Complex-System Engineering

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Abstract

This paper proposes recognizing complex-system engineering as the second branch of general system engineering – alongside traditional system engineering.

There are problems for which the problem solving template of traditional system engineering is not appropriate – problems that continually change as they are being addressed, or that must be conceptualized at multiple scales in order to be fully comprehended, for example. Such problems are, however, amenable to solution using another problem solving template that is also faithful to the fundamental predicates of general system engineering. This is the template of complex-system engineering. Its developmental methods are summarized as the regimen of complex-system engineering.

Understanding both the similarities and the differences between the problem solving templates of traditional system engineering and complex-system engineering requires an explicit appreciation of the three propositional predicates that underpin general system engineering. These are explicitly formulated and then used to juxtapose and distinguish traditional system engineering and complex-system engineering. Emphasis in the discussion, however, is given to the proposed new branch of general system engineering, complex-system engineering.

1. INTRODUCTION

Complex-system engineering (cSE) should be recognized as a second branch of general system engineering (GSE). Currently there is only one branch of GSE. That branch is known as "traditional" system engineering (TSE).

GSE itself is just one branch of engineering, and all of engineering is about solving problems. More fully, engineering is about actually realizing solutions to problems, not just imagining what a solution might be. The TSE branch of GSE employs a well understood template for solving problems. This template doesn't always work. cSE provides an additional problem solving template.

Both templates should be considered expressions of a more general template that can be associated with GSE. The cSE and TSE templates of GSE are distinctive, however.

The overall GSE problem solving template rests on three propositional predicates:

- Any problem can be understood in terms of a system that is a solution to the problem. In this sense a system is the realized equivalence of a problem and its solution. Knowing what a system is is the *sine qua non* of system engineering.
- The solutions to non-trivial problems do not instantly appear and disappear. The realizations of solutions to problems (as systems) exhibit life cycles.
- The realizations of solutions to non-trivial problems involve a melding of multiplicities.[1]

This concise summary of GSE's three propositional predicates is not currently available in the general literature.

It should not be assumed that no one is practicing GSE beyond the bounds of TSE. Many engineers are, albeit in an ad hoc and informal way. For example, practitioners of such an expanded GSE (although not explicitly termed as such) recognize that pursuing precision or exhaustive completeness often distracts from, or delays, or even frustrates rather than contributes to working solutions. Precision and completeness are important in the practice of good TSE.

Practicing GSE in this ad hoc fashion amounts to applying the fruits of hard won personal experience as "rules of thumb." Rules of thumb seem to work most of the time – even though the reasons for why remain elusive. GSE has now reached a point in its own development at which it is increasingly necessary to appreciate why and when (and when not) these rules of thumb work, and whether or not there are other methods applicable to situations like those in which these rules of thumb seem to work. One way to do this – and thereby to distinguish between TSE and cSE – is to revisit the three propositional predicates of GSE.

[1] Underlined terms are explicitly elaborated later in the text.

The differences between TSE and cSE can be understood as differences in the way that a system is (or should be) conceptualized; as differences in the life cycles that account for their realization; and as differences in the multiplicities that must be melded, and how that melding is accomplished. These differences account for the different problem solving templates of TSE and cSE.

Section 2 examines the notion of a system. As noted above, this notion is central to GSE. This section summarizes a substantial refinement in the way that any system is defined, and then it restates this notion of a system from the perspectives of both TSE and cSE.

Section 3 looks at the notions of life cycles and the melding of multiplicities. There is a strong reliance in this section on the reader's familiarity with these topics, especially as they are interpreted as part of TSE. As a consequence most of the discussion in this section focuses on how these two predicate propositions are interpreted in cSE. TSE and cSE are also briefly compared.

Section 4 looks briefly at the analytical notions apropos to complex-systems. The processes of evolution are identified as central in this regard – but there are many other concepts that deserve attention as well.

Section 5 focuses on the regimen of cSE. The regimen is the overall approach to synthesizing complex-systems by intervening in the processes of evolution that dominate the self-directed realization of such systems. The intervention serves to focus and accelerate the otherwise normal course of events in the self-directed development of complex-systems.

2. A SYSTEM

The notion of a system, although central to GSE, is still very loosely defined in the contemporary literature.[2] This often leads to ambiguity and outright confusion – although many commentators continue to view this looseness as an advantage! In order to appreciate the differences between TSE and cSE, an improved definition for a system is essential. Such a definition has to be able to deal with what is called here the multi scale aspects of almost any system; and it has to continue to allow for the expression of the structural, the substantive and the dynamic aspects of a system. All of these considerations are important if a system is going to be realized.

This topic (defining a system) is covered more extensively in a MITRE technical paper MTR 06B0000060, *A Multi Scale Definition of a System*, portions of which were presented at the International Conference on Complex Systems, 2006 (ICCS 2006). What is provided here is based on that paper.[3]

For a system engineer, a system has to be a part of reality – so that a real world problem can be solved. But a system also has to be conceptualized. A system also has to be "in the head" of an engineer, as it were, so that an engineer can think about the system. An engineer generally thinks about a system in terms of its structure and substance, and its dynamics or behavior (or what the system does). The reality of a system and the conceptualization of a system are different manifestations of the same system; but they are not independent. And one is not simply the reflection of the other. In particular, the system "in the head" of an engineer is not simply a reflection of the system as it might exist in the real world. The purpose of a system, for example, (the reason or motivation for what a system is, or why a system does what it does) exists only in the head of the engineer. This is just one facet of the "entanglement" of the objective (real world) and the subjective (humanly conceptualized) aspects of a system. Despite this entanglement, it remains worthwhile to consider these objective and subjective manifestations of a system as separately as possible.[4]

Objective and subjective reality will be treated as disjoint here, so a vocabulary is needed to explicitly capture what can only be *assumptions* about objective reality. These assumptions include that objective reality has an extent and a richness that can be

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[2] Most of the relevant literature is a discussion *about* systems with little attention given to defining the term. The **Encyclopedia Britannica** defines a system as a regularly interacting or interdependent group of items forming a unified whole. The **IEEE** defines a system as a collection of interacting components organized to accomplish a specific function or set of functions within a specific environment. **INCOSE** defines a system as an integrated set of elements that accomplish an explicit objective. **DSMC** defines a system as an integrated composite of people, products and processes that provide a capability to satisfy a stated need or objective.

[3] Kuras, M L; *A Multi Scale Definition of a System*; MITRE; 2006.

[4] The reader is encouraged to consider the ideas of Erwin Schrödinger in chapter 3 of his little pamphlet, *Mind and Matter*, first published in 1958. This entanglement of the subjective and the objective can be ignored, of course. But if the influence of this entanglement is *not* insignificant then the practical utility of courses of action predicated on notions ignoring this entanglement will be jeopardized. As conceptual notions of reality are better understood, this cautionary remark becomes increasingly relevant. This applies, of course, to methodical problem solving – the essence of all engineering.

distinguished and differentiated. Extent and richness refer, respectively, to the immeasurable expanse of the soup of objective reality and to the uncountable details that might be found anywhere in that expanse. These terms or assumptions should not be construed as exclusively spatial. They should also be construed as temporal, acoustical, geometric, emotional, etc. The terms are meant to span all features of objective reality.

A vocabulary is also needed to discuss human conceptualizations of reality. A human conceptualization of reality has three fundamental attributes that can be called its **Scope** (SCP); its **Resolution** (RES); and its **Content**.[5] Briefly, SCP and RES capture, respectively, a conceptualization's inclusiveness and its granularity. They correspond to how much of the extent of objective reality can be captured in a conceptualization and to how much of its richness can be captured.[6]

The Content of a human conceptualization can be distinguished and differentiated. **Patterns** are the most general way to discuss this. Patterns make up the entire Content of a human conceptualization of reality. Patterns are configurations of similarities and differences in the "irreducible quanta" of any given conceptualization.[7] A system is *a portion of* the patterns that make up *one or more* conceptualizations.

The link between objective reality and human conceptualizations are the **Modalities of Conceptualization**. Six are identified in *A Multi Scale Definition of a System*. They label features of the functionality of the human brain (thinking or conceptualizing) without positing explanations for these features. A conceptualization (its SCP, its RES, and its Content) is the consequence of the operation of these Modalities of Conceptualization.

