Chapter 13 – Complex Artifactual Systems

Abstract

Artifactual systems are complex, adaptive, and evolvable systems that are composed of humans and artifacts in multifarious relations. Sometimes called socio-techno-systems to emphasize the human and 'machine' components, these systems are integral parts of human social system cultures. Artifacts themselves can be CAESs. And the special relation between humans and artifacts that is their conception, design, and construction is shown to be the result of a new kind of ontogenesis, one that involves intentional-organization and intentional-selection replacing auto-organization and 'natural' selection as operated on material systems prior to the evolution of human consciousness. We focus on CAS/CAESs and how they are conceived and designed. The design/engineering process is shown to be an evolutionary one even though intentions replace the much more stochastic processes involved ontogenesis prior to human intentional approaches. We also argue for the inclusion of evolutionary approaches in the design/engineering process.

13.1 The Purpose of this Chapter

The concern for the next three chapters is to explore the meaning of the larger human social system (HSS, introduced in Chapter 6) which includes not just human beings but a vast and complex array of artifacts created by them forming what we generally think of as human cultures. The term "cultural artifact" is used in fields such as archeology, anthropology, and sociology to mean any object that is the result of human production in any period prehistorical to modern times[1]. An *artifactual system* is a set of interconnected cultural artifacts and the humans that did the production and those who use the artifacts to accomplish other work. The emphasis is on the systemness of the objects, their producers, and users[2]. We will offer a definition of what is meant by the term 'artifact' below.

We will also offer a new approach to understanding artifactual systems and the cultures in which they are embedded. This larger scale systems perspective is needed in order to better understand the 'context' or environment of artifactual systems. The intent is that we will develop a new approach to conceiving, designing, and engineering such systems by using the concepts and procedures developed in this book, derived from our understanding of ontogenesis in Chapter 2.

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[1] See the Wikipedia article: https://en.wikipedia.org/wiki/Cultural_artifact for background. Accessed 2/11/2020.

[2] Artifacts have relations to humans and to each other in a complex entanglement. For a thorough treatment of this see Hodder (2012).

Artifactual systems represent a new ‘state’ for matter in the Universe in the same way that life itself is now seen by some researchers as a new state (Smith & Morowitz, 2016, see section 1.3.3.2 for an introduction). That is artifacts are the product of a wholly new kind of dynamic in the course of ontogenesis and they are obtained from a phase transition from unconstructed form to structures that could not have obtained by some energy minimization process. Prior to human intentions and interventions in the process of combining material or organizing social structures such as communities or institutions, matter had been subject to auto-organizing (e.g. as in chemistry) and phase transitions between states such as solids, gases, liquids, and plasma. And all systems were subject to the laws of thermodynamics and mechanics. Living systems have been characterized as resulting from a phase transition by virtue of the seeming ability to go against the Second Law as dissipative systems (Smith & Morowitz, 2016; Prigogine & Stengers, 1984). It is the new kind of organization, behavior in obtaining free energy, and the capacity to dissipate waste heat to the environment (thus not really going against the Second Law after all) for material objects that has led to the characterization of life as a new state of matter. We assert that the same kind of logic applies to artifactual systems. Artifacts, as defined here, did not exist anywhere until humans applied intelligence and creativity as well as imagination to the combining of components to obtain a new object (system) that served a purpose. Human consciousness was itself a phase transition of living matter, networked brains, from which emerged the capacity to imagine and consider the future and mentally manipulate objects with various forms of affordances to create new objects, more complex, able to be used in new ways.

Artifact-hood cannot be taken for granted. This new state of matter exists because a new kind of organizing process has emerged in the evolution of human consciousness; we replace the notion of auto-organization with *intentional-organization* and natural-selection with *intentional-selection*. That is, the combining and recombining of components to create new systems is done with foresight and purpose and the on-going replay of doing so is done based on a human perception that the new system successfully fulfils that purpose.

There may be good arguments for considering some kinds of artifacts as not really being systems and not even atomic components as described in chapters 2 & 3. For example, a marble statue is clearly an artifact having symbolic meaning, but it does not process energy or material so far as meets the eye. It would, at first glance appear not to have inputs and outputs so therefore not qualify under our definition of a system. The statue appears to be inert. However, on closer inspection we find that the marble is itself a composite of minerals and those of atoms. So, from the hierarchical organization perspective it embodies, albeit in an essentially static way, that nested quality of subsystems[3]. Moreover, the statue exists in an ambient environment that can include, for example, temperature variations, meaning that heat energy is being absorbed when the temperature is higher and radiated when it is lower. In other words, energy, though of a

[3] In Appendix A we examine a deuterium atom in systems terms and show how it can fit the definition given in Chapter 3.

low quality, is indeed flowing in and flowing out as conditions change. These flows, in turn act on the marble minerals by changing the energy modes (or at least the vibrational mode) of the atoms in the minerals. One effect of these changes is that minerals tend to break down over long enough time scales and cycles of heating and cooling. The statue will last a long time relative to the human lifetime, but eventually it too will return to dust. So, is the statue an artifactual system? We would argue, yes, but clearly a very simple system in terms of, say, behavior.

Yet a statue, like all forms of artwork, literature, poetry, even architecture, even though static from the perspective of human perception, is the product of human intention and imbued with human-relevant meaning. It has a purpose, if nothing more than the communication of the affective state of the artificer. For now, we will accept all such objects as artifactual systems and remain open to counter arguments.

In this chapter we have several main goals. The first is to understand what we mean by artifacts and how they are the product of human intentions – this is the mechanism by which a phase transition to a new state of matter is achieved. The second is to understand what is meant by the relations between artifacts and human beings, as well as between artifacts and artifacts – the nature of artifactual systems. And the third is to consider artifactual systems in the mold of the CAES model introduced in Chapter 9 (and Part 3). This latter is the setup for the next chapter in which we introduce the methods for designing and engineering CAES-based artifactual systems, especially the human social system itself. In the final chapter we demonstrate the application of all of this thinking to the actual design of an HSS for the future of the planet.

The purpose of this chapter is several-fold. We will be proposing a radical new approach to the design and engineering of complex adaptive and sometimes even evolvable artifacts. This new approach is based on the subject of Chapter 2 – Ontology, specifically the nature of ontogenesis and the coming into existence of new systems. We will explain the rational for adopting an ontogenic process for design and engineering when it comes to CAS and CAESs. We argue that Nature long ago worked out the process by which these systems come into being and achieve sustainable existence; they persist in otherwise chaotic environments by being 'fit' and adaptive to changes. We also argue that this process will be found to be essential to the success of design and engineering of seriously complex systems as the human social system (HSS) moves into the future. This chapter will introduce the concepts of ontogenic artifice and the next chapter will go into the details of the process of designing based on the CAES archetype model (model-based design) as used to 'design' a particular social module (a food producing domicile) which is an example of a CAES. The final chapter of the book will extend the example of the social module design to the design of a complete HSS that, because it is designed as a CAES from the start, will be sustainable.

