under the influence of mutual gravitational attraction.

This is what one wants: analysis of the interactions at the component level yields a simple explanation of the apparent complexity of phenomena observed at the system level. Systems that yield to this paradigm are what might be called upwardly predictable.

2.2 Complex systems aren’t upwardly predictable

A distinguishing feature of systems that are considered complex is that they tend not to be upward predictable: there is no

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3 The algorithmic complexity of some information is the smallest computer program required to reproduce that information. A random sequence, a sequence with no internal structure, has maximal algorithmic complexity because it is impossible to find a computer program shorter than the sequence itself that will reproduce the sequence.

4 The images used in this paper a copyright free from Wikipedia.
(known) way to reduce the complexity of a description of the system as a whole by formulating it in terms of descriptions of the system’s components. In other words, the properties and behaviors of a complex system are not describable as a simple, closed-form, mathematical function of the properties and behaviors of the system’s components. Typically the best one can do is to propagate the descriptions of the component interactions and see what happens at the system level.\(^5\)

An example of such a class of systems are n-body gravitational systems for \(n > 2\). As indicated above, Poincaré showed that Newton’s laws cannot be used to provide a reduced description of the trajectories of more than two gravitational bodies. There is no simple way to combine descriptions of the system’s components to produce a description of the system as a whole that is simpler than propagating the descriptions of the components.\(^6\)

Systems deemed to be complex in this sense are not claimed to violate traditional notions of scientific causation: no additional forces are presumed to contribute to the complex functioning of the system as a whole. The only claim is that there is no compact mathematical equation that will characterize the behavior of the system as a whole as a function of its components.

\(^5\) This approach is now known as agent based modeling.

\(^6\) Another example is quantum mechanics. There is no simple way to evaluate the Schroedinger equation for systems of more than a very few particles. Another way of putting this is that nature is complex.

3 Emergence

3.1 Emergence and Complexity

Sometimes higher level systems have properties that seem to be both complex and not complex in the sense just described. Such systems have properties that may be characterized in relatively simple terms—much simpler than the terms required to characterize the elements of which they are composed. Even so, those systems still cannot be usefully understood in terms of a function from their components to their higher level properties.

An example is a computer program that computes a mathematical function. The mathematical function itself is a straightforward characterization of the input-output behavior of such a program. Such a description is far simpler than the description of the behavior of the computer on which that program is running. If one were to describe the sequence of states (at virtually any level of abstraction from quantum mechanics to gates to machine language) through which the computer passes as the program runs, that description would be far more complex than the description of the function itself. Furthermore, there is no general way to map the states of the computer (or the computer program that generates them) to the mathematical function the software is computing.\(^7\)

\(^7\) In general it is not decidable what function an arbitrary computer program computes. In using this example, we are not identifying complexity with undecidability. But we are categorizing the undecidable as complex.
Typically the best one could do would be to trace through the step-by-step operation of the computer and see what happens. So even though our software-plus-computer system is simple to describe at the system level, it is also complex in the sense described earlier.\(^8\)

So here we have an apparent paradox. We have both (a) complexity: there is no natural complexity-reducing transformation of the descriptions at the lower level into descriptions at the higher level and (b) simplification: the higher level may be described in simpler terms than those needed to describe the lower.

We have come to use the term *emergence* to describe situations such as these. In his PhD dissertation Shalizi captures this algorithmic complexity sense of emergence as follows.

One set of variables, \(A\), emerges from another, \(B\) if (1) \(A\) is a function of \(B\), i.e., at a higher level of abstraction, and (2) the higher-level variables can be predicted more efficiently than the lower-level ones, where "efficiency of prediction" is defined using information theory.\(^9\)

### 3.2 Emergent properties are autonomous

Although Shalizi's definition gets at the algorithmic complexity issues, it misses an important point about emergence. The relationships between the lower and higher level variables are typically much less important than the emergent property itself. In fact, the higher-lower relationships are typically a matter of convenience rather than necessity.

In our example of software that computes a mathematical function one doesn't care what sequence of states the computer traverses. All one cares about is that the function be computed correctly. There may be any number of ways to compute the function. Each may produce a different sequence of computer states but the same eventual output. It doesn't matter which one is used as long as the final result is correct.

To capture this aspect of the issue, I defined (Abbott, 2006) *emergence* as the situation in which one can describe properties of a system in terms that are independent of its components. From this perspective, the property of interest (in this example the computation of a mathematical function) may be implemented by lower level components (the program must run on some computer after all), but it is defined independently of those components.\(^10\)

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\(^8\) Because of this seeming inversion of control—a simpler higher level appears to spring from a more complex lower level—there has been a temptation to look for an explanation in terms of "downward causation"—the simpler higher level *causes* the phenomena observed at the lower level.

Of course there is no downward causation. But because we are so used to thinking in terms of simple abstractions giving rise to complex phenomena it's easy to understand why downward causation may seem like an attractive possibility.

\(^9\) The extract is from his website: [http://www.cscs.umich.edu/~crshalizi/notebooks/emergent-properties.html](http://www.cscs.umich.edu/~crshalizi/notebooks/emergent-properties.html).