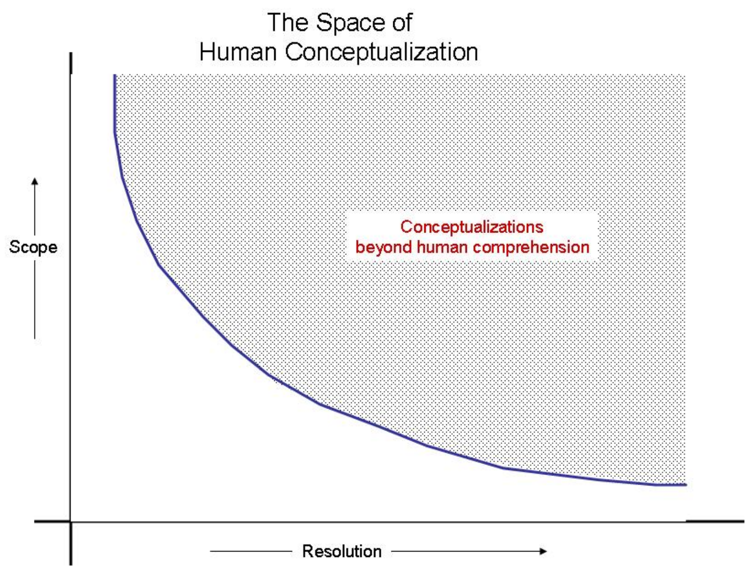
These Modalities of Conceptualization can be understood themselves as consequences of the operation of the human brain. The human brain, or its capacity and capability, is not unlimited. It is bounded. It is finite. These limits impose limits on conceptualizations. But these imposed limits are very difficult to recognize or acknowledge since they are intrinsic to human thinking or conceptualizing, per se. These limits are important, nonetheless. They guarantee, for example, that there actually are "irreducible quanta" in any conceptualization – since all conceptualizations are finite.

There is an even more important consequence.

The range of possibilities *for any one conceptualization* can be thought of as a 2-dimensional space of points where each point represents a particular SCP and RES, denoted as <SCP, RES>. The human conceptualization of reality involves establishing a correspondence between a particular <SCP, RES> and what is sensed (directly or

[5] In *A Multi Scale Definition of a System*, Scope is termed Field of View. This phrase, unfortunately, has suggested for some, that conceptualizations are visualizations. They are not.
[6] A discussion of any distinction between "real" and "imagined" conceptualizations is beyond this paper. Doing so requires revisiting the disjoint distinction between objective and subjective realities that has been asserted.
[7] In *A Multi Scale Definition of a System*, these "irreducible quanta" are discussed as properties and relationships and their aggregations.

indirectly) of the extent and richness of reality. The range of possibilities can be denoted as the space of such points, {SCP; RES}.



The bounded capacity of the human brain imposes limits on SCP and RES and on establishing any correspondence between some <SCP, RES> and some portion of the extent and richness of reality. The SCP and the RES of a conceptualization cannot be increased indefinitely. Not all the points in the 2-dimensional space {FOV, RES} are available. These unavailable points would correspond, as it were, to conceptualizations beyond human comprehension. This is represented in the figure above as the hatched region.[8] *There are aspects of objective reality that are beyond direct human conceptualization.*

The human brain, however, has a way to partially compensate for the limits to a conceptualization imposed by its bounded capacity to conceptualize. It is termed here changing scale**.**

All of the patterns in all humanly possible conceptualizations of reality can be designated as a set, $\{\text{pattern}_c\}$, where pattern_c designates a particular pattern, and $c \in C$ where C is an index set for the enumeration of all the patterns in all humanly possible conceptualizations. It is not possible to conceptualize all of these patterns at once, however. This is due to the bounded capacity of a human brain. In other words, $\{\text{pattern}_c\}$ does not correspond to the Content of any human conceptualization.

For any given human conceptualization, the Content of the conceptualization can be designated as a set, $\{\text{pattern}_\kappa\}$, where $\kappa \in K$, and K is a finite index set enumerating the

[8] This figure is only suggestive of any actual interdependence between selections of SCP and RES. More accuracy in this regard awaits future research.

finite set of patterns in the conceptualization. Another set, $\{\text{pattern}_\varphi\}$, can be analogously defined and used to characterize a second conceptualization; and so on. What can be said of such sets of patterns in juxtaposition with one another?

The Content of any given conceptualization might be changed (yielding another conceptualization) by altering its SCP and/or its RES, and/or by altering the aspect of objective reality that is linked to the conceptualization (its subject). (This linking is due to one of the Modalities of Conceptualization called the Focus of Attention.)

The Content of any given conceptualization can be increased in this fashion, but not indefinitely – because of the aforementioned limits imposed on conceptualization. Nonetheless, SCP, RES and Focus can still be changed.

Because of the finite capacity of the human brain, the set of patterns of a first conceptualization cannot always be expanded to include the patterns of a second. A definition of a system must be formulated that explicitly deals with the implications of this basic fact of human conceptualization.

A **change of scale** in conceptualization occurs if the following conditions are met.

$\{\text{pattern}_\varphi\} \cap \{\text{pattern}_\kappa\}$ is not empty (the subject of the conceptualizations overlap).
$\{\text{pattern}_\varphi\} \not\subset \{\text{pattern}_\kappa\}$
$\{\text{pattern}_\kappa\} \not\subset \{\text{pattern}_\varphi\}$

The above is meant to summarize the observation that in many changes of conceptualization there can be the addition, the deletion and the reformulation of patterns so that the Content of one conceptualization does not contain the other *and vice versa* but the overall subject of the conceptualizing is the same.[9]

Explicitly noting overlaps in certain conceptualizations at multiple scales has been given the label of emergence. In any case, if a system is going to be conceptualized, and its patterns are only available at multiple scales of conceptualization, then a definition of a system must account for this phenomenon.

The human brain always has to make a choice of which patterns to include in a conceptualization (focus on). And still, it can continue to toggle between different sets of patterns (different conceptualizations of the same subject). There is a loss of patterns in a new conceptualization as well as the gain or reformulation of others as this toggling occurs. In other words, the conceptualizations at two scales overlap in terms of their Content but neither contains all of the patterns of the other. The patterns at one scale are wholly or partially absent in the conceptualizations at another scale. This re focusing is how the human brain can partially compensate for the seeming limits to its powers of conceptualization due to its bounded capacity.

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[9] The reformulation of patterns that might be involved is not obvious and is discussed in the paper *A Multi Scale Definition of a System*.

As noted above, any system, S, is *a portion of* all humanly possible conceptualizations, $\{pattern_c\}$. This might be written as $S = \{pattern_s\} \subset \{pattern_c\}$, except that the patterns that are S are not arbitrary. They have a cohesiveness and a distinctness that such an expression omits and that is essential in capturing what is meant by a system.

A system, S, is $\{pattern_c\}$ *along with* something called a Holon (H).

$S \equiv \{pattern_c\}; H.$[10]

The Holon selects, aggregates and distinguishes just those patterns that belong to the system. Holons are discussed further below.

Human beings can only conceptualize one scale at a time. (And each conceptualization is at some scale.)

A conceptualization at any one scale always includes some (but not all) of $\{pattern_c\}$. $\{pattern_\kappa\}$ designates all of the patterns included in a conceptualization at a scale, say, ν. $\kappa \in K$, and K is the finite index set that enumerates the patterns at this scale.

$\{pattern_\kappa\} \subset \{pattern_c\}$.[11]

It is possible to augment or to refine the patterns available at any one scale by increasing SCP and RES so that

$\{pattern_\kappa\} \subseteq \{pattern_{\kappa'}\}$ where κ and κ' index two sets of patterns in two conceptualizations at the same scale.

However this is not possible indefinitely. At some point the addition or refinement of patterns in a conceptualization requires the deletion or dilution or reformulation of patterns available in a previous conceptualization. This is a change of scale of conceptualization as noted above.

A system can be conceptualized, if necessary, at more than one scale. At each scale of conceptualization a system is *approximated* by the patterns of S that are available at that scale, ν, and that are subject to the operation of the Holon at that scale. These patterns can be designated S^ν.

$S^\nu \equiv \{pattern_\kappa\}; H^\nu$

where κ is understood to range over only those patterns available at the scale ν, and H^ν is the Holon at this scale.

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[10] Another way to write this might be $S \equiv H(\{pattern_c\})$.

[11] In particular, $\{pattern_\kappa\} = \{pattern_c\}$ is explicitly excluded. It is not a possibility.