The process we propose is a definite departure from classical engineering approaches. It does not abandon certain elements of those approaches entirely but, rather, incorporates them within a larger holistic framework based on ontogenesis. Prior to the emergence of the human mind able to invent purposeful tools Nature operated on the basis of auto-organization (as in Chapter 2), the not entirely random, but stochastic (chance) coming together of simpler systems that could form strong associations from which emerged new systems forms and functions that none of the components could demonstrate before their combination.

Subsequent to the emergence of early human minds the organizing process entered a new dynamic. Rather than chance encounters between components, humans for a variety of reasons (described more fully below), began to *intentionally* bring components together. Even in auto-organization, the encounters of components, bringing them close enough that free energy might generate a coupling, is seen to not be completely random. In Mobus & Kalton (2015, Chapter 10) the process that gives rise to encounters and auto-organization is described as resulting from directed energy flows (e.g. convective cycles) that can also determine sorting mechanisms (e.g. a convective cycle operating in a gravitational field) that increase the probability of certain components having encounters[4]. So, auto-organization, pre-humans, had a larger stochastic element, but it was from the start not purely random (e.g. a uniform distribution across pair-wise encounters of all types of components). There were already organizing constraints on what sorts of encounters would happen. Geometry and boundaries greatly influenced what could transpire. For example, the nature of a rotating planetary body orbiting in the "Goldilocks zone" and bathed in sunlight provided the necessary conditions for the auto-organization of the various geospheres and the pre-life molecular systems. And, eventually, life itself.

Intentional-organization is a far more directed process than those found in more physical versions of auto-organization. Nevertheless, mental intentions are not, themselves, wholly deterministic. Human intentions retain an element of stochasticity (for example imperfect memory recall can result in mistakes).

Another big difference between intentional- and auto-organizing processes is that the former is based on 'teleological' outcomes. That is, a human mind often desires a particular result from the act of organization. Whereas the latter do not involve any particular insights into outcomes, desired or otherwise. This is the distinction between living, purposeful, systems and merely mechanical/chemical systems. Life, as a state of matter and energy, has an overall objective function that leads to perpetuation of form and function. It is teleonomically purposive[5].

Human artifice is an ontogenic process that introduces an element of cognitive purposiveness. Humans, by virtue of their ability to construct complex models of things in their

[4] This is opposed to a "purely" random process in which there is no directed flow of energy, just an ambient temperature. For example, an adiabatically isolated system such as an insulated flask of gas molecules will be subject only to random encounters and chance combinations.

[5] Teleonomy, as opposed to teleology, recognizes an Aristotelean final cause in the sense of an end purpose. In universal evolution we see that the Universe appears to produce increasingly complex, hierarchically organized entities – systems. See the Wikipedia article: https://www.ecologycenter.us/ecosystem-theory/the-maximum-power-principle.html for background. Accessed 5/19/2019.

mental representations (Mobus & Kalton, 2015, Chapter 1, Principles 9-12), are able to ‘imagine’ what a new or improved thing could be. They can test, to some degree, manipulations of the thing mentally before actually building that thing. The evolution of animal life led to the emergence of brains able to conceive of new arrangements of matter and energy in virtual reality (that is mental space). The conception may be motivated by some desire to achieve a goal – the new thing may be instrumental in solving a problem – and the mental manipulations are essentially simulations of how well the new thing will work toward that end. Those mental simulations may result in further modifications of the ‘design’ of the thing. Motivation and mental simulations contribute to the meaning of the word ‘intentional’ coupled with ‘organization.’

In this chapter we explore this new kind of ontogenic cycle, involving intentional-organization (including the selection processes that lead to extinction or further improvements) and purposive construction of artifacts. We bring everything together to describe the general principles and approaches to systems design and engineering of complex adaptive and evolvable artifacts.

13.1.1 What is an Artifact?

What do we mean by an artifact? Fundamentally, anything that comes into being by the devices of human artifice, anything conceived of and constructed by human effort, and anything that could not exist or come into being by mere physical or biological evolution is what we shall call an artifact[6]. This includes not only physical devices of various kinds, but also the design of sequences of actions, procedures, methods, etc. that produce other artifacts. A computer program that results in a physical output (however transient it might be) and its underlying algorithm(s), is an example. We also include organizations and institutions such as commercial companies or the market economy. We include governments and city- or nation-states.

In other words, everything that humans have created from their attempts to improve their existence counts as artifactual[7]. Chimpanzees have social organization as a natural consequence of their social psychological natures (de Wall, 2005, 2010, 2014, 201616; Tomasello, 2014, 2016, 2019). They didn’t invent them. Humans also once had naturally evolved social organizations (i.e. the tribe), but the various forms of contemporary societies demonstrate the inventive urge to do things ‘better’, which, of course, is a relative term.

[6] This includes non-useful by-products of human artifice such as sawdust piles or rock chips resulting from flacking a stone to make an arrowhead.

[7] Artifacts are still considered ‘natural’ in the sense that what humans are and do is still the result of natural evolution, so by extension, their artifacts are natural outcomes of the ongoing process. The human capacity to invent and construct artifacts represents a major transition in the senses used by Maynard Smith & Szathmáry (1995) and Morowitz (2002). See also: https://plato.stanford.edu/entries/artifact/ for a philosophical treatment of the nature of artifacts.

The sum of artifacts constitutes the cultural milieu above natural human sociality and moral behaviors.

Various kinds of artifacts we include:

- Physical objects, tools, toys, etc.
- Methods and procedures – ways of doing something, including algorithms for performing computations, manufacturing process instructions, and interpersonal interactions, such as rules of manners
- Institutions and organizations – social structures that facilitate cooperative behavior (e.g. moral and ethical norms), production of artifacts, governance, and economic exchanges. This includes societies with cultures and social norms, governments, and economic structures like markets
- Policies – abstract rules for regulating the above.

In this chapter we will be interested not only in artifice itself, but how it is accomplished and how it has evolved with the evolution of human knowledge of how the world works – or, in other words, with systems knowledge. Since the invention of writing and mathematics, humans have accumulated impressive knowledge about materials, mechanics (including electronics), and conceptual architecture/design. This knowledge is passed down to new generations along with the methods for using the knowledge in creating new things. Culture has been growing in 'bulk' and complexity ever since.

13.1.2 Artifact/Cultural Evolution

Initially humans probably did more tinkering and used trial and error methods to see if their 'invention' worked as intended. When they didn't work, humans wondered why, which led to investigations and more trials employing variations. In this tinkering with reflection on results, they learned what variations worked and which ones didn't (so-called "best practices".) Human understanding of causal relations in the world of artifacts had to go through a 'bootstrap' procedure, the gradual accumulation of knowledge of how things worked and didn't (c.f. Carey, 2016 for a thorough treatment of the origin of and changes to concepts.)

The accumulation of knowledge through the Paleo- and Mesolithic was slow; cultures remained remarkably similar with only minor improvements, for example in the knapping of stone tools. Then in the Neolithic and early Bronze Age, people began to take things like measuring time and distance seriously, recording the results of various 'tinkering' and using those more formal characterizations to learn to reason about the rules for how the world works. The Agricultural Revolution (approximately 10,000 to 12,000 years before the present) also saw the invention of recording symbolic messages on external media (clay jars and tablets). The emergence of civilizations (particularly in the Middle East, roughly modern-day Iraq), was possible because of the inventions of measurement, recording (numbers and names of commodities and owners, etc.), and accounting (Nissen, Damerow, & Englund, 1993)[8].