\(^10\) As developed in (Abbott 2006) this leads to the notion of downward entailment, a phenomena similar to but scientifically more acceptable than downward causation. The specific example developed in the paper shows that because one can simulate a Turing Machine using the
Standard examples of emergence include the hardness of diamonds (static emergence) and the tendency of some species of birds to move in flocks (dynamic emergence). In both cases, the higher-level properties are not only defined *ab initio* at the higher level, they are often meaningless when thought of as properties of the system components.

A diamond is hard because of how its component carbon atoms fit together. But the notion of a collection of carbon atoms fitting together in this way is expressible only at the level of the diamond itself.

Similarly, our notion of a flock is not just a collection of birds; it is a collection of birds that satisfies our intuitive sense of what it means to be a flock. The notion of a flock is no more accessible in the language in which one describes individual birds in isolation than the notion of a diamond is accessible in the language in which one describes individual carbon atoms in isolation.

Game of Life, the Game of Life is undecidable. The undecidability of Turing Machines downwardly entails the undecidability of the Game of Life.

A diamond also provides a nice example of downward entailment. Because the carbon atoms of a diamond implement a rigid lattice, the position and orientation of the diamond as a whole downwardly entail the position of each of its carbon atoms.


3.3 Emergence and requirements

Systems engineers are familiar with emergence as the requirements that a system must satisfy. Consider what we would now consider a simple system such as an automobile. A primary requirement is that it can be driven from here to there. That property is emergent. It is not meaningfully applied to any of the components of the automobile. Nor is it expressible as a closed form mathematical function of the automobile’s components.

Thus systems engineering (in fact, engineering in general) may usefully be understood as the design and development of systems that have desired emergent properties. As Rechtin put it,

A system is a construct or collection of different elements that together produce results not obtainable by the elements alone.

4 Emergence and entities

In all three of the preceding examples, emergent properties were defined in terms of a higher level entity—often using language that is not even applicable to the components of the entity. If one thinks about it, this is quite strange. What are these higher level entities we are talking about? On what ontological grounds do we permit ourselves to speak about them? Perhaps more to the point, are such higher level entities objectively real in any way that we can make sense of? Is a diamond or a flock or an automobile (or any other system)

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a real entity? Or is it simply a collection of its components?

In (Abbott, 2007) we conclude that entities are objectively and recognizably real in that (a) they have either more or less (but not the same) mass as the combined mass of their components considered separately, and (b) they bind their components together in a form that reduces entropy.

It is only because of the entropy reduction contributed by entities that it is possible for Shalizi’s definition of emergence to be realized. How is it possible after all for the algorithmic complexity of a system’s description to be reduced? A description of a system is a description of a system. If one description is simpler than another, it is only because the simpler description takes advantage of some entropy-reducing structure that the more complex description ignores.

So if a description of a system expressed in terms of “higher level” constructs is simpler than a description expressed in terms of “lower level” constructs, that means that the “higher level” constructs have built into them some structure that the lower level constructs lack. But that raises the question of how the “higher level” constructs embody and maintain that structure.

That’s what an entity is, a means to embody and preserve structure.

4.1 Kinds of entities

There are two kinds of entities: static and dynamic. Static entities (for example, atoms, molecules, and solar systems) maintain structure because they exist in energy wells—and hence have less mass as an aggregate than their components.

Dynamic entities (for example, living organisms, social and political organizations, and, strikingly, hurricanes) maintain structure by using energy they import from outside themselves. Because of the flow of imported energy, they have more mass as an aggregate than the combined mass of their components.

Entities have emergent properties that are defined at the level of the entity itself. That a government is democratic or that a diamond is hard are properties defined at the level of the government or the diamond. They are not properties of the components of a government or a diamond.

15 Paul Humphreys (1997) suggested a similar notion, which he called fusion. The following is Timothy O’Connor’s summary (2006) of Humphreys’ position.

“[Emergent properties] result from an essential interaction [i.e. fusion] between their constituent properties, an interaction that is nomologically necessary for the existence of the emergent property.” Fused entities lose certain of their causal powers and cease to exist as separate entities, and the emergents generated by fusion are characterized by novel causal powers. Humphreys emphasizes that fusion is a “real physical operation, not a mathematical or logical operation on predicative representations of properties.”

16 See (Abbott, 2007)

17 Speaking poetically one might refer to the energy flowing through a dynamic entity as its spirit. When the energy stops flowing, the entity dies.
4.2 The wonder of entities

One must wonder whether this isn't slight of hand. How can one speak of an entity and discuss its properties independently of its components?

Do entities spring into existence fully formed? How is that possible? Because this seems so mysterious, one may be tempted to speak of mechanisms for self-organization. We see this as a distraction. There is nothing mysterious about how entities form. Static entities form as a result of well understood physical reactions: atoms are created from elementary particles; molecules form from atoms; etc. Dynamic entities also form as a result of natural processes. Governments form when people create them—either explicitly or implicitly. Hurricanes form when the atmospheric conditions are right. Self-organization is not the point.