In a conceptualization at a given scale, ν, S^{ν} involves a portion of the entire content of the conceptualization. It is never the entire conceptualization. S^{ν} is both a *whole*, and *a part of* another more expansive or inclusive whole. This characteristic (this dualism) has been labeled (by Arthur Koestler) as a **Holon**.[12] By convention, the rest of a conceptualization of which a system is a part is called the system's environment or context. A system's cohesiveness and distinctness at any scale of conceptualization is determined by its Holon at that scale. A Holon can be roughly understood as a conceptualization operator (the expression of a Modality of Conceptualization) that gives cohesion to a specific system (as a whole of parts) and that distinguishes it from the rest of the conceptualization.[13]

In many actual cases, not all of the patterns that constitute a system are available at a single scale of conceptualization. And it is not generally possible to conceptualize combinations of conceptualizations at different scales together. *So multiple scales of conceptualization are required.*

A more complete *definition* of a system has to cover both the overall characterization and the *approximations* available at specific scales of conceptualization.

$$\begin{array}{c}
\mathbf{S \equiv \{pattern_i\};\ H} \\
\text{---------------} \\
\mathbf{S^{\mu} \equiv \{pattern_j\};\ H^{\mu}} \\
\cdot \qquad\qquad\qquad \cdot \\
\cdot \qquad\qquad\qquad \cdot \\
\mathbf{S^{\nu} \equiv \{pattern_k\};\ H^{\nu}}
\end{array}$$

Again, S cannot be *directly* conceptualized if multiple scales of conceptualization are necessary to comprehend all of the patterns pertinent to a problem and its solution. At the same time, the various approximations available at different scales are not independent. They are approximations of the same subject. Understanding how this coupling across scales of conceptualization might work (what underlies the rather vague notion of emergence) requires a deeper appreciation of what constitutes the patterns that make up the content of conceptualizations, including the portions of them that constitute approximations of systems. The reader is referred to *A Multi Scale of Definition of a System* for this. That paper also discusses how these patterns can be interpreted as the substance, structure, and dynamics of systems.

A system at any scale of conceptualization, S^{ν}, obeys the laws of reductionism, determinism, completeness, and the law of the Excluded Middle. For example, a system at a particular scale of conceptualization can be disjointly partitioned from its environment. This gives rise to what is frequently called the boundary of the system. However, these analytical techniques do not extend beyond any one scale of conceptualization of the system. The assumptions underpinning these techniques are

[12] Koestler, A.; *The Ghost in the Machine*; 1976.
[13] A Holon can also be understood as giving a system its identity in a conceptualization.

generally not valid is such cases. Their use in such cases can be the source of all sorts of mischief.

Given this newly revised definition of a system, *if* the patterns available at more than one scale of conceptualization are pertinent to a problem and its solution, then multiple individual scales of conceptualization *must be* explicitly used. A failure to do so will lead to partial solutions (at the very best). In most cases, it will lead to no solution at all.

TSE proceeds on the basis that a single scale conceptualization of a system is adequate to realize a solution to a problem. *In many cases, it is.*

A **TSE system** can be designated as $\mathcal{S}_{TSE}$**,** and then

$$\mathcal{S}_{TSE} = S^{v} \text{ for some } \underline{\text{fixed}} \text{ scale of conceptualization, } v.$$

In the case of a TSE system, everything (in a conceptualization) is both a system *and* its environment at the chosen scale. Everything can be understood to be (is conceptualized as) a set of patterns at that scale. In this case, $\mathcal{S}_{TSE}$ is not an approximation of the system; it is the system. The whole of the system is the sum of its parts; and the system is a part of the conceptualization; the rest is the environment of the system. And there is a well defined and fixed boundary between the system and its environment.[14]

When a system is treated as the realized equivalence of a problem and its solution, the above single scale definition means that the problem and the solution have both been (or can be) stabilized, meaning that the subset of patterns that comprise the system doesn't change (although some of the patterns can be our conceptualization of how the system behaves or functions). Various degrees of resolution and scope at the chosen scale can be employed to refine the patterns included in the system (or environment) and related to one another according to the rules of reductionism and determinism; and the system can be partitioned into disjoint layers or modules according to these same rules.

cSE uses the more general (multi scale) definition of a system provided above. This definition should be used when multiple scales of conceptualization must be used to adequately characterize a problem and its solution. Such a system is the realization of equivalence between such a problem and its solution and can be designated as $\mathcal{S}_{cSE}$.

$\mathcal{S}_{cSE}$ can only be *conceptualized* at distinct scales. But the TSE definition of the system *at each such scale* suffices for that scale. It must be remembered, however, that this scale

[14] For additional information outlining how this boundary can be more precisely described, how reductionism and determinism can be understood to apply to this system, and how inputs and outputs can be described, *A Multi Scale Definition of a System* should be referenced.

specific treatment only provides an incomplete *approximation* of the system.[15] This multi scale definition of a system is not currently available in the literature.

A **complex-system** is a particular kind of system that requires multi scale conceptualization. A complex-system is a system that continuously maintains or increases its fitness, and that employs the processes of natural evolution and maturation in its self-directed development. A subset of all complex-systems can be understood to be what are typically called social systems.

2.1 SOCIAL SYSTEMS

Although cSE is applicable to the evolution of all complex-systems, the discussion in this paper is cast primarily in terms of social systems.

The notion of a social system can be understood generally or narrowly. When understood narrowly, it applies only to systems dominated by the presence and behavior of people. Absent people, there is no social system in this narrow sense. Also, if people play only an incidental or minor role in the system, it is not considered a social system in this narrow sense. It is in this narrow sense that much of the remainder of the discussion in this paper is framed.[16]

Social systems of interest function at multiple scales. They must be conceptualized at multiple scales in order to properly appreciate all of the pertinent patterns that capture their relevant forms (substance and structure) and behavior. The most general terms that can be used to discuss their forms are agent and social unit. Social units are, in general, populations of agents. People are agents, and they form a variety of social units. Many of these social units exhibit behavior at multiple scales of conceptualization. At some of these scales, some social units can be understood as (conceptualized as) individual agents themselves.

An **agent** is a system as defined above. In a social system an agent is an individualized locus of actions, including so called decision making. People do things and make decisions. So can social units when conceptualized as an individual agent in a social system.

Agent behavior is always self directed. Such behavior can either be autonomic or autonomous. Autonomic behavior follows a fixed script (or “program” or “algorithm”) regardless of the consequences of that script. To the extent that an autonomic agent interacts with its environment (exchanges inputs and outputs with its environment, including with other agents), its behavior can vary, but it can only vary according to its

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[15] A scale specific approximation is *not* an abstraction of the system. See *A Multi Scale Definition of a System.*

[16] A more general interpretation of social systems would include, at least, so called social insects or social animals (such as bees and bee hives, or baboons and troops of baboons). However, an even more general interpretation can also be employed. In this sense, social systems are not implicitly limited to the biological realm.

fixed script, as modulated by exchanges of inputs and outputs. In contrast, and roughly speaking, autonomous agents can rewrite their own behavioral scripts.[17] People can be understood as exhibiting both autonomic and autonomous behavior. If something is externally controlled (not self directed), it is not an agent. It is quite possible for existing agents to create new agents in a social system.

3. LIFE CYCLES and MELDING MULTIPLICITIES

TSE and cSE also use different understandings of a system's life cycle; and they differ in how the melding of multiplicities is accomplished.

A **life cycle** is defined as the complete unfolding of changes of form and activity during the lifetime or during the useful life of a system (like an organism, an organization, an institution, or a manufactured product).

Form is understood to be inclusive of both substance and structure. Other words for activity are behavior, dynamics and functionality.

Lifetime is understood to designate the duration of a system "from lust to dust" or "from conception to disappearance." When the notion of a system's life cycle first became explicit in system engineering, attention was focused on the early portions of this overall duration. However, as GSE has continued to mature, the later portions of this duration have also been accorded attention and discussed in terms of retirement or disposal or dissolution. This paper, for reasons of brevity, focuses only on the earlier portions of the life cycle.

In the case of TSE, a system's life cycle is resolved into a progressive series of phases. Progression from one phase to the next can be monotonically sequential, iterated, or a combination of these. In all cases, however, progression from one phase to the next is marked by the satisfaction of explicit criteria. Progression is not supposed to happen otherwise. This is another manifestation of the assumed correctness of a disjoint partitioning of a whole into parts that can be "summed" to the whole. As a result, the phases are treated (in the ideal) as always disjoint. The earliest expression of the TSE life cycle was the so called waterfall model.[18] More recent expressions include the spiral model which is highly iterative. In all cases, the operation of a system *per se* is understood to be a distinct and separate phase in the life cycle of a system. When TSE is used, development is not supposed to happen during the actual operation of a system.[19]

[17] A more precise definition would be that an autonomous agent is an open, self-organizing, autocatalytic system that is capable of performing thermodynamic cycles (work) while not at equilibrium. This is an extension of the definition offered by Stuart A. Kauffman. A full discussion of this definition is beyond the scope of this short paper.