Humanity embarked on a scientific procedural formulation of how to more rigorously conduct those investigations. As scientific knowledge grew so too did the application of that knowledge to the prior design and engineering of artifacts. And those artifacts became more complex as well as more functional and esthetic over time. Humans learned to live in settled locations where they could practice agriculture (Scott, 2018). They became 'entangled' in ever more complex webs of relations and dependencies on the things they created (Hodder, 2012).

In the modern, highly technological age, human beings have begun to design and engineer extremely complex artifacts. Specifically, in the age of so-called "smart" devices that are connected to one another, we have reached a position of trying to engineer CASs and CAESs. This is having powerful consequences on the process of design and engineering itself. We need to re-envision the process in light of emergent behaviors that inevitably arise from the construction and operation of adaptive networks of adaptive agents (e.g. The World Wide Web as an evolvable system).

Thus, we will introduce a new way to look at design and engineering of artifacts (including the socio-techno-economic systems we call modern societies). This new way derives directly from the prior chapters defining and demonstrating how we should use principles of systems science to deeply understand CAS/CAESs. And, in particular, it derives from our current understanding of ontogenesis from Chapter 2 wherein auto-organization is replaced with intentional-organization.

Engineering has been perceived and characterized as a positivistic and deterministic process. Apply the mathematical models from nature to the design specification and you will be able to produce an artifact that does precisely what was intended. When designing and engineering various 'complicated' machines in the late 19th and early 20th centuries this actually worked fairly well. On the other hand, the experiences of the last half century, particularly in the realm of software engineering, demonstrate that this deterministic attitude is not correct. Recall the discussion of what goes wrong in section 1.5. As we develop more and more complex artifacts (hardware, software, mechanical, etc.) we begin to see too many things going awry with them, too many bugs and glitches, too many failures to operate properly even when the artifact was built to specifications. Even more importantly we witness the emergences of behaviors unintended and unpredicted from the poorly understood interactions between complex components operating in multiple time domains. And it suggests that the process of designing and engineering them is fundamentally flawed, or at very least missing something important. The reason that our approach to design and engineering is no longer serving us well is that the overall complexity of our artifacts has reached a tipping point. High complexity in systems breeds

[8] See the Wikipedia article: https://en.wikipedia.org/wiki/History_of_the_Middle_East#Ancient_Near_East for background. Accessed 8/6/2019.

emergent properties and behaviors, as we have seen. When our machines were merely complicated (like an automobile of the last decades of the 20th century) the deterministic approach to design and engineering worked very well. But even as this is being written, we are embarking on a new path for creating truly complex machines (let alone organizations) in which we seek to embed adaptive components (so-called smart technologies). We are now experimenting with self-driving vehicles and are being surprised by unexpected behaviors. A whole new field called "Systems of Systems" has emerged in which embedded devices interact with each other, a stochastic world, and human (uncertain) behaviors. From systems science, and especially from the nature of evolutionary development, we know that we should expect many surprises as we continue to push for increasing complexity toward adaptive and evolvable systems.

This, in turn, suggests that it is time for a new paradigm for design and engineering. We will suggest that this new paradigm involves the explicit role of evolution (and the ontogenic cycle) as being a fundamental part of artifice. Culture, including its artifacts, evolves. The forms and functions of artifacts evolve from generation to generation already.

The key difference between biological evolution and cultural evolution is that the latter includes a brand-new factor, itself having been a product of biological evolution, which changes the dynamics of increasing complexity in ontogenesis. That new factor is *intentionality* as previously mentioned. Human minds do experiments (both as mental models and as tinkering) in an attempt to solve a problem with some kind of artifact. They intend to improve their own conditions by altering the environment through the use of artifacts. Cultural evolution is still Darwinian-like evolution but with different mechanisms for replication, variation, and selection (Buskes, 2013). The development of all the components of cultures is still explained by the ontogenic cycle. But now we need to recognize the role of human intentionality as a factor in determining the various stages of ontogenesis. Humans direct the organization process (replacing auto-organization with intentional-organization) even though it still retains an element of non-determinism depending on the degree of complexity. They are still doing some degree of tinkering. And humans act as selection forces in several different ways. They are involved in the use of artifacts and determine their desirability or utility. Those deemed less fit will succumb to obsolescence being replaced by newer, better versions.

13.1.3 The Artifact Creation (or Improvement) Process

Human beings, and to a limited extent some other species, employ behaviors intent on changing some aspect of their environment in the service of their own advantage. Beavers construct complicated dams that alter the flows of streams to create ponds that act as moats for their protection while raising their pups. Bower birds build elaborate bowers to attract mates. Often this takes the form of using some kind of 'tool' to acquire otherwise inaccessible resources. Crows, for example, are known to use twigs to dislodge food from tight places. Chimpanzees fashion fishing sticks to obtain termites.

Affordance is the capability of an animal to 'imagine' the use of some existing element, like a twig, to serve their own purposes. Second-order affordance is the ability to see how to modify an element in order to be better able to serve. In humans we witness third-order affordance in their abilities to see how to combine several existing elements, naturally occurring or previously manufactured, in new ways (invention) to accomplish those ends. And this is the beginning of design and engineering.

Consider a stone ax as developed during the late Pleistocene era by early *Homo sapiens*. Humans had already been fashioning and using stone cutting tools with some heft to them that could be used to butcher large prey or cut down trees (slowly). They had also already been using wooden clubs to beat rivals (as depicted in the 1968 film, *2001, A Space Odyssey*[9] where a primitive hominid primate conceives of the use of a femur bone to bash an opponent from another clan) or prey. They also knew how to use sinew from animal skins to bind things. It was, however, a major advancement in technology to recognize that a new kind of tool could be made by combining these three elements in the right fashion to produce a much more effective wood cutting tool. This is third-order affordance and the basis of the human ability to conceive of and construct complex artifacts.

But another cognitive factor has to enter the picture before a human being conceives of how to construct an artifact for use, namely the conceptualization of the need. Needs are the result of the biological mandate that motivates growth (and reproduction) against the problems posed by an environment with limited resources, namely energy and materials. What all biological systems seek is the accomplishment of getting food and avoiding being food. Anything that will help get these done more efficiently, which is with a lower energy expenditure per unit of growth, is to be pursued. For humans this is experienced in the form of three related motives.

Convenience means that a task or chore can be done by an artifact, generally a machine, rather than require human labor. Buying groceries at a store means that people don't have to spend time and effort growing, harvesting, and preserving foodstuffs themselves. Related to convenience is the ability to do things quicker by using an artifact. Going to the grocery store in an automobile is much faster than going in a horse-drawn wagon. And even the latter is faster than walking into the field to hunt a rabbit. All of this reduces the amount of effort that an individual or society needs to expend on the tasks that can be accomplished "better" using artifacts (like stores and cars). Humans, like all other living systems, seeks the minimum energy state of affairs, looking for leverage to conserve biological energy. Where humans have transcended the usual biological constraints is the use of energy-channeling artifacts and the supply of high-powered energy sources other than their own. The result is a positive feedback loop for generating ever newer, more efficient and faster artifacts (and here we mean primarily machines and technologies) that provide more convenience and save time.