The marvel of entities is not in some seemingly magical process of self-organization; the marvel is that entities exist at all and that they have properties and behaviors that in some sense may be described autonomously.

The fact that entities seem to spring into existence in some sense fully formed and that they have properties that seem to be defined self-referentially is the basis of the argument from Intelligent Design. How can something that is altogether new and has altogether new properties appear apparently from nowhere?

One answer—not related to Intelligent Design—is that the “new properties” we attribute to entities are really nothing more than ideas in our minds. Properties as such don’t exist in nature. Entities are what they are no matter what properties we attribute to them. A second answer—also not related to Intelligent Design—is simply to look around and see that it happens. The fact that entities come into existence means that nature provides some way for this to happen. It is our job as scientists to understand it, not to deny its possibility.

In attempting to understand how entities form we encounter the real mystery—a mystery deeper than we can explore in this paper. What it is about nature that allows entities, which in some sense are self-contained, to interact at all? In software we implement interaction with method calls. How does nature do it?

In quantum mechanics primitive elements act as both particles and fields. As fields they interact because they inhabit a common environment of an assumed three-dimensional space—although that doesn’t seem to be the complete answer. However nature

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18 It is still an open question how one might form a biological cell “from scratch.” There is no known mechanism for producing a cell other than through cell division, i.e., from an existing cell. How did the first cell form? We don’t yet know.

19 We discuss below why it is important for systems engineering to distinguish between ideas in our minds and properties of real entities.

20 What is the mechanism, for example, whereby fermions, e.g., electrons, obey the Pauli exclusion principle? What mechanism prevents two fermions (but not two bosons) from occupying the same state?

What about virtual particles and the vacuum? What about quantum gravity? Smolin (2006) argues that we need a background-free theory.
does it, it seems quite clear that entities both exist and interact—and in interacting they often give rise to new entities.

4.3 Emergence and systems engineering

As indicated above, emergence is central to systems engineering. Virtually every important property of an engineered system is emergent. Although we tend to think of human-produced and naturally occurring artifacts as different, emergent properties that result from an engineering effort differ from those that occur in nature only in that they are produced intentionally.

Yet there tends to be a significant difference between these two kinds of systems. Human-built systems are often functionally fragile; their emergent properties don’t hold up as robustly as we would like. Naturally occurring systems tend to be more robust, flexible, and adaptable. Why is that?

One reason is that human engineered systems are typically built using a top-down design methodology.21 We tend to think of our system designs hierarchically. At each level and for each component we conceptualize our designs in terms of the functionality we would like that component to provide. Then we build something that achieves that result by hooking up subcomponents with the needed properties. Then we do the same thing for the subcomponents. Etc.

This is quite different from how nature designs systems. When nature builds a system, existing components (or somewhat random variants of existing components) are put together with no performance or functionality goal in mind.22 The resulting system either survives in its environment or it fails to survive.

This approach doesn’t necessarily make nature a brilliant designer. Some of nature’s designs suck,23 and some are wonderful. But what’s significant about how nature designs systems is that nature never has to satisfy a requirement.24

Of course systems engineers don’t have that luxury. But is there anything we can learn from how nature develops designs that we can apply in our work?

5 Externalizing our thoughts

A useful way to think about the difference between systems designed to satisfy requirements and naturally occurring systems is that requirements-based systems typically result from an attempt to externalize our thoughts. We think, “I want a system that does this, this, and that—i.e., with these properties and behaviors.” Dreams of this sort, no matter how dressed up and legitimized in terms of formal requirements are still nothing

22 Nature doesn’t have a mind.

23 Silver (this conference) points to “the panda’s thumb, the placement of the windpipe in front of the esophagus (so that food can go down the wrong tube), traversal of the urethra through the prostate gland (so that if the prostate becomes inflamed and swells, it becomes difficult to urinate)” as examples of bad natural design.

24 Nor does nature have to work within budget and schedule constraints.
but ideas in our heads. Use of the term *nothing but* is intentional. Ideas by their nature can only exist in the mind of someone who is thinking them. That’s all an idea is and can ever be, a subjective experience in the mind of the idea’s thinker.

Yet when our ideas involve systems, we want more from them than just pretty mental pictures. We want material embodiments of our ideas. We want to have the ideas in our heads converted into physical reality. We want to externalize our ideas and to make them materially concrete. And we often succeed—spectacularly. Much of what we experience in our post-modern 21st century lives is the result of successfully externalized thought.

But let’s consider what it means to externalize a thought. There is no *externalize button* on our foreheads which, when pressed, causes our ideas to materialize as physical reality. One cannot simply imagine something and expect a material embodiment of it to spring into existence. Furthermore, even when we do build something that reflects our ideas, it is impossible to create an external replica of a thought. Anything outside our heads is different from something inside our heads. Nothing outside our heads is an idea. The best we can ever do in externalizing a thought is to create something that we can understand as representing—or better yet embodying—that thought.