[18] See, for example, the *Survey for System Development Process Models*; Center for Technology Development, University of Albany/SUNY; 1998.

[19] In the TSE life cycle, pseudo-operation (or ersatz operation) is an important aspect of the so called testing phase. The quality of this phase is understood to improve as the congruence of pseudo-operation

In the case of TSE, a system is not normally understood to be a social system. And the system is treated as an autonomic agent (and/or as a collection of autonomic agents). The life cycle of such a system refers to the period from the system's conception to its eventual retirement. This life cycle is not treated as self directed, but as under the control of one or more outside agents. (The controlling agent during developmental phase may not be the same as during the operational phase.) Since the overall purpose of this paper is to introduce cSE, it is assumed that the reader is already familiar with the life cycle of systems as understood in TSE.

In order to accomplish a realization of a non-trivial (non-social) system, multiple disciplines must be brought to bear in a deliberate way. This deliberate integration of multiple disciplines is one of the two aspects of the **melding of multiplicities** in TSE. This integration assumes a single and external locus of overall control during development in order to specify and oversee the integration of all discipline specific activity. The "work breakdown structure" (WBS) and GANTT charts are familiar tools in this regard. The other aspect of the melding of multiplicities in TSE also assumes the existence of a predominant point of view and ultimate (and external) locus of control for the development of the system. However, this aspect also explicitly acknowledges the validity of other points of view in determining how to proceed with development. These other points of view are generally associated with "stakeholders" or their interests (such as that represented by the overall locus of control during the operational phase). These must also be melded (or aligned, or balanced, etc. as there are many terms used to capture this aspect of TSE). Tradeoffs and the Analysis of Alternatives are frequently referenced methods in this regard; they are strongly influenced by stakeholder interests. TSE is seen as being completely successful when criteria can be found that balance (or that make coherent, or that successfully compromise) *all* of these interests.

cSE interprets life cycles and the melding of multiplicities differently.

In cSE, a system's life cycle can be resolved into a progressive series of phases. The initial progression, when successful, must be understood to follow an s-curve (as shown below).[20] The phases are *not* disjoint; they overlap at the two knees of the curve. The different phases of the cSE life cycle can be associated with the dominance of one of the several predicates of evolution (identified below) which are understood to be governing the development of the system. These phases can also be given labels that are understood to characterize a dominant aspect of the overall population of autonomous agents which are understood to constitute the (social) system that is involved – such as emergence, convergence, and efficiency.

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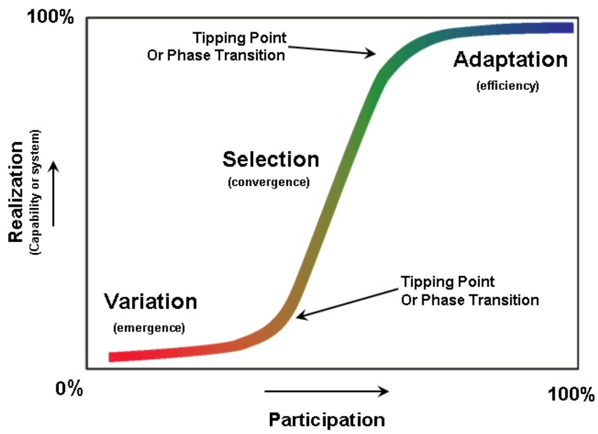
with actual operation improves. Nonetheless, it is always (if implicitly) understood that the actual operation of the system is a distinct, disjoint phase of the system's life cycle.

[20] This is a partial representation of the full life cycle. It only captures the initial phases of the life cycle. It is beyond the scope of this paper to explore the full life cycle. The s-curve progression of the life cycle is also not representative of failures in the development of systems.



In the case of social systems, the s-curve can also be understood to summarize a relationship between the participation of the members of a population (as individual autonomous agents at a particular scale) and an entire population as a system, or of a particular capability associated with the entire population (at the same or a different scale). If it is a capability associated with the entire population as an aggregated and undifferentiated whole (a unity), then multiple scales of conceptualization are involved, and the knees in the curve can be both phase transitions and tipping points.[21] Tipping points are characterizations at the scale of individual population members; phase transitions are characterizations at the scale of the whole aggregated and undifferentiated population.[22]

The autonomous agents of a social system drive the development of a complex-system. Autonomous agents are not limited to a single scale. Autonomous agents can be found at multiple scales. More specifically, people are not the only sort of autonomous agent in a human social complex-system. Business enterprises, government agencies, nations, and even entire cultures can also function as autonomous agents at the scales at which they are conceptualized as wholes (i.e., at scales at which individual people are not conceptualized). Regardless of scale, autonomous agents are assumed to follow or to pursue their own individualized interests. They are self-directed. These interests are not uniform. These interests can combine as competition or as cooperation (with or without direct coordination) among the autonomous agents at their respective scales. When direct coordination is not present, competition and cooperation can be facilitated by stigmergy.[23] Direct and stigmergic coordination are the two known forms of coordination.

Because of the self directed involvement of all of these autonomous agents in overall system development, overall system development is also termed self directed. More

[21] Examples from the military domain may be useful. Jointness, net centric operations, and the formation of a Total Force are examples of capability at a scale other than the one that makes individual population members available for conceptualization. These capabilities are properties (degrees of freedom) of a population as an aggregated unity that cannot be conceptualized at the scale at which individual members of the population are conceptualized. Capabilities of this sort are also frequently identified as emergent properties.

[22] Participation, as shown here, can be understood to combine a measure of the intensity of individual participation and a measure of the fraction of the membership participating in some fashion.

[23] For those not familiar with stigmergy, "googling" it is recommended. Doing so will yield results such as http://www.stigmergicsystems.com/stig_v1/stigrefs/article1.html. Stigmergic coordination is indirect and involves, generally speaking, marking the environment. A bulletin board is another example of stigmergic coordination.

specifically, there is no assumed external single point of control that determines the course of development for the system. Development includes both maturation and evolution.

This self-directed aspect of the development of complex-systems voids the key assumption underpinning the melding of multiplicities in TSE and must be approached in a different way. The melding of multiplicities in cSE amounts to focusing and accelerating the interactive aspects of self directed autonomous agent decision making and action (their cooperation, competition, and coordination).

Operation and development cannot be isolated from each other if cSE is used. And operation *and* development occur in all phases of the life cycle. These phases are best treated as two regimes of the same system. The melding of multiplicities in cSE focuses on the autonomous agents of a complex-system in one or more regimes and at one or more scales in order to focus and accelerate the complex-system's self-directed operation and development. The methods of doing so are captured as the regimen of cSE, discussed below. However, it can be noted here that the "controlling agents" responsible for the development and the operation of a system in TSE can be treated in cSE as "dominant agents." For example, an "acquisition agent" such as a Program of Record can be a dominant agent in the acquisition regime and an Operational Unit such as a tank squadron can be a dominant agent in the operational regime of a particular system.

3.1 Comparing TSE and cSE

Two different classes of problems can be addressed using GSE. One class of problems is best addressed using the problem solving template now associated with TSE. The other is best addressed using the template associated with cSE. It is important to keep in mind that, in engineering, a system represents the equivalence of a problem and its solution. A problem (and solution) is a manifestation of human conceptualization and is therefore always an entanglement of the subjective and objective. Starkly put, problems, solutions, and systems do not "exist" without the human conceptualization of them.

The TSE template is used to address problems that can be stabilized (see above) and for which their solutions (as systems) can be adequately isolated from incidental issues in their environments. The subjectivity in such problems (and solutions and attendant systems) can be largely isolated or made uniform for all or most human observers. What, for example, is a watch or a clock, regardless of how it is realized? What is its purpose? What "problem" does it solve? There is an almost universal agreement that a watch or clock is realized to tell time.

cSE is used to address problems that constantly change (i.e., problems that can't be stabilized). This means that their solutions must constantly change as well. And there *are* problems (and their solutions) that can't be stabilized. (This is very difficult for many engineers comfortable with the underlying assumptions of TSE.) Moreover, such problems and their solutions (as systems) can never be isolated from their environments. There are countless examples of such systems even if the problems that they solve are not as readily apparent or even articulated. The latter is due, in large part, to an inability to adequately isolate or make uniform the subjective aspects of their expression. Everybody thinks of such problems differently. What is a human being, and what is its purpose? What “problem” does it solve? What is a corporation, and what is its purpose? What “problem” does it solve? What is a church, and what is its purpose? What “problem” does it solve? There are very many different (and seemingly valid) answers to these questions.