[9] See the Wikipedia filmography article: https://en.wikipedia.org/wiki/2001:_A_Space_Odyssey_(film) for background. Accessed 3/5/2019.

We should note that the ability to produce more goods and services faster also allows humans to spend time on creative endeavors such as painting and movie making. Here too, though, improvements in artifacts (like CGI for motion pictures) forms part of a positive feedback that promotes an ever-expanding cycle of ontogenesis and increasing complexity.

13.1.4 The Artifact Cycle

The artifact cycle, we will argue, is just another version of the ontogenic cycle introduced in Chapter 2. Recapping that chapter, the cycle involves auto-organization of elements combining to form more complex entities under the influences of energy flows and geometric constraints (boundaries). Those entities display new emergent properties and behaviors. These emergent properties and behaviors are then subject to selection forces in the extant environment, including interactions with the other new entities just emerging. Said new interactions, due to emergent potentials, lead to the next round of the cycle. Since each round of combining and interaction leads to more complex entities, we can think of the overall process of ontogenesis as a spiral that grows on the complexity scale over time, what Teilhard de Chardin called “complexification” (recall Figure 2.6).

The artifact cycle is fundamentally the same but with the twist as noted above; the introduction of intentionality in the organization phase.

The organization process is not as subject to random encounters as, say, is the case in chemical interactions. This is not to say that the combination mental modeling is not subject to some degree of randomness, or is in some ways stochastic. The human brain is not a deterministic modeling engine like a digital computer. It does not have detailed representations of the components it seeks to combine. It makes mistakes in judging interactions, e.g. not completely understanding the “personalities” of the various components. Moreover, it might not have a complete grasp of the problem it is attempting to solve – that, after all, was the point of using the deep analysis methodology promoted in Chapter 5.

Even so the artifact cycle introduces an element of teleology, an end purpose, into the ontogenic cycle. Prior to the introduction of human purpose, evolution was non-teleological. It was “blind” to purpose, purely experimental in the search space of biological possibilities. Chance and necessity

Artifact evolution is the result of on-going attempts to invent new combinations of component artifacts in the cycle and to improve on existing designs of artifacts, which often involves an organization stage itself (recall Principles 11 and 12 in Chapter 1).

Cultural evolution combines artifact evolution and mental model evolution, which is to say what humans believe about themselves and their world. These two domains of evolution are locked into a kind of dance, co-evolution, which results in increasing complexity in both. As per the principle of complexity described in section 1.3.5 (Chapter 1) the increase in complexity of a system is achieved by modularization and increasing the depth of a hierarchical network. It turns out that how the brain represents concepts exactly replicates this phenomenon (Carey, 2009). The human mind is capable of representing an incredibly complex world through the modularization of concepts and the organization of hierarchies of categories and kinds, e.g. my pet is a dog, a dog is a mammal, a mammal is an animal, etc.

Complexity itself cannot grow without boundaries. The human brain has limitations in terms of what it can ultimately represent about the world. As that world becomes increasingly complex the human mind may rebel at having to learn so much new stuff and at increasing rates. This is just as true for artifacts as for natural systems. At some point our artifact designs are more complex than any one mind can represent in totality. After a brief survey of the formal design and engineering procedures that we currently adopt to produce artifacts we will consider the implications of the increase in complexity rendered by designing CASs and CAESs. We are just at the beginning of building limited CASs on purpose, that is intentionally. As we proceed down that route, and the motivation for doing so will be explained below, the nature of the design and engineering procedure must itself become more complex! Complexity begets complexity for a purpose. And then the world will determine whether the increase was worth it.

With the advent of the industrial age, the artifact cycle has been formalized into what we will call the design-engineering (DE) process where intentions themselves are encoded into forms that can be manipulated directly, and modified. At first the DE process was applied only to physical artifacts, machines, bridges, buildings, etc. Organizations, institutions, and nations (generically, societies) were generally left to form and organize at the whims of the people doing the organizing[10].

The DE process actually includes the up-front mental modeling, these days assisted by a number of formal tools (e.g. computer-based modeling languages), as well as a more formal approach to testing, deployment, and as-used feedback (for guiding improvement in future versions). The artifact cycle is employed in the creation of new physical products but also in the creation of new policies and procedures in organizations. The basic process is outlined in the next subsections.

13.1.4.1 Realization of a Need

Also called recognizing a *problem*. A problem exists when a perceived or desired need cannot be met by any existing artifacts. It could be that no relevant artifact exists or it could be that current artifacts need refinement or adjustment in order to meet the need. Our first furless ancestors experienced a need when the climate in East Africa began to cool and they found themselves without protection. They would surely have understood that they were experiencing the colder weather and needed more than a campfire to keep warm.

[10] Chapter 15 will more deeply address the design and engineering of societies.

13.1.4.2 Conceptualization

Seeking a mental model of what kind of artifact could possibly alleviate the need is called conceptualization. This is the use of imagination and affordance in the construction of an idea of what the artifact should be and how it should fulfill the purpose ascribed to it. Returning to our ancestors, one or more, at some point, noted that the animals they hunted that had furry coats seemed to be immune to the chill. They imagined using their hides (which were basically inedible) to cover their own bodies. They conceived of clothing.

13.1.4.3 Architecture

Architecture is generally considered a transition activity moving from concept to design. This phase involves larger-scale aspects of the artifact but particularly how the artifact will interact with its environment (e.g. serving the needs of users). The '*architecture*' can be considered as a kind of first pass at design, establishing the major aspects of the to-be-created new artifact. Several activities, such as modeling and applications of patterns, are similar to what happens in design (see below) but at an abstract level. In systems terminology, an architecture corresponds with the system of interest looked at as a whole or possibly the first one or two levels in the hierarchy depending on how complex the artifact is in fact. The design, then, will correspond to the rest of the analytic hierarchy deeper into the system. Sticking with the example of early human clothing, the architectural phase would identify the main components, say breeches, torso covering, etc.

13.1.4.4 Design

Conceptualization and architecture provide only a fuzzy representation of the artifact. A person can create a mental picture of what the artifact should be like and what it should do, but then comes the act of formulating an actual design (also called a "detailed design"), that is the design of all of the subsystems down to the level of components. In the modern world so much knowledge of what works and what doesn't work in specific circumstances and for specific needs has been accumulated that design (and engineering too) is approached based on existing models or patterns of structures and functions. The basic patterns of the design, for example, of a jet aircraft engine, are well known and available to base new designs on. Whatever conditions exist that are new, e.g. heavier aircraft to propel, can be handled by modifications to the basic patterns, for example, by scale modifications such as has been the case for reduction in scale of electronic components on integrated circuits. Opportunities for including new features show up during the process so modifications in the basic patterns can be handled. With modifications new patterns in the family of patterns for that artifact are created and added to the family. Thus knowledge of design approaches increases.