### 5.1 Molding reality to resemble thoughts

Consider a word processing computer program. We design word processors to (appear to) operate in terms of characters, words, paragraphs, etc. Characters, words, and paragraphs are ideas. Word processors operate (when described at one reasonable level of abstraction) in terms of character codes, sequences of character codes bounded by white space character codes, and sequences of character codes bound together as what the word processor may internally refer to as a paragraph data structure.

What we do when we attempt to externalize an idea is to mold elements of physical reality into a form onto which we can project the idea we want to externalize. That’s all we can ever do. We can never do more than mold existing reality.

But even though we cannot incarnate our ideas as material reality, we can mold physical reality in such a way that it has—or at least appears to have—properties a lot like those of the ideas we want to externalize.

Thus there is always a tension between (a) building something out of real physical substance (even if that substance involves bits) and (b) externalizing one’s thoughts about what one wants.

This tension is easiest to describe with respect to software—but it is true of every constructive discipline, including systems engineering. When one writes software, one is writing instructions for how a computer should perform. That’s

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25 This, of course, is the engineer’s credo.

26 My wife, an English professor, objected to my claim that word processors don’t work with paragraphs. They do such a good job of manipulating text in a way that corresponds to her sense of what a paragraph is, that she wants to credit them with working with actual paragraphs.
all that one can ever do: tell a computer first to do this and then to do that. The this and that which the software tells the computer to do are the computer’s primitive instructions. But what we want in the end is for the computer’s this-ing and that-ing to produce a result that resembles some idea in our heads.

Thus in software (as in any engineering discipline) our creations always have two faces: a reality-molding face whereby the software tells the computer what to do and a thought externalizing face which represents our ideas about what we want the result of that molding process to mean. The eternal tension is to make these two faces come together in one artifact.

5.2 Thought externalization in computer science

Because software can be about an extraordinarily wide range of possible thoughts, computer science has had to face the reality-vs.-thought confrontation more directly than any other human endeavor. And possibly because software as text seems to be the only example of an artifact that directly embodies both aspects of this tension, computer science has been relatively successful in finding ways to come to grips with this problem.

Computer science has developed languages in which we can both express our thoughts and control the operation of a computer. We invented so-called higher level programming languages (Fortran being one of the earliest) in which one could write something like mathematical expressions which the computer would evaluate. We invented declarative languages (Prolog is a good example) in which one could write statements in something like predicate calculus and have the computer find values that make those statements true. We combined Prolog and Fortran when we invented constraint programming (which has not been as widely appreciated as it deserves) in which one can write mathematical statements of constraints which the computer ensures are met.

We invented relational databases in which one can store information about entity-like elements—along with their attributes and their relationships to each other. We invented languages that allow one to query those databases more or less on the level of that conceptualization.

We invented object-oriented programming languages—which led naturally to agent-based and now service-oriented environments—in which one writes programs that (seem to) consist of interacting entities.

At the application level, virtually every computer program—from a payroll program to a word processor to an image processing program—embodies an ontology of the world to which that application applies.

To help us write application programs we invented tools and frameworks that define meta-ontologies within which one can create a desired ontology.

We did all this by writing programs that tell computers first to execute this instruction and then to execute that instruction. The gap between the underlying computer and the languages in which we write programs is often enormous. But that doesn’t mean that we can forget about the computer. No matter what else it is, and no matter how well our programs (seem to) express the thoughts in our heads, a program is
nothing unless it tells a computer which instructions to execute and in what order. In the end, that’s all a computer program is: a means to tell a computer what to do.

Computer Science has been called applied philosophy: one can think about virtually anything as long as one can express those thoughts in a form that can be used to control the operation of a computer.

I like to think of the computer as a reification machine: it turns symbolically expressed abstract thought into concrete action in the physical world. As a reification machine, the interface between thought and action is the computer program.

When we write in a programming language we are expressing our thoughts to the extent allowed by the programming language.

When a computer reads what we have written, it takes our writings as instructions about what operations to perform.

We have developed programming languages that come close enough to allowing us to express our thoughts well enough that the resulting programs, when executed, can be identified with those thoughts.

5.3 Thought externalization in systems engineering

Systems engineering is just beginning to focus on this issue. Model-based development, e.g., SysML, attempts to allow systems engineers to think in a language that both expresses our thoughts and represents how we mold reality. But systems engineering is at a significant disadvantage. In computer science we write in languages that control real computer.

There are no systems engineering languages that generate real physical systems.

When one writes a computer program, loads it into a computer, and presses the Start button, the computer becomes the program we have written. There is nothing comparable for systems engineering. We don’t have a systems engineering language and a device into which descriptions written in that language can be loaded that will become the system the language is describing once one presses a Start button.

The closest systems engineering can come to this dream is to write in a language that represents a model of a physical system. But models aren’t reality. Programming languages succeed because they are grounded in the reality of an actual computer executing actual instructions. Models, by contrast, are always divorced from reality. One can’t ever model all aspects of a system. So one chooses what one considers the most important aspects and models them. But that’s always dangerous. See the discussion below about the difficulty of looking downwards.