This constancy of change and/or variability exhibited by such systems is crucial in problems and solutions amenable to cSE. In order to appreciate this observation it is important to distinguish between the operation of any system (almost all systems operate and therefore are changing) and changes in the totality of a system – its form (its substance and structure) as well as how it operates. This “constancy of change” is what is informally or intuitively used to distinguish animate (or living) systems from inanimate systems. This distinction is also frequently referred to as the ability to learn. Inanimate systems are understood to be (after development and during operation) generally constant in terms of substance and structure. Animate systems are understood to involve continual changes in terms of their substance, structure, and operation.

Social systems are animate systems, although that description is seldom used. (The distinction of animate, or living, vice inanimate is usually reserved for individualized biological systems.) Again, for reasons of brevity, this discussion of cSE is centered on a discussion of human social systems. Human social systems are animate systems.

For an engineer what is important to grasp is that there is a class of problems and solutions for which development cannot be isolated from operation; in which a system (as the equivalence of a problem and solution) cannot be isolated from its environment and that exhibits relevant functionality at multiple scales; that is social in nature (involves people and their behavior); and whose development involves either or both maturation and evolution. TSE cannot successfully deal with such problems, only with parts of such problems; cSE addresses such problems and their solutions.

The separation of operation from development is a natural aspect of TSE. When development cannot be separated from operation, GSE becomes engineering by intervention (another possible name for cSE). In other disciplines (such as those of medicine or teaching) erasing or blurring this distinction between operation and development is almost too obvious to mention. This is because practitioners know (even if unconsciously) that they are dealing with animate systems. The TSE template for problem solving seeks to segregate development and operation. The TSE template is not generally applicable to animate systems (to systems that constantly change in terms of substance and structure as well as functionality). The cSE template is.

Constantly changing systems (animate systems) have been studied for a long time now. Sociologists, biologists, economists, and historians all do this, for example. Much is now known about such systems. The engineering perspective, however, has not typically been brought to bear. That perspective, again, is one that seeks to realize solutions to problems. As a consequence, little effort has been directed at explicitly articulating the “problems” that such systems are "solving," and how such systems do that. Focus has been, instead, on the operation of such systems and how such systems change. Much of the latter is currently labeled as a study of either maturation or evolution (or both).

cSE is the deliberate focusing and acceleration of the processes that drive the natural evolution of such systems. There are two intertwined aspects to cSE. One is the analytical. The other is the developmental or synthetic. These aspects cannot be fully appreciated in isolation.

The analytical aspect of cSE is centered on a recognition that complex-systems must be understood to operate and develop at multiple scales and in multiple regimes. This requires, in turn, a more thorough appreciation of the role of human perception in the formulation of problems and solutions. The discussion, above, of a system is meant to elaborate this last point.

The developmental or synthetic aspect of cSE is summarized in what is termed the regimen of cSE. There are eight methods in this regimen. These methods are also intertwined. They cannot be fully appreciated in isolation from one another.

4. Analysis of Complex-Systems

In order to methodically analyze anything, basic concepts are needed to explicitly and consistently center what are considered to be the pivotal aspects of the analysis. These are the basic tools of any analytical approach. Placing these concepts in relationship to one another yields an analytical framework.[24] Applying such an analytical framework to specific cases or situations requires an appreciation of these basic concepts and how they relate to one another (and not just to the particulars of any specific case).

Any analytical framework is unavoidably a generalization. As a consequence its proper fit to any specific case depends on the degree to which its basic concepts are understood. In many cases doing this successfully requires at least a familiarity with concepts or notions that underpin the "basic" concepts themselves. This leads to an inquiry into a so called deeper conceptual analysis of an analytical framework.

4.1 Basic concepts

There are a number of basic concepts in cSE analysis. These can be cataloged as follows. References to some of these concepts have been underlined in the foregoing discussion.

- system
  - environment
  - Holons and identity
  - scales, changing scales, and the ladder of scales
- complex-systems
- statistics, statistical mechanics
- evolution[25] and maturation[26]
- life cycles
- melding of multiplicities
- autonomous agents (and autonomic agents)
  - OODA Loops (Observe, Orient, Decide, Act)[27]
  - populations, social units
  - cooperation, competition, coordination, stigmergy
- regimes
- classical and relational phase spaces
- state, order, complexity, and fitness

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[24] Such frameworks are often termed systems in their own right. This is why faithfully applying such frameworks is often termed "systematic." The notion of a framework introduced here is consistent with the notion of a system discussed above. The framework has elements and relationships, has an overall identity, and so on.

[25] The term evolution, as used here, refers to distinguishable differences in successive generations of a population. Jean-Bapiste Lamarck (1744 – 1829) offered the first comprehensive theory in an attempt to explain what was then known about biological evolution.

[26] Maturation is a set of processes that recapitulates the *outcomes* of prior evolution. Maturation does not generally recapitulate the processes of evolution themselves.

[27] OODA Loops are the signal contribution of John Boyd to the appreciation of social complex-systems.

This paper's brevity does not permit a discussion of each concept area separately. The notion of scale is discussed above because it is so central to cSE. Some discussion of evolution is also appropriate since the regimen of cSE is the deliberate focusing and acceleration of the processes that drive natural evolution. Regimes are introduced in the discussion of the regimen. Measures such as state and order are applicable to all systems (and to scale specific approximations of systems). If you cannot measure something, you have not engineered it.

Evolution as a notion is distinct from the various theories or models that would account for it. There is more than one such theory and there is no reason to assume that they are all mutually exclusive. The so called Darwinian theory of evolution (and its derivatives) is distinct from the so called Lamarckian theory, for example. Each may be applicable to different classes of evolutionary systems, or to different scales of the same system.

Evolution identifies one form of change.[28] Not all changes are recognized as evolutionary. Theories of evolution are attempts to account for this particular expression of change.

Evolution identifies changes that are seen as gradual or progressive or cumulative but that are not seen as arbitrary or random. They are specific changes that do not appear to be the consequence of an explicitly identifiable outside agent's intervention – and so are frequently termed self-directed. Such changes are generally understood to apply to the substance and structure of things and in turn to changes in their behavior. Since this form of change is not arbitrary it may be due to some process or processes. Theories of evolution are attempts to identify and characterize these processes. Theories of biological evolution are the ones most frequently and explicitly examined. The processes associated with most theories of biological evolution are centered on the following predicates.

- **Superfecundity** – there is an excess of new members in a population above strict replacement.
- **Heredity** – new members of a population and their characteristics are derived from existing members and their characteristics.
- **Variation** – the characteristics of new members are not uniform.
- **Adaptation** – members of a population do not behave uniformly and behavior is not independent of other members and the environment.
- **Selection** – members in a population are subject to attrition as a consequence of their characteristics and behavior.

[28] There are many ways to understand change. As noted above, change can be treated as a synonym for operation. But it can also be applied to the structure and the substance of things. Erwin Schrodinger, in his *What is Life?* pamphlet, distinguishes between changes that arise out of order and those that arise out of disorder. Max Planck does much the same thing in his pamphlet, *Dynamical and Statistical Types of Law*. As a consequence, recognizing change (evolutionary or not) is best understood as pattern recognition in temporal frames of reference.

There is a "sixth" predicate as well that is frequently overlooked – no member of a population persists indefinitely. There is also a "zeroth" predicate – that evolution applies to a population of members and that not all populations evolve regardless of what their members do. Populations that do evolve obey the remaining predicates.[29]

What is also of significance with respect to evolution is that while the mechanisms or processes that drive evolution (and that are based on the above predicates), can be expressed at one scale, their most persistent consequences are only apparent at another (and "higher") scale.[30] At this higher scale, the populations involved are conceptualized in the aggregate as undifferentiated unities. It is at this scale that the populations involved assume distinct identities themselves. And these populations will have properties (degrees of freedom) associated with them that cannot be conceptualized at a "lower" scale that permits the conceptualization of individual members of such populations.