Once again, to belabor the example, the design of cloths would include 'specifying' the layout of the legs and considering how long they should be.

13.1.4.5 Engineering

Using the best scientific knowledge of how things work, in general, engineering is the activity that formulates a design specification for a particular artifact so that it fulfills its purpose, that is attaching numbers to the dimensions, flows, and capacities. An engineered design ensures that all the parts fit together and perform their functions according to the needs of the wholes system. Whereas architecture and design specify what the parts should be and what they should do, engineering, based on detailed knowledge of the physical properties of the components and how they will interact with one another, assigns numerical values to the specifications.

The animal hide pants need to be sized to fit the "customer" and the method of stitching with sinew of a certain thickness determined.

Engineering also considers the mechanical aspects of how the artifact is to be constructed, tested, deployed, and used in the field.

13.1.4.6 Construction, Deployment, and Use:

Artifacts are built through various construction procedures dependent on what sort of artifact it is. Obviously computing systems differ from propulsion systems and all physical hardware systems differ from policy implementation procedures and institutions. These latter are just as 'constructed' as are machines so this formal procedure applies in some form to them as well.

The afore mentioned pants are constructed by cutting the skins to the right size and sewing the legs to form column-like extensions from a abdomen-skirting base. The customer can then try them on!

Deployment refers to the actual placement of the artifact within its environment of use. This may involve installment, training of personnel, and other subsidiary operations needed to join the interfaces between the entities in the environment and the artifact, for example training pilots to fly a new aircraft.

A complete, closed-loop, procedure also involves collecting data on performance and as-used in the field. Data on problems encountered during use should be analyzed and fed back to one of the previous stages depending on the nature, e.g. perhaps a major subsystem turns out to not be appropriate to the overall performance or mission of the artifact and needs to be re-architected. The on-going performance and uses of the artifact will also be used as feedback input to the next round of the DE procedure when a new generation of artifact is needed.

The next phase of artifact design, however, will transcend the human monitoring and improving cycles. Today we are seeking to produce artifacts that can adapt to variations in their environments to remain stable and preform properly. Additionally, we seek artifacts that can learn from experience, approaching an ability to evolve with changed conditions in their environment. Ultimately, we look at the need for artifacts to emulate biological-like evolution, allowing internal modifications to take place in the process of seeking increased viability and sustainability. Our cultural systems, such as organizations and governments, are already evolvable, but not always with insights that prevent or at least lessen unintended consequences. We need to better understand intentional-organization and evolvability to do a better job of designing such systems. That will start with an approach to understanding the application of the CAS/CAES architypes to the DE process.

13.2 CAS/CAES Artifacts

The current DE approach to engineering has worked reasonably well for many kinds of complex artifacts such as machines and business processes and with humans in the loop to detect problems and reactively mitigate them the artifacts tend to perform reasonably well over the long term. Human beings are the components of such systems that provide the ‘adaptivity’ aspect. That is, the artifact in combination with users and maintainers constitutes a CAS capability. But when we enter the realm of complex adaptive artifacts in which adaptivity is to be inherent in the design of the artifact and not just dependent on the human factor, the situation changes quite drastically[11].

Artifactual systems need to be designed to incorporate adaptive components because they are becoming so complex that humans in the loop cannot be expected to understand all of the operating parameters sufficiently to know what to do in case of deviations from the norm in operations. Moreover, and more importantly, humans cannot react fast enough to some kinds of environmental changes that can disrupt normal operations. Think of the situation with a nuclear power station in the face of tsunami flooding as happened at the Fukashima Daiichi Nuclear Power Plant in Japan. Human reactions might not be fast enough in many time scales to keep the station from catastrophe. Or consider a pilot of a commercial jet when confronted with unusual turbulence while on auto-pilot. If their training is adequate and they are awake at the yoke things might turn out OK if they react in time. But what if they don’t?

At the time of this writing we are exploring many artifacts that will require built-in adaptivity. There are a number of autonomous mobile machines that will need to be able to react to unanticipated conditions in their environments. But real adaptive response or even anticipatory actions, as described in Chapter 9 will require much more than mere ‘learning’ (really training) no matter how ‘deep’ it might be. At a minimum to achieve real adaptivity it will require an agent with the ability to modify its learned models with the accumulation of real-time experiences. Methods for real-time, on-line learning will be needed as well as a principled

[11] Indeed, the motivation for putting ‘smarts’ into our artifacts is in order to get humans out of the loop! Machines that have internal subsystems that can adapt to changes in their environment should, in principle, not be subject to human foibles such as falling asleep at the wheel.

approach to concept modification[12]. One promising area for this is the use of Bayesian networks[13]. See section 13.2.1.3 below.

Truly evolvable artifacts, as of now, are found only in social organizations where human beings exercise some forms of strategic management and construct entirely new subsystems in response to perceived permanent changes in environmental conditions. See section 13.2.1.4 below for a discussion on persistence to be achieved in CAESs.

In the next chapter we will cover the methods for DE based on the CAS/CAES archetype along with the other component archetypes. In what follows we will assume the use of those models to guide the DE process.

13.2.1 Design and Engineering for Increasingly Complex Artifacts

In this general discussion of how artifacts come into existence, and evolve over time, we collapse the various stages of the DE procedure into a single overarching category, "engineering," since the kinds of activities outlined above are similar in all of them varying only in details and precision. They are stages of refinement of the detailed design of an artifact so we will collapse them into that single rubric.

Systems engineering (henceforth, SE) has come into focus from the realization that many artifact projects are becoming increasingly about complex systems. We've mentioned a few in the opening chapters of the book. But even complex systems such as a passenger airliner or a supercollider can be developed using traditional design/engineering methods augmented with systems level purview. As mentioned above, as long as human operators are in the loop to provide the adaptivity component these complex systems generally work. The same is true for business enterprises in which talented, smart people are manning the desks and sales counters. The same may be argued for local, smaller, governments, such as cities and counties. It is becoming increasingly evident that when the scale of government exceeds some level (say a state like California) it works less well. Human decision makers cannot adequately compensate for poor mechanisms of governance. This is not just a matter of the heterogeneity of the population and range of physical characteristics, economic interests, industries, etc. It is now appearing to be a core problem with the way governments are "designed." Recall the discussion in Chapter 11 of the nature of governments of various scales.

[12] Here we only consider modification of existing models (concepts) as opposed to construction of new concepts, which is considered under the heading of evolvability.

[13] See the Wikipedia article: https://en.wikipedia.org/wiki/Bayesian_network for background. Accessed 1/30/2020.

At present, a systems engineer[14] is someone, usually coming from one of the traditional disciplines, who possesses a high-level vision of the whole project and manages a number of data tools that keep track of components and processes that involve multiple traditional disciplinary engineers[15]. In the typical process none of those specialists need understand or even know much about the engineering of other components from other disciplines. The electrical engineer need not know what the metallurgist does about the wing material. But someone sitting high above the whole operation needs to know what needs to be known, by whom, and when to apply that knowledge.