6 Dissipative systems

Systems engineers tend to build special kinds of entities which are intermediate between static and dynamic entities. Prigogene coined the term dissipative system (see, for example, 1997) for a

Fred Thompson, one of my early mentors, is now Emeritus Professor of Applied Philosophy and Computer Science at Cal Tech.

UML is an unfortunate step back from computer science’s traditional loyalty to executable languages.
static entity that exhibits regularities when energy is pumped through it.\(^{29}\) Most of the widely cited examples of dissipative systems consist of relatively unstructured static entities which exhibit somewhat surprising structures, e.g., Rayleigh-Benard convection patterns, when they are forced to respond to energy inputs.

But virtually any static entity will exhibit some response to an energy flow—especially when that energy flow is both sufficient to have some noticeable effect on the entity and moderate enough not to destroy it. Much of what engineers build, e.g., automobiles and computers, are static entities whose (necessarily dissipative) responses to energy flows are in some way useful to us.

### 6.1 Dissipative systems vs. dynamic entities

A dissipative system is intermediate between a static entity and a dynamic entity in that it consists of a static entity skeleton (which is more or less stable without an energy flow) through which one pumps energy. Dynamic entities do not have such stable static skeletons. Dynamic entities depend on their own ongoing processes to maintain their structures.\(^{30}\) A living organism, a hurricane, or a government would not persist even as a skeletal structure without a continual flow of externally supplied energy.

By working primarily with dissipative static entities engineers save themselves from having to build systems that are continually rebuilding and repairing themselves. But the price for that convenience is that the systems we build are not self-persistent.

### 6.2 Self-persistent dynamic entities

To date, we don’t know how to build systems that persist on their own. To the extent that we try it at all, our approach tends to be backwards: design a dissipative static entity and then add features to it that might allow it to repair itself. That isn’t how naturally occurring dynamic entities work. Most naturally occurring dynamic entities are built to be self-persistent—although not eternal—from their core. A hurricane by its very functional structure maintains that structure. The same is true for a government and a living cell.

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\(^{29}\) That’s my summary of what a dissipative system (also known as a dissipative structure) amounts to.

\(^{30}\) See (Abbott, 2007) for a more detailed discussion.
autonomous, but involves [pre-existing] enzymes or regulatory molecules that link [developing elements] to the larger whole. But there are three more fundamental rea-
sons ... First, some cellular components are not fashioned by self-assembly, par-
ticularly the ... cell wall which resembles a woven fabric and must be enlarged by cut-
ting and splicing. Second, many membrane proteins are oriented with respect to the mem-
brane and catalyze vectorial reactions; this vector is not specified in the primary amino acid sequence, but is sup-
plied by the cell. Third, certain processes occur at particular times and places, most notably the formation of a septum at the time of division. Localization on the cellular place is not in the genes but in the larger system. Cells do assemble themselves, but in quite another sense of the word: they grow.\textsuperscript{31}

Strange as it may be to use this term, compared to a cell a hurricane is somewhat ethereal or insubstantial. Hurri-
canes have no material structural framework that holds them together. Cells clearly do. Because hurricanes have no structural framework they would appear not to be a good candidate as a starting point for additional functionality: there are no attachment points for adding anything on.

A related and perhaps even more significant difference between hurricanes and cells is that a hurricane has no DNA. Contrary to the popular image, DNA is not an internal representation of a cell’s (or any biological organism’s) design. A more appropriate way to un-
derstand DNA—along with the machinery that accompanies it—is as an internal “factory” that converts raw materials into the physical stuff out of which a cell’s (or more generally a biological organ-ism’s) material framework is composed.

As Harold points out, DNA does not in-
struct a biological organism how to use the proteins that are generated; it con-
tains no master plan for the cell. DNA and its associated mechanism simply generates the proteins, whose disposi-
ton is taken care of outside the DNA mechanism.\textsuperscript{32} Hurricanes have no similar manufacturing core.

It would seem that if we are to build self-
persistent systems, the first step is to learn how to build minimal dynamic enti-
ties that have as their core (a) a means for converting available raw materials into the substances needed to create and maintain the physical structure of the entity and (b) mechanisms for using those materials for self-persistence.

Once we learn how to build physical enti-
ties that have such self-persistence as a core process, perhaps then we will be able to figure out how to add additional functionality to them. Our DNA mecha-
nism, for example, produces hemoglo-
bin, which is not used for individual cells. It would appear, though, that the core mechanism of self-persistence must be in place first before we work on using it to support additional functionality.

In the mean time, we are stuck with dis-
sipative static entities.

\textsuperscript{31} Recall our previous discussion of self-
referential entities. This passage illus-
trates how self-referential cells are.

\textsuperscript{32} Of course DNA and its associated mechanism is also responsible for deter-
mining which proteins are generate and when they are generated—all of which plays a major role in how the proteins are used.
7 Service-oriented design

Much of what succeeds in nature consists of processes that build on other processes. Food web analysis illustrates how species depend on other species. Ecologies are built on seasonal cycles and resources flows (energy from the sun being the most basic but ocean and river currents being other examples). A species, a seasonal cycle, and a resource flow can all be understood as emergent phenomena. In other words, nature builds new emergent phenomena on existing emergent phenomena.