What has been only sporadically studied to date with respect to evolution is the impact of functionality at this higher "aggregated population" scale on the functionality at a lower scale at which individual members of a population are conceptualized. It is simply wrong to assume (or to stipulate) that functionality does not exist at this higher scale or that it has no bearing on the functionality (operations or dynamics) at the scale at which individual members are conceptualized. This is like stipulating that the pressure and volume of a population of molecules have no bearing on the kinematics of individual molecules.[31]

This is also true in the realm of social complex-systems, but it is even less studied and hence even more poorly understood. Attempts have been made to identify this influence and its predicates, however. An example is the work of Richard Dawkins in which the notion of a cultural "meme" and "memetics" was introduced.[32]

Referring to the s-curve shown above, it is also important to recognize that in the earliest phase of development shown, the predicate of variation dominates. In the subsequent

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[29] As an important aside, it is the failure to appreciate the "zeroth" and the sixth predicates of evolutionary theory, along with a failure to grasp the significance of scale (when *all* is not the same as *every any*), that accounts for the frequently heard misinterpretation of the notion of the "survival of the fittest." Individual members of a population do not persist as does the whole population, and it is increases in the fitness of the whole population (not of individuals in it) relative to characteristics of its environment that accounts for this population persistence. No member of the population "survives," and certainly the "best" or the fittest do not survive. Evolutionary theory does not account for (nor does it depend upon) "survival of the fittest" members of a population.

[30] The notion of "higher" and "lower" scales of conceptualization give rise to the metaphor of a "ladder" of scales in which each rung of a ladder corresponds to a scale of conceptualization. The metaphor of a ladder should be contrasted to the often heard references to a hierarchy of scales. Scales of conceptualization as discussed here cannot be organized hierarchically. There is no way to completely deduce the content of adjoining scales given a particular scale of conceptualization. However, a particular scale of conceptualization with its attendant SCOPE and RESOLUTION can be understood to be inclusive of another. In such a case, that particular scale can be understood to be a "higher" scale of conceptualization than the other.

[31] Many of those who explicitly recognize this trans scale dependency refer to "causal loops" since, as in this case, the pressure and volume of a gas also depend on the kinematics of its constituent molecules.

[32] Dawkins, Richard; *The Selfish Gene*; 1976.

phase, the predicate of selection comes to dominate. And in the third phase shown, the predicate of adaptation comes to dominate, especially with respect to the environment. However, none of the predicates cease to influence development regardless of phase.

4.2 Deeper conceptual analysis

- Cognitive Sciences (modalities of conceptualization)
  - patterns as configurations of similarity, and difference
  - focus of attention
  - identification (localization, aggregation and labeling)
    - cohesion, boundaries
  - frames of reference
- degrees of freedom and relationships; elements (simple and compound),
- radial category theory (basis for regimes)
- thermodynamics and cybernetics (for the flux of energy and information)
- reductionism and constructionism and determinism
- The Law of the Excluded Middle and completeness
- Ontology and Epistemology

5. The Regimen of cSE

The regimen of cSE is a set of humanly directed processes (methods) for intervening in the continuous operation of complex-systems. Together, these methods serve to focus and accelerate the evolutionary aspects of complex-system development. Specific outcomes of complex-system development cannot be specified in advance,[33] but they can be shaped (strongly and persistently influenced) and their appearance can be accelerated. These methods constitute a regimen. As such, they should *not* be understood as a sequence of steps, or as a recipe, or as activities that can be pursued in an independent and separate fashion. They are to be used in combination as specific cases warrant.

The following is a very brief overview of each of the methods of the regimen of cSE. These are methods that are meant to continually synthesize a solution to a constantly changing problem. They are engineering methods for intervening in the continuous reformulation of a system that is the realized equivalence of a changing problem and its changing solution. They are not methods for the specification and the control of a development that unfolds prior to and independent of operations. The specifics of these methods depend on the actual complex-system of interest – and in particular on the autonomous agents driving the development of the system.

5.1 Analyze **the environment** of a complex-system and attempt to temporarily modify that environment in order to influence the complex-system's *self-directed* development.

The environment of a system is everything that is not the system. However, in the case of a complex-system, a system cannot be completely isolated from its environment (due to the need to conceptualize it at multiple scales). At a minimum, a complex-system must be understood to be an open system. More importantly, a complex-system cannot be disjointly partitioned from its environment (since multiple scales of conceptualization are involved). As a consequence there is no way to frame a complex-system (in its entirety) so that the environment can be ignored or treated as incidental or as a given. (This frustrates efforts to establish the requisite TSE span of control for system development – which in turn frustrates efforts to fix responsibility and accountability for development, and so on.) The positive consequence of this ambiguity, however, is that acting on the environment will have an influence on the system. This impels the need to understand and characterize the environment of a complex-system (not just the system) and to understand their mutual influences.

As an example, consider what a gardener does when a gardener waters a garden. The garden is the complex-system, and the gardener is a complex-system engineer. The gardener is temporarily modifying the environment (modifying the amount and distribution of water and nutrients in the immediate environment of the garden). The gardener does not do this when it is already raining, or when the garden is sufficiently moist. The gardener leaves to the individual plants in the garden, however, the tasks of taking in the water and the nutrients necessary for their individual development. This is

[33] To do so would at least require conceptualizing at multiple scales at once.

not the behavior that a watchmaker would exhibit (by way of contrast) in building a watch. A watchmaker, as a traditional system engineer, attends to every single component (element) of a watch at a particular scale, as well as with all of the relationships elements have with all other elements. The watchmaker proceeds on the basis that the whole is exactly the sum of its parts. If the watch doesn't work, it is because a particular component doesn't work as expected or a relationship between specific components is not as expected. So fixing one component or relationship will fix the entire watch. Also, the gardener would not start a garden in the middle of the winter; but the watchmaker proceeds in the fabrication of a watch independent of such environmental considerations. The solution to the watchmaker's problem has been isolated from incidental factors in the environment and no longer depends on any analysis of that environment in order to accomplish the realization of a watch. The gardener, on the other hand, understands (even if unconsciously) that any attempt to isolate or take as a given the environment of a garden would be folly in realizing a garden.[34]

For the gardener, the environment is always a factor in realizing systems. The environment must be analyzed, taken into account. And then it must be perturbed in order to alter the way that the autonomous agents of the system proceed with their own self directed and localized interpretation and exploitation of that environment for their own purposes which are by no means uniform but that collectively will determine the realization of the entire system.

5.2 Tailor developmental methods to specific **regimes and scales** of the complex-system and its environment**.**

A complex-system cannot be comprehensively conceptualized. Nor can it be disjointly partitioned as a problem so that solutions to the separated parts can be assembled into a whole solution to the whole problem. Alternate analytical and synthesizing strategies are necessary. It becomes necessary to find and leverage non-disjoint distinctions and partitionings. The non disjoint partitions associated with scales of conceptualization are unavoidable. Others are voluntary and induce what are termed here analytical regimes.

Any complex-system operates at multiple scales (each of which includes features of the system and its environment). Central to any intervention in the developmental aspects of a social system is the identification of the autonomous agents (people and their organizations) driving its self-directed development. Deliberately identifying these agents should be done at multiple scales. The factors motivating their behavior (more than their intrinsic capabilities) should also be carefully considered.

Regimes are the deliberate (and subjective) filtering or partitioning of the patterns available in conceptualizations. For a particular regime, patterns in conceptualizations are either deliberately emphasized or ignored. Patterns can belong to more than one such partitioning (one such regime). Furthermore, entirely subjective patterns are

[34] A green house is a more complete and permanent (but still partial and temporary) manipulation of the environment of a garden.

superimposed on the otherwise reality-based patterns of conceptualizations in order to reinforce the filtering and partitioning of the regimes. Regimes are not generally disjoint however, as are the “layers” or “modules” in TSE. The methods of regime based analysis acknowledge the non disjoint partitioning of patterns. The foundation for these methods is known as radial category theory.[35] The overlap of development and operation in a complex-system is an important example of the non-disjoint partitioning of regime based analysis.

The patterns that comprise any regime can have labels such as ideas, concepts, notions, etc. As just one example, a so called “loose coupler” can be understood as a regime. The patterns of such a regime overlap with the patterns of many other regimes. It is not that specific elements or patterns of the “loose coupler” regime constitute an “intersection subset” of all (or most) other regimes; it is that the “loose coupler” regime contains patterns that are also present in all (or most) other regimes. (The patterns involved don’t have to be the same ones.) The notion of an intersection subset is apropos for the disjoint style analysis of TSE, but not for cSE.

Understanding “loose couplers” as regimes not only aids in understanding how they function, it also aids in recognizing them. The Internet Protocol (IP) is frequently cited as a “loose coupler” (which it is). But so are the Microsoft Operating Systems and text string search engines. And it also suggests how additional “loose couplers” can become the focus of cSE based development, for example the appearance of “imagery” search engines based on “imagery fragments” rather than on text strings that are attached to images.