Even in the realm of merely complex systems the role of the systems engineer is formidable. To date there seems not to be universal agreement on what it means to be a systems engineer[16]. Nor is there total agreement on what a systems engineer does. Different organizations adopt various standards and practices with, naturally, variations in effectiveness.

In this book we have made the case repeatedly that at least part of the problem has been the lack of a real science of systems. Mechanical engineering is informed by several areas of knowledge in physics. So too, is electrical engineering. But systems engineering (and its companion design process) has very little systems science informing it. To be fair the systems engineering community is acutely aware of this problem and some are trying to rectify the situation. There are several groups and projects within the community trying to define systems science so that they can get on with the work at hand. This author has participated in several of these but remains somewhat skeptical as to the progress or the results to date. The "ordinary" sciences were not "defined" by engineers but grew in understanding as a result of scientific investigation. Being fair, we should note that engineering practices did often provide useful information to the science practices, as when experiences with designing more efficient heat engines in the 18th century provided useful data in formulating the theories of thermodynamics.

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[14] A reminder that by "systems engineer" we include people who design and develop processes and policies. In the discussion here we mostly describe engineering in the traditional sense, e.g. mechanical, since this involves the most rigorous design and engineering standards.

[15] Things are slowly starting to change in the USA. There are an increasing number of mechanical and industrial engineering degree programs that include some systems engineering in their curriculum. Additionally the Accreditation Board for Engineering and Technology, Inc. (ABET) is planning to develop a set of accreditation standards for any academic program that has 'systems' in its degree title.

[16] Though note that several engineering professional organizations have attempted to codify standards for processes and data tools. For example, the International Council on Systems Engineering (INCOSE) has published an extensive document, the *Systems Engineering Book of Knowledge* (SEBoK) available on-line at: https://www.sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK), accessed 3/4/2019.

Consensus among systems scientist about what systems science *IS* is also not at hand. Within the systems science community the majority of people today[17] are involved with using "systems thinking" to guide their application of systems concepts to specific problem domains. This, too, is problematic since these concepts have not yet been formalized (as was suggested in Chapter 3 of this volume) in a way that can be readily applied to applications. Thus, at present, the basis for systems design and engineering (as well as more general problem solving) is sketchy at best. This is indeed a problem since the continuing trend toward producing more complex systems continues unabated.

Consider, however, that if the systems design and engineering process for merely complex systems is still wide of the mark, what then will be the case for complex adaptive and evolvable systems? Throughout this book we have argued that such systems can be understood deeply through the application of an adequate formal process (chapters 5 and 7) and an underlying formalism (given in chapters 2 and 3). We looked at examples from the biosphere and the noosphere. Socio-techno-economic systems along with their governance infrastructures are CAESs of the highest order. Moreover, we have noted that it might be useful to consider actively working to design and engineer such systems so that they actually do the job of keeping human beings alive and thriving on the planet. DE for such systems has to meet several important objectives.

13.2.1.1 DE for Purpose

Every system interacts with other systems in the embedding meta-system. Some of the outputs of the SoI should be of value to some other systems, that is, they should be products that serve the purposes of the whole by being of value. In general, the system to be designed must serve this larger purpose. It will do so by internalizing the larger purpose into its own governance system (see below).

Value, however, needs to be carefully examined. Humans as recipient systems have valued faster, more powerful vehicles for transportation, so the designs of, for example, cars that consumed larger amounts of fossil fuels were previously deemed designed for that purpose. Now we come to realize that that purpose is antithetical to a healthy planet. SE cannot just look at the immediate 'customers' of the system's outputs. They need to examine a much larger environment that will be impacted by the operations of the system. They must consider longer time scales and issues such as resource depletion as well as consequences of waste and by-products. They must consider the rates of flow versus the volume of stocks relative to the larger environment's capacities. These are, of course, not simple issues to consider. And they could bring into question the original purpose of the system.

[17] Ascertained from an informal observation of the interest groups and kinds of papers/presentations given at the annual conference of the International Society for the Systems Sciences (ISSS, see the Wikipedia article: https://en.wikipedia.org/wiki/International_Society_for_the_Systems_Sciences for background.

13.2.1.2 DE for Resilience – Adaptability

As we seek to deploy our artifacts in environments in which numerous factors demonstrate high variability in values affecting the system, we will want to design adaptability into the system that is not necessarily dependent on human capabilities.

The various forms of adaptivity were covered in Chapter 9, under that heading. These models of adaptivity were derived from living systems examples but have been explored in artifact autonomous agents (Mobus, 1999; Mobus & Kalton, 2015, Chapter 9, section 9.6.3.1).

There have been a number of engineering forays into adaptive systems that will continue to be important for systems, such as adaptive filters and adaptive controls. Thus far, these explorations have not extended to the wider variety of adaptivity mechanisms as seen in living systems, but we expect that with the use of the systems approaches advocated in this work, there will be an array of opportunities and methods that will allow the DE of more broadly adaptive autonomous mechanisms (modules) in future designs. It bears stressing here, however, that the current spate of artificial intelligence (AI) applications, using 'Deep Learning' neural networks does NOT produce autonomous adaptivity. Such 'AIs' learn through supervision and only laboriously (many iterations of exposure to target patterns). The deployed AI-based agent cannot adapt to conditions for which it was not trained; such conditions should be expected in the real world. The author (Mobus, 1999, 2000) has provided a model of autonomous adaptivity in an artificial agent that is more like that found in animals. More advanced AIs might be able to use that or similar methods to become truly adaptive.

Systems engineering is challenged with the need to build resilience into designs that will increasingly rely less on human reactions to changing conditions and more on the system's own ability to adapt. Reactive capability is already being designed into artifacts; think cruise control. These kinds of devices are not much more than a proportional response "thermostat." They respond to variable demand with proportional response. Real adaptivity is another matter. That requires the system have a modifiable memory of the trend in conditions.

Adaptive response is the ability for a system to change its response "curve" as a result of on-going experience (Chapter 9 and Mobus & Kalton, 2015). Note that what we mean by adaptive response is not the same thing as merely response to changes in environmental conditions (e.g. ordinary homeostasis). Essentially the phenomenon is demonstrated in biological systems. For example, consider what happens when a person decides to work out with weight lifting to build muscle mass. Initially, lifting weights takes considerable effort and requires more energy to accomplish. But after repeatedly and often exercising, the muscles grow in bulk and the energy required to lift the same amount of weight in any one repetition is less. The body has adapted to the demand for doing more work than had been normal by building the capacity to do so. The muscles constitute a memory of past demands and will be at the ready for future demands. It turns out that the amount of energy needed to maintain the additional capacity is less than the energy needed to respond to the demands when those demands are made relatively frequently over time.

In the realm of artifacts, we are just entering an era of adaptive response designed into machines. Specifically, computational systems implementing forms of reinforcement learning have the ability to modify their responses to changing demands (c.f. Mobus, 2000). It will be interesting to see if adaptive response can be developed for mechanical aspects of artifacts, emulating the muscle development example. More likely it will involve a combination of mechanical and computational processes as in the Agent model described in Chapter 10.