When this happens in an ecological system, we call it *succession*—a territory proceeds though a series of relatively stable stages. At each relatively stable stage, the species that populate that stage depend on each other and on the other aspects of the environment.

Progression occurs either because something disturbs the status quo and destroys some of the structures on which some of the participants depend or because there is an inefficiency in the system that can be exploited by some new mechanism.

This is pretty much the same picture one sees in a market-based economy. A collection of products, services, and community-supplied infrastructures (such as a monetary system, a postal system, a judicial system, etc.) develops into an ecology of mutual dependencies. Such a system remains stable until either a disturbance destroys something on which part of the system depends or a new invention draws off some of the existing energy.

Natural ecologies and market economies are both examples of what we call innovative environments—which we discuss below. In this section we focus on how such environments work and how the principles underlying how they work may be applied to system design.

The fundamental principle of innovative environments is that new things are built on top of existing things. Because we have a well-developed transportation system, for example, we can produce products in one location and move them to other locations to be consumed—or otherwise used. One doesn’t have to develop the transportation system from scratch in order to establish a off-shore production facility.

This web-of-interrelationships perspective has implications for systems engineering from two perspectives.

7.1 Products and services evolve

Even though most marketed products and services tend to originate as externalized thought, well-managed companies are always looking for new applications of their products—even applications that have little to do with the originally conceived market. In other words products and services evolve to fit their environments.

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33 See (Abbott, 2006) and (Abbott, 2007).

34 See, for example, http://www.mansfield.ohio-state.edu/~sabedon/campbl53.htm.

35 This resembles what on an evolutionary scale we refer to as punctuated equilibrium. The difference is that in succession outside species replace existing species in a habitat. But the outside species are not generally created as new species.

36 We have all encountered the now familiar version progression among software products. Version 5.0 is frequently quite
Products and services that survive over the long term are not stuck attempting forever to implement the original vision of what they were intended to be. A product or service may have been born of externalized thought, but the original externalized thought is not considered a constraint on the evolution of the product or service. It’s the environment that determines how a product or service will evolve.

In order for a product or service to evolve, its design must support change. If a system is designed in such a way that modification of that design is not feasible, it will die. Thus any system that is expected to survive over the long term must have evolvability as a primary design consideration.

Unfortunately, we tend not to build systems this way. Customers often want a set of functional requirements satisfied as inexpensively as possible. Normally that entails sacrificing design flexibility and evolvability for a rigid focus on specific functionality.\(^{37}\)

Furthermore, for a product or service to survive it must be robust. We don’t build products for robustness except to the extent that the requirements specify a specific degree and form of robustness. Of course one aspect of robustness is to survive the unanticipated. So in some sense requiring robustness is a self-contradiction.

### 7.2 Products and services are built on top of an established base of other products and services

The second and perhaps more significant lesson to be learned from the web-of-interrelationships perspective is that when building something new it’s a good idea (actually more than just a good idea) to make use of existing products and services. This is quite different from how most of our systems work.

As we said earlier, we tend to build systems hierarchically. We formulate a top-level design that meets top level requirements and then determine what components we need to implement it. We then decide how to build the components in terms of sub-components, etc. This approach doesn’t take advantage of existing products and services except when we use standard parts—and we do that too rarely.

A hierarchical design approach has (at least) two disadvantages. Firstly, it tends to result in what have been called stove-piped systems—systems that may work successfully on their own but that are very difficult to use in conjunction with other systems. That such a consequence will occur is quite understandable. When a system is built from the top-down without regard to what else exists, it is likely to be incompatible with other systems.

\(^{37}\) This is one reason why it is a bad idea for a customer ever to buy a major system. If the system developer has a financial interest in seeing the system flourish over the long term, that developer will (presumably) design it to allow it to evolve. In contrast, a customer, who has no idea about these sorts of things, cannot define evolvability as a requirement. (We don’t know how to do that in any case.) Even if the customer could require evolvability as a product property, he or she would probably not be in a position to exploit it. After all it is the developer who is on the lookout for new uses of the system, not the individual customer.
Secondly, the internal design of such systems tend to be rigid in the same way. Just as a hierarchically designed system isolates itself from other systems, the system components of a hierarchically designed system isolate themselves from other system components. Hierarchical design results in stove-piping both inside and out.

The alternative is to take advantage of what exists and build on top of it. In software there are now innumerable tools, frameworks, components, and libraries (both open source and commercial) that serve as the basis for further development. The prototypical example of building on top of existing products and services is a service-oriented architecture (SOA). Service oriented architecture is a nice example because it illustrates how systems can be built on top of existing elements at both the system-to-system and internal design levels.

Through an SOA, systems can provide services for other systems. Similarly system components can provide services for other system components through an SOA. In both cases, one is building on two foundations: (a) the network itself as a service (e.g., a level of abstraction) that all elements that reside on it use and (b) the design principle whereby elements provides service for each other.