To tailor developmental methods to specific scales means of course that the methods of TSE may well apply and should be considered. This is particularly true for Information Technology based *components* of a social complex-system. However, since the overlap of functionality at multiple scales is important in solutions expressed as complex-systems, it is also important to identify where functionality at multiple scales may be interdependent in some fashion. In going from lower to higher scales, statistics, statistical mechanics, quantum mechanics and the like may provide useful insights. As suggested earlier, the properties and behaviors of aggregated populations, as distinct from the properties and behaviors of their individual members, are best considered at separate conceptual scales. This is especially true in the case of social complex-systems in which individual people are autonomous agents at one scale, and their persistent organizations are autonomous agents at higher scales. (As a rule of thumb, if the persistence of an organization is three times that of its longest lived first generation member, then the organization is also an autonomous agent.) Specific expressions of the regimen should be formulated that address these scales (and their agents) directly, as well as that address cross-scale dependencies as revealed by the techniques suggested. There is at present a

[35] Lakoff, George; *Women, fire, and dangerous things;* University of Chicago Press; 1987.

paucity of formal analytical methods that reveal influences working from higher scales on lower scales. So, at present, these methods must remain ad hoc.[36]

One regime of any social complex-system is its operational regime. The operational regime is directly associated with the purposes or mission of the whole system as seen from the scale of individual people. Another regime is the developmental regime and it is associated with changes in the social system. These two regimes cannot be sufficiently isolated for a complex-system so that operation and development could proceed in generally independent ways as is done in TSE. As a consequence, changes to a complex-system must always leave the whole system operational, and a feasible way to tailor developmental methods for a complex-system is to do so directly in the context of its operational regime. This interdependence is also a part of the last method of the Regimen. This leveraging and incorporating actual operational experience in the ongoing development of a system is exemplified in the US Military's rapid incorporation of new technologies and tactics, techniques, and procedures (TTPs) in the continuing execution of missions in Afghanistan and Iraq.

It is also feasible to pursue development using partially isolated or artificially constructed environments. The use of playgrounds and schools[37] is perhaps the most ubiquitous example of this strategy in social systems.

5.3 Identify or define **targeted Outcome Spaces** at multiple scales and in multiple regimes rather than attempting to specify exactly aligned outcomes at all scales in all regimes.

Outcome Spaces are indistinct sets of possible and acceptable individual and detailed outcomes at specific scales and in specific regimes considered separately. (All outcomes together actually achieved by a complex-system at all scales and in all regimes are the **results** of the complex-system. The complex-system itself will choose the exact combinations of outcomes that it achieves as results.) This self-directed selection of combinations of outcomes can be understood as being performed collectively by the autonomous (decision making) agents of the complex-system. See Surowiecki.[38] It is also worthwhile to explicitly identify Outcome Spaces to be avoided. The formulation of Outcome Spaces is as close as one can come to specifying "requirements" or "desired capabilities" for a complex-system. The selection of Outcome Spaces for a complex-system guides the focusing aspect of the regimen. Outcome Spaces should be regularly reviewed for currency (as a collateral aspect of methods such as Judging and Continuous Characterization, discussed below).

[36] And, of course, it must be recognized that autonomous agents at higher scales can be pursuing their own agendas that may well frustrate (or contribute to) agendas at the scale where individual people can act directly – which is, or course, what the regimen of cSE is all about.
[37] And green houses in a different context.
[38] Surowiecki, James; *The Wisdom of Crowds*; 2005; Anchor Books

So called net centricity[39] is often confused with networking. Net centricity is better understood as (and should be defined as) an Outcome Space at a scale above that associated with the agents (both autonomous and autonomic) that function at the scale at which the networking occurs. Net centricity should be understood as a property of the aggregated social unit of the agents that are networked. Net centricity is not a property of such individual agents directly. Net centricity should be treated as an Outcome Space for the social unit(s) of aggregated agents that network. The specificity in its actual definition will stem from the actions and the decisions of the agents that network.

5.4 Establish **rewards (and penalties).** This entails the explicit formulation of reward criteria and prizes explicitly associated with satisfying the criteria.

Reward criteria are the explicit conditions that must be met (or the events that must be happen) in order for an agent to be eligible for the prize associated with the reward. Reward criteria should be tailored and expressed in terms that are familiar to specific groups of agents that are driving the development of the complex-system (vice the way that Outcome Spaces might be expressed for other audiences). This requires scale and regime specificity for rewards. Reward criteria are not necessarily outcomes or Outcome Spaces. Reward criteria can be either direct or indirect (and partial) expressions of Outcome Spaces. Indirect means that the criteria are understood to enable (or to partially enable) outcomes. **Reward prizes** (or penalties) should be treated as the injection of *additional* considerations that will influence the decision making of autonomous agents in a complex-system. Money is an obvious (but not the only) example of a Reward's prize. The formulation of Rewards (and especially their prizes) depends heavily on understanding the considerations that (already) form the motivations of the autonomous agents of a complex-system. The X-Prize and DARPA's Grand Challenge are examples of employing a Rewards-based approach to focusing and accelerating development in a social complex-system.

People are obvious autonomous agents in a social complex-system. But social units at higher scales can also be autonomous agents and the intended targets of Rewards (both criteria and prizes). Rewards (and penalties) are established in order to influence the behavior of individual (but not specific) autonomous agents in a complex-system at specific scales and regimes. Rewards (and penalties) are not direction or guidance. Direction and guidance speak directly to agent behavior; rewards and penalties speak to agent generated outcomes. The formulation of Rewards (and penalties) should be understood as efforts directed at both focusing and accelerating the realization of instances of outcomes in Outcome Spaces.

5.5 **Judge** actual **results** and allocate prizes**.**

Judging results is a shorthand term for the consideration and judgment of actual outcomes in many or all of the regimes and scales of a complex-system together. Judging

[39] http://en.wikipedia.org/wiki/Net-centric

is centered on outcomes associated with the criteria of Rewards, but it also involves the explicit consideration of other anticipated (intended and unintended) and unanticipated outcomes. And it involves a deliberate determination and explicit assignment of responsibility to the autonomous agents in a complex-system most closely linked with acceptable results that include (or satisfy) the criteria of Prizes.

Attention should be given to actual results (not promised results, or isolated actual or promised outcomes) in terms of targeted Outcome Spaces; and only then should prizes be given to the most responsible agents, *whether they were explicitly pursuing the Rewards or not*. (While it is impossible to predict actual results based on possible causes in a complex-system, it is always possible to determine causes for actual results. See P. W. Anderson.[40]) This should be done in ways that preserve or even increase the opportunity for more new results. There should also be a bias for results that can be reversed easily, or that can be easily repeated (in whole or in part) by other autonomous agents. It should be kept in mind that the purpose of the regimen is to focus and accelerate the development of an entire complex-system and not parts of it.

The formulation of rewards and judging actual results stands in sharp contrast to the practice of Contract Awarding – which is strongly associated with the practice of good TSE. A Contract Award is assigned to the winner of a (subjective) assessment of the most cost-effective proposal (from an agent) to deliver something in the future. The assignment of reward prizes (in judging) is based entirely on actually results.

5.6 Formulate and apply **developmental stimulants.** These are direct actions or conditionings that modulate the number of, or the intensity and persistence of, interactions among autonomous agents *without* attempting to address what specific interactions are about. It is like stirring the pot. This includes injecting additional, new agents into a social complex-system (as catalysts, for example).

Specific forms of this method depend heavily on the phase of the developmental cycle of a capability that is being addressed. A capability is a shorthand way to refer to a trajectory into or through one or more Outcome Spaces (or to just the culmination of such a trajectory).

Establishing or facilitating markets is one form of developmental stimulant. Markets exploit variation, variety, and interdependence among autonomous agents; markets also include mechanisms to aggregate the interactions of their constituent agents. (Brokers are one such mechanism to accelerate and aggregate the actions of individual autonomous agents. Injecting them into a market can focus and accelerate the formation or operation of a market.) Mechanisms can also be formulated to modulate the variation, variety, and interdependence of agents in specific kinds of markets.

[40] Anderson, P. W.; *More is Different* in Science, New Series, vol. 177, no. 4047; 1972.08.04

Other examples involve modifications to standardized contract vehicle language (for engaging any contractor or sub contractor) and the formation and facilitation of so called communities of interest.