For social systems such as organizations the capacity for adaptive response already exists but is not generally recognized as such and thus not particularly well managed. Organizations do adapt to trending changes. For example, when the demand for a product increases, the manufacturer will increase capacity, perhaps through capital investments in more equipment or space. What is less clear is how organizations respond to fluctuations in demand, as in a non-stationary environment. What happens when the demand for a product declines and investments have already been committed? In some sectors we see an increasing reliance of “flexible production cells,” reconfigurable robotic systems that can readily be reprogrammed to produce other products as demand changes. Another example of adaptive response in the business world is the supply chain. Of course, in this instance it is the final retailer that benefits from an ability to flexibly switch from one supplier to another as demand changes, not necessarily the suppliers.

13.2.1.3 DE for Sustainability – Governance

In Mobus (2017) the author lays out the requirements for achieving a sustainable, that is, a lasting, CAES. Every complex system requires management mechanisms in order to assure continued reliable performance of the parts, interactions between the parts, and between the whole system and its environmental conditions (as they change).

The design of a CAES is as much about the design of an appropriate hierarchical cybernetic governance system (HCGS), covered in Chapter 11, as it is about the functionality of components. Our experience with designing organizations (and maintaining their functioning) has provided a number of examples of this and should be considered as a prototype for the designs of all CAESs.

13.2.1.4 DE for Persistence – Evolvability

Artifacts are constantly subject to modification in design followed by a selection process (for example how well the artifact does in the market – how well it sells). Later in this chapter we describe a process of intentional-organization, mentioned above, that replaces the auto-organization phase in the human development of artifacts. So, in a larger sense in which human designers are a part of the on-going evolution of artifacts, ontogenesis is at work. But what we seek is something that is, like the adaptivity described above, autonomous. That is, the artifact is, itself, capable of evolving to be sustainable and persistent in the face of a changing environment.

As already pointed out, our ordinary machines are far from evolvable. The first artifact that humans have created that approaches evolvability is the Internet and the World Wide Web (WWW). But even here, the evolution depends on some human intervention. For example, the Web has been subject to revisions in its underlying protocols and the browser technology (software) has been developed to allow more interactivity, etc. The most one can claim about the autonomous evolvability of the Internet/WWW is that the network of nodes and links (e.g. web pages and hyperlinks) can be characterized as an evolving graph (Barabási, 2003).

So, what would it take to design and engineer a truly autonomous artifact that was able to evolve in response to changes in the environment? This is quite obviously an open question. But it is a question that deserves attention as our artifacts are becoming increasingly complex and expected to do significant work without humans in the loop.

The epitome of CAESs is those that can alter themselves in response to significant long-term changes in the environment. As already noted, this goes beyond the notion of adaptivity, which is just a system's built-in capacity to respond to short-term changes that lie within an operational range. As demonstrated in the muscle-building example above, the body can respond to increased demand for muscle power to lift heavier weights, but within limits. What the body can't do is grow a whole new muscle group to handle demands beyond that range, or to address a completely new kind of movement. This would require evolution. Many kinds of systems are evolvable. We count the human brain, by virtue of the neocortex's ability to represent what might be considered an infinite variety of concepts, as an evolvable system even if the body is not. Organizations have a capacity for evolving in the sense of being able to learn from experience (Senge, 1990) though most organizations seem not to be able to do this very well[18]. To make evolution and learning realizable requires a working strategic management layer in the HCGS subsystem. Some organizations have cognizant CEO's, the ones who are nominally tasked with strategic management. But, unfortunately, most heads of organizations do not really understand the concept, as presented in Chapter 11.

Biological genera are evolvable, i.e. speciation in response to changed environments. So too are human organizations. They can make varying scales of changes internally to accommodate changes in their environments. This ability requires the most advanced aspects of the HCGS and governance capacity, strategic management and highly adaptive tactical management. The

[18] In fairness this subject is actually well understood by, for example, organization systems scientists like Peter Senge (1990) who has characterized the 'learning organization.' The subject is often encountered in business school curriculum regarding management theory. However, critiques of how well the concepts are adopted have shown that real organizations, particularly those that are profit-oriented, have great difficulty implementing the requisite mechanisms and culture. See the Wikipedia article: https://en.wikipedia.org/wiki/Learning_organization for background. Especially look at the section on "Barriers" to see why the claim in the text generally holds.

organization has to possess the ability to acquire new resources and their needs to be an internal mechanism for implementing new processes/subsystems to carry out the strategic directives.

In the design of autonomous CAESs, the designers will need to understand the need for and implementation of strategic and adaptive governance subsystems in order to achieve full CAES capacities. They will need to design and engineer for all of the above capabilities. This is "virgin" territory in so far as the DE enterprise is concerned. It extends far beyond mere complexity. It is needed for the "management" of complexity. For autonomous systems, those not relying on human intervention to cover adaptive responses, this designing of an adequate strategic layer in the HCGS will be a major challenge and a focus of needed research. Below we will address some ways to consider evolvability in CAESs through the modeling process. Essentially this involves (as noted in Chapter 5) the tagging of certain components as "evolvable" and providing parameters for the ranges of variations (of different kinds). In simulation runs we introduce new elements or changes in conditions beyond the range of adaptivity which then trigger an evolvable response to the affected components. That response may be stochastic, replicating genetic mutation, for example, but it still involves intentional response.

The most advanced artifacts that humans have yet built (but not necessarily designed or engineered) are our societies with their various cultures and economic subsystems. These are systems in all of the senses developed in this work. They are the product of a species-wide auto-organization processes with intentions generally limited to local problem solving. Let's designate such systems as socio-techno-economic artifactual systems (STE or cultures for short). We assert, without an attempt to prove it here that the natural auto-organization and subsequent emergence/selection processes of ontogenesis has created something of a conundrum. Our societies are operating in ways that are a major threat to the Earth's biosphere (see Christ, 2019, esp. chapter 1). Perhaps it is time to think about systems design and engineering being applied to the design of societies that can achieve the above requirements for autonomous CAESs embedded in a super complex world. This is, in fact, what we will outline in the final chapter of this book.

13.2.2 Design Considerations

Here we review several DE considerations that have appeared throughout this book. These are overall architectural aspects of all CAESs. They are essential to incorporate into any CAES artifact. In what follows we assume the reader understands that the analysis of the CAES SoI has been (or is being done) in accordance with the procedures given in Chapter 5. That is, the system as a whole is the original SoI, is analyzed in terms of its environment and interactions with elements of the environment followed by recursive decomposition. This procedure ensures that functional and structural modules (e.g. work processes) will be properly identified. It also ensures that the complex networks of material, energy, and information flows are properly mapped within the SoI. The recursive decomposition will reveal the hierarchical network structure of subsystems. Finally, the capture of dynamic properties at each level in the hierarchy ensures that appropriate time scales for behaviors are recognized. Lower level component subsystems operate on smaller time scales than higher level ones and it is necessary to get this right in order to avoid some of the more typical blunders that have been seen in too many systems engineering efforts.

13.2.2.1 Structural and Functional Modularity

Throughout the book we have emphasized that complex systems are composed of sets of interacting modular components. Modularity is one aspect of the management of complexity. By designing modules that are functionally and structurally "limited" we keep them, relatively speaking, simple. It is in the composition of supra-modules, that is, those higher function modules that contain the lower-level modules as components, that complexity rises yet is managed.