It’s a positive development that service-oriented and net-centric architectures are becoming desirable attributes within the systems engineering world. But it’s important to remember that SOA and net-centricity are examples not principles. The principles are (a) to build upwards on top of existing capabilities and at the same time (b) to conceptualize whatever we are building not as an end in itself but as a service that others will use.

### 7.3 Dynamic entities need energy to persist

The second principle captures one difference between most systems engineered systems and systems that appear either in nature or in a market-based economy.

The systems we are talking about are almost all dynamic entities. They are not just static objects, they generally do something as a result of energy flows. Even static objects, such as a bridge, require maintenance. The real system is not just the static bridge. The real system is the bridge along with the maintenance process that keeps the bridge in good repair. When understood from

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38 The term *level of abstraction* is sometimes used to characterize the use of an abstract specification of a service as part of a design.

39 This is a design fad that has staying power. It’s useful to think of our entire economic system as a service oriented architecture: every economic transaction is essentially a service transaction. The SOA nature of our economic system is one of the reasons it is both strong and agile.

40 Hence SOA provides a natural framework for exploring system-of-systems issues.

41 This perspective explains the Thesius’ ship paradox: is a ship maintained in port so long that all its parts have been replaced “the same ship” as the original? The answer is that the ship maintenance process is the same entity (even if it involves numerous people cycling though it—a property of entities). The physical
that broader perspective, it’s clear that most of the systems that systems engineers build are dynamic entities.

Dynamic entities persist only as long as the energy that flows through them continues to flow. For a business, which is also a dynamic entity, money is a proxy for energy. A business exists only while the money flowing into it is at least as large as the money flowing out of it.

Unfortunately, it very rare that we ask ourselves about the energy flows needed for the persistence of the systems that we are asked to build. Long term energy flow considerations (i.e., funding) should be fundamental to any system development project. But it generally isn’t. Because it isn’t we don’t think about systems in terms of what it would take to make them self-persistent.

This is not to say that every system must be profitable in the traditional sense of profitable. Many of our systems, e.g., our judicial and monetary systems are both so central to the functioning of our society and so ill suited to be funded by their direct customers that we properly treat them as a commons. Commons too must be funded, but they are funded in different ways from most entities.  

But whether the system we are building is expected to be a commons or self-sustaining, we must understand from the start how the energy flow required to allow it to sustain itself will be provided.

In business the answer to this sort of question would be recorded in a business plan. In systems engineering we don’t have a name for where we record answers to these questions because we rarely ask these questions.

8 Feasibility ranges
Emergence occurs within feasibility ranges. A visible and tragic illustration of this is the Challenger disaster in which the O-rings lost their (emergent) sealant property because the temperature was too low.

Since there are always feasibility ranges for emergent properties we should make it standard practice to identify and determine the feasibility ranges of each emergent property we expect our system and system components to display. For each emergent property we should explain why its feasibility range won’t be violated—and what happens if it is. Had this been done for the Challenger, we would not have lost our astronauts.

For computer and software systems, feasibility range concerns typically involve such issues as data rates, access rates (for quality of service issues), data storage demands, assumed data (and other input) ranges and limits, computational demands, accuracy assumptions, and precision needs. In software these are often lumped together as performance (as distinguished from functionality) issues.

Although many of these issues are not new, it is useful to see them as instances as the more general category of emergence feasibility ranges and to be aware that feasibility range issues arise throughout our systems.

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42 Elinor Ostrom (1990) began the modern era of understanding how successful commons function.

43 See (Abbott, 2006).
Feasibility range issues are often orthogonal to other design considerations. The term *cross-cutting* is typically applied to such situations. In software, aspect-oriented programming (and in some cases creative application of constraint programming) may be used to handle cross-cutting issues. I am not aware of a standard approach for handling cross-cutting issues in systems engineering.

9 Modeling and Simulation

9.1 For want of a nail ...

An important characteristic of most complex systems is that they are multiscale. Every system that exhibits emergence exists on at least two scales, the scale at which the emergent property appears and the scale at which the emergent property is implemented. Often there are many more scales. This is especially true when emergence is built upon emergence, as it often is. The poem telling the story of how a missing horseshoe nail led to the loss of a kingdom illustrates the potential significance of multiscale phenomena.

Much of the work in systems engineering relies on the results of simulations. We build models of possible system designs, and we run them, watching what happens as we vary the parameters.

Even with our advanced modeling and simulation capabilities, however, it would be virtually impossible for us to model all the nails in all the horseshoes on all feet of all the horses ridden by all the men in King Richard’s army. Certainly we can’t do anything remotely like that if we were to model today’s massively larger systems.

Since we depend profoundly on simulations, and since we are unable to simulate our intended systems at the many scales at which we build them, and since multi-scale phenomena pose a potential threat to successful systems engineering, what are we to do?

This is a major research issue and one for which I have no answer. In (Abbott, 2006) I called this the difficulty of looking downward. The first step, though, is to recognize that we have a serious problem.