5.7 **Characterize continuously.**

Continuous characterization is about capturing and publicizing the way things currently are in a complex-system. (It is not specification, although it requires many of the same skills in order to perform it.) It employs techniques aimed at both gathering and organizing information and making summaries of that information available to the autonomous agents of a complex-system. Information is gathered at multiple scales and in multiple regimes pertinent to Outcome Spaces and to the health and fitness of a complex-system and expressed or presented in ways that can be directly and immediately interpreted by the autonomous agents operating within the complex-system. This general method, from the perspective of the autonomous agents, elaborates and supports the adage of thinking globally while acting locally. This method also informs judging. It provides the factual basis for determining when and by whom reward criteria are satisfied, and for assessing the cumulative significance of changes within a complex-system. This includes the aggregation of actual outcomes into the results that are judged. Continuous characterization can be understood as the "as is" "specification" of a complex-system with the understanding that emphasis is never on completeness (which is impossible) but on pertinence or relevance in terms of Outcome Spaces, Reward criteria and policing.

The daily (and longer period) assembly and publication of stock market summary activity is an example of Continuous characterization. It does not serve to direct autonomous agent activity, but rather to inform it. Most highway traffic reports are intended to do the same thing: to inform all individual drivers of general conditions, but not to direct individual driver decisions.

Autonomous agents make their own decisions. They desire information to do that. Continuous characterization supplements their own efforts to acquire such information.

5.8 Formulate and enforce **safety regulations (policing).**

These regulations and regulatory efforts are always specific to individual complex-systems. However, several generalizations are possible. For example, procedures can be initiated aimed at detecting and screening changes in the complex-system in all regimes (not just a developmental regime) and regardless of Outcome Spaces and Reward criteria so that fitness is maintained but without addressing the putative purposes of changes that modify fitness or that modify characteristic periods. Screening agents, both existing and new, against explicit criteria for continued participation is one example of active policing. Temporary preservation rather than elimination of redundancies is another.

Policing can be tied to "leading indicators" associated with the more direct indicators of measures such as fitness and characteristic period. Identifying these "leading indicators" is best accomplished using validated stochastic, multi scale models of autonomous agent decision making in the social complex-system. Validation is not accomplished globally, but locally, and with representatives of various kinds of agents being modeled.

6. Using cSE Analysis and the Regimen of cSE

cSE begins with a careful and explicit characterization of an existing complex-system and its environment *and* the problem that is being addressed. This is done at scales and in regimes that seem the most convenient for capturing the important aspects of the problem as well as the existing conditions bearing on the solution. Accuracy and not precision should be emphasized. Continuous characterization continues this initial effort. In the case of a social complex-system, autonomous agents and their respective OODA Loops are always important. In today's context, autonomic agents are also frequently important. The patterns of organization (of the agents) at the selected scales are also frequently important (hierarchical, peer-to-peer, mixed, etc.).

The desired direction of the evolution of the system is then cast in terms of targeted Outcome Spaces. This in turn motivates both the methods of continuous characterization and the formulation of rewards (both criteria and prizes). Reward criteria also motivate the efforts of continuous characterization.

In doing these things it is always imperative to keep in mind that the complete development of a complex-system can never, ever, be imposed on it. To do so successfully would be to destroy the very nature of a complex-system. It is in this respect, more than any other, that attempts to apply TSE to problems and solutions amenable to cSE pose the greatest risk to the engineer's objective.

The environment is analyzed, as well as the system itself, and ways are identified to modulate or influence the behavior of the system by modifying or augmenting (however briefly) aspects of the environment. This can be done generally as well as in terms of specific regimes and scales. It can be done for the whole system, or for selected portions (e.g., for selected agents).

Both developmental stimulants and rewards are formulated and applied in order to modulate and accelerate the behavior of autonomous agents within the complex-system (at one or more scales).

Continuous characterization is employed to track the evolution of the system and to inform autonomous agents. Continuous characterization is also an important aspect of analyzing and then shaping the environment of the system. It also informs judging.

Judging is central to cSE. Because detailed outcomes cannot be pre planned (as they can be with TSE), emphasis must shift to explicit recognition of the desirable results being generated by the self directed development of a complex-system. This is what judging does. The overall stability of the complex-system is also explicitly attended to since the above methods (by focusing and accelerating the evolution of the complex-system) also increase the risk that it will either disintegrate or stagnate. This is the purpose of policing the fitness and health of the system.

6.1 Fitness

Measuring is essential to engineering. Complex-systems evolve and so measuring the evolution of complex-systems is essential to complex-system engineering. Fitness is one of the ways to measure evolution. It is beyond the scope of this brief paper to fully explore this topic. Nonetheless, a few words are in order.

Order and State are two measures of any system. Using the framework provided in *A Multi Scale Definition of a System*, State can be used to characterize the form (substance and structure) of any system; and Order can be used to characterize its behavior.

The **State** of a system can be defined as the phase point in a (classical) phase space in which the degrees of freedom of the objects of the system provide the dimensions of the (classical) phase space. (The degrees of freedom are then said to span the phase space.) The sequence of such phase points can be understood as the State Trajectory of the system.

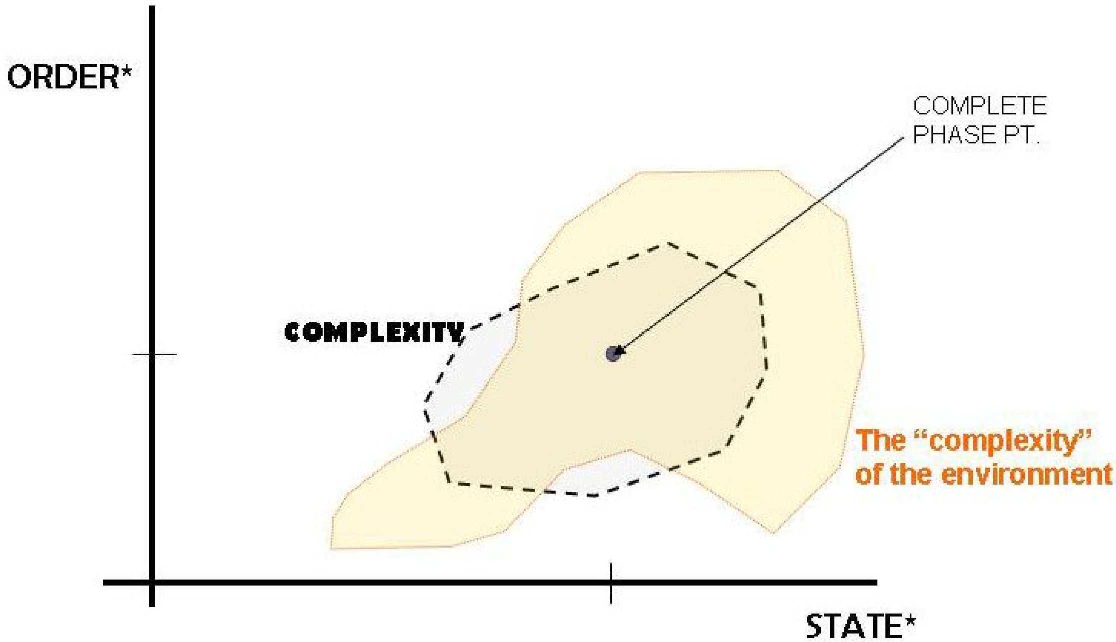
The **Order** of a system can be defined as the phase point in a *relational* phase space. In a relational phase space, the relations in the system span the relational phase space. The sequence of such phase points in the relational phase space can be understood as the Order Trajectory of the system.

The Complexity of a system is linked to the orthogonal combination of the system's State and Order. (Complex numbers, a + bj, are orthogonal combinations drawn from two sets of real numbers.) The orthogonal combination of State and Order can be termed the Complete phase point in the Complete phase space for a system. Complexity is linked to this Complete phase point.

It is important to note that neither a classical nor a relational phase space is necessarily a normed metric space.

State and Order are multi dimensional quantifications. **Complexity** is the "accessible region" of the Complete phase space, where accessible region refers to all points in the Complete phase space that can be the next point in the Complete phase point trajectory and *that preserves the identity of the system*.

For the sake of this brief discussion, State* and Order* are one dimensional summaries of Order and State in the diagram below.



Complexity is the "region" within the black dotted lines. It includes all of the possible changes to the State and Order of the system that preserve the identity of the system. When the system's Complete phase point trajectory moves to a point outside this region, the system loses its identity (it collapses or disintegrates or "dies"). This "region" is not constant and continually changes as the Complete phase point changes.

There is a measure of the environment of a system that is analogous to that of the Complexity of the system. **Fitness** is defined as the overlap of these two regions in a combined Complete phase space of the system and its environment. This is consistent with, but extends, the work of Ashby.

This treatment applies to single and to multi scale systems. It must be remembered, however, that there is no way to combine the various measures of Complexity as each scale of a multi scale system to arrive at some "comprehensive" measure of Complexity. Doing so provides only an approximation of the Complexity of the multi scale system.