As demonstrated in Chapter 5 modularity does not necessarily mean hard boundary conditions for subsystems. We saw several examples of fuzzy boundaries characterized by the fact that different module components can participate in the activity of the module on a temporally differentiated basis. That is a component may participate for some period of time (in the appropriate time domain for the module's level) and then move to a different module to participate for a complementary amount of time. The example from Chapter 8 was the human being participating for some period in a work process (employee), in the home (parent), or, periodically, in a congregation.

A related phenomenon for some kinds of modules is that of a 'subroutine.' The concept name is taken from software systems in which some particular code modules are called from different places in the program, being passed parameters and returning a result value. The internal work is the same for all such calls, only the parameter values and return value are particular to the specific call. But consider a rental shop that rents lawnmowers to different people in the area. One lawnmower can be used by different customers at different times. The same is true for the services of a barber and, indeed, all service providers. The barber, giving a haircut to one customer at a time, is a social subroutine. No household needs to have a dedicated barber in residence! Finally, think of people as subroutines that participate in various social organizations and families. They, of course, play different roles in each but they can be thought of as very talented subroutines, each with its own set of sub-subroutines.

13.2.2.2 Hierarchical Network Structures

As we saw in Chapter 5 the relations between subsystems discovered within any SoI at any level above the atomic component level is based, functionally, on the flows of materials, energies, and messages (information). That is, we expect to map out a flow network within the module under examination. Those flows enter the various modular processes, get transformed, and exit as products and wastes observing the rules of conservation (matter-energy/information-knowledge). Then, within the module, after doing a decomposition on it, we find that the input/output flows of the module are distributed among the component modules forming another, lower level, network. Thus, we conceptualize the system as a network of sub-networks.

When we are doing recursive decomposition of a CAES system to be designed and engineered this concept should be foremost in the mind(s) of the architect/designer/engineer. It should guide their analysis and discovery process. Fortunately, network theoretic work, based on graph theory mathematics, provides a rich assortment of analytic tools for ‘checking’ the validity of designs, such as ensuring that all inputs and outputs are accounted for (the above mentioned conservation principles).

13.2.2.3 Time Domains and Levels of Organization

As noted, the time domains of dynamics are based on the level in a hierarchy, lower levels have time constants that are small relative to those of higher levels. By following the methods of functional/structural decomposition from Chapter 5, and identifying the transformation functions (dynamics) one has the basis for ensuring the coordination among modules at any level, thus avoiding things like parasitic lag times within a level.

13.2.3 Design for Emergence

This is a consideration, which is aligned with evolvable systems, that is just beginning to be tackled in systems engineering circles (Pendleton-Julian & Brown, 2018). By a common definition of emergence, that the behavior of a whole complex system cannot be predicted by the behaviors of its components, it would appear on the surface that it would not be possible to intentionally design emergent properties or behaviors into a CAES. However, our position is that that definition is a bit of a cop out. It is true that as we have entered the realm of designing very complex systems, we have been often surprised by behaviors that were not predicted in the DE phase. Defining emergence in this way can be more of an excuse for missing something potential when combining components. This is especially the case when, for example, positive feedbacks or nonlinear behaviors produced unintended consequences (in behavior).

By the arguments in Chapter 2 regarding ontogenesis, however, it should be realized that there is a possibility to design so as to encourage the emergence of positive properties and behaviors. What the procedures of Chapter 5 show us is that by doing a complete analysis of the environment of a CAES, including, especially, entities that can potentially couple with the SoI as sources or sinks, we are in a better position to specify internal modules/processes that would be needed to realize such a coupling. Assuming that the coupling is desirable, the specification becomes part of the design for emergence, i.e., a new property or behavior. By the arguments for generating models given in Chapter 7, with respect to the sufficiency of analysis of the environment, it should be possible to simulate a wide range of environmental conditions that would elicit emergent behaviors.

This is actually not new for artifact designs. Common examples of it are just not always recognized in engineering circles. For example, consider the nature of entrepreneurship. Someone has a vision for a product or service that has a potential for serving a market need and constructs a proforma design of a company to actualize this (the artifact). What emerges is an actual organization with couplings to venture capital and, if successful in producing the product or service, results in a coupling with customers in an emerging market. Note that in advance of the actualization of the firm, no one can predict the exact results. There is still a large element of non-determinism involved in the enterprise. Moreover, the actualization may reveal additional opportunities (or problems) that were not anticipated originally but in hindsight seem perfectly logical. Entrepreneurism is an act of intentional-organization with stochastic variability in specifics. It does, of course, depend on human adaptability and foresight to succeed, but we can see the effects of emergence in the results.

We should ask, then, how do we apply this notion of emergence to designs of all CAESs? At present this is not an easy question to answer. We do see emergent properties and behaviors in some complex systems that have been designed already. One very interesting example of this may be the design of autonomous vehicles (cars and trucks). Already, even at an early stage of experimentation with self-driving cars, for example, we are witnessing the emergence of interactions between the use of these vehicles and the needs for roadways and streets to include extra cue signage for both cars and pedestrians to improve the safety issues[19].

Ultimately, design for emergence is coupled with the last two considerations of designs for CAESs, adaptability and evolvability. A system that is composed of adaptable components may be expected to exhibit some forms of emergent behavior, that is, behavior not necessarily predicted in advance (c.f., Mobus & Fisher, 1999; Mobus, 2001)[20]. The possibility of emergence requires that the simulations of the system should be done in as wide a range of environmental variations as possible to encourage such emergence to obtain. This, of course, requires that a substantial analysis of those environmental conditions (level -1) will have been undertaken.

[19] See this article, "Driverless Vehicles Set to Change the Way We Design Our Roadways?": http://www.sehinc.com/news/future-what-do-driverless-cars-mean-road-design for background. Accessed 8/13/2019.

[20] These papers describe the emergence of a strange attractor dynamics in a neural oscillator, known as a central pattern generator (CPG, see the Wikipedia article: https://en.wikipedia.org/wiki/Central_pattern_generator for background). The circuit had been designed with the intent that it would produce a smooth zero-centered sinusoidal wave form to drive a foraging robot to-and-fro as it looked for stimuli. The positive values would drive the left wheel of the robot while negative values would drive the right wheel. Instead, the circuit produced a 'noisy' sinusoid that caused the robot to conduct what we called a "drunken sailor walk," not quite random but also not quite directed. Analyzing the data generated by the CPG we discovered the strange attractor dynamics (see Figure 4 in the first referenced paper). The pattern that had emerged was serendipitous in that the search approach that it drove improved the robot's chances of finding the sought stimuli over a pure sinusoid. Additionally, we discovered that it replicated the actual kinds of search patterns found in foraging animals. This experience showed that we should expect unexpected, but possibly better, behaviors when our system designs include adaptable components.

13.3 Intentional Ontogenesis and Evolution

We will describe the process by which human beings, both as individuals and as collectives in socially cooperative fashion, conceive of and construct complex artifacts. We contend that the process by which human beings bring new artifacts into existence