9.2 For want of imagination ...

Imagine (unrealistically) that we were able to simulate our air transportation system and everything else relevant to how airplanes are used and maintained in this country. Would that capability have helped prevent 9/11?

My answer is “No.” The problem is that 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.

Earlier we urged that new systems be built on top of existing capabilities. That’s exactly what the 9/11 terrorists did. They used the capability provided by the airlines of carrying and delivering large amounts of explosive material to virtually any location within the country. All the terrorists had to do was to take over the planes at the critical times—a brilliant example of using an existing capability to produce a new capability.

We know how to write simulations in which emergence occurs. Any agent-based model is capable of fostering emergence. But we don’t know how to write simulations that will recognize that emergence has occurred and issue a
report about it. In (Abbott, 2006) I called this the difficulty of looking upward.

10 Innovative environments
As we have seen, emergence occurs in a wide range of situations. Four environments that are justifiably celebrated for an outpouring of emergent products, services, and other phenomena are the Internet (in particular the World Wide Web), the U.S. (and now global) market-oriented economic system, our system of scientific research, and biological evolution. We mentioned or alluded to some of these earlier.

Although quite diverse in their underlying domains, all four have been extraordinarily fruitful and have fostered an ever-broadening flow of innovative products, services, and other elements.

Transformation in the Defense Department—including capability-based acquisition, net-centric operations, and service oriented architectures—has been motivated at least in part by a desire to produce similar benefits within the DoD.

Although it is widely believed that environments that enable and facilitate emergence share some common characteristics, we have no universally accepted list of exactly what those characteristics are or why they matter. Whichsoever characteristics appear on a final list—if there is a final, definitive list—the following (or variants thereof) are likely to be candidates.

1. **Access to a supply of externally provided energy and means for exchanging it.** All environment that foster emergence are what is commonly known as far from equilibrium: externally supplied energy continually flows through them. The overall creative process can be summarized as consisting of finding increasingly innovative ways of using the available energy. To facilitate this process, mechanisms must be available to support the fungibility of energy and its proxies such as money, power, and attention.

2. **Standards.** New products, services, and other items are almost always created from existing products, services, and other items. Composition is greatly facilitated when the elements to be composed adhere to widely accepted standards. Standards facilitate the composition of products and services to produce new products and services.

3. **Communication and transportation infrastructures.** Communication and transportation infrastructures facilitate the exchange/transfer/flow of (a) information throughout the environment and (b.1) energy (in one direction) and (b.2) products and services (in the other) among trading partners.

4. **A reasonable level of confidence in the stability and continuity of the products and services installed in the environment.** Mechanisms must be available to allow agreements to be made and for installed products and services to be relied upon.

5. **Minimum overhead.** Cultural or other mechanisms must exist to discourage corruption along with enforcement mechanisms to make it harder to siphon off energy flows for non-productive uses. More generally, the environment must incorporate mechanisms that minimize the overhead of participating in the environment.
6. Both (a) centralized but quasi-democratic and transparent governance of the overall system, its infrastructure, and the standards making process and (b) decentralized overall control (“power to the edge”) in which as much autonomy as possible is ceded to environment participants.

7. Mechanisms that ensure that a certain amount of the available energy is devoted to the exploration of the space of possible new elements. There must be some means to encourage the exploration of new possibilities.

8. Mechanisms that allow new products and services to be developed and installed in the environment and then made known to other participants in the environment.

9. A primarily bottom-up means for allocating energy (or its proxies) according to use: the more (less) useful a product or service is found to be (according to actual usage), the more (fewer) resources it will have at its disposal. This implies a market-like means for allocating most of the resources available in the environment. All of the participants in the environment must be self-sustaining in terms of their overall energy transactions. Since the environment itself is predicated on an external source of “free” energy, this should be possible.

10. An ability to form communities of interest (formal, informal, voluntary, and fee-based) to facilitate the sharing of information, experience, and expertise. The value of shared information is typically enhanced when it is shared in groups.

11. Both (a) sufficient stability of the overall environment that participants can establish regularized modes of participation and (b) (generally collaborative) means to allow the environment to evolve as conditions change. This implies treating the environment as a commons and finding a successful way to govern it as such.

11 Summary
Innovative environments are important to systems engineering for at least three reasons.

1. We want the systems we build (or at least many of them) to be innovative environments. Look at how the example of the internet has inspired transformation in the DoD. We want the other systems we build to further enable that vision and to provide additional innovative environments for our customers.

2. We want our own processes to be innovative. As we build systems, we want to encourage innovation among our analysts and developers.44

3. We want our own intellectual environment to be innovative. Systems engineering is constantly innovating; it has never stood still. This symposium is an example of continued vigor. We want to encourage innovation in our systems engineering community.

As we understand more about how to make environments innovative, we will be able to approach all three of these goals.

44 See Horowitz (this conference) for an example.
In this paper we have taken a brief tour of the landscape of emergence and explored how it may be useful to systems engineering. We hope that the ideas presented here will be useful to the systems engineering community.

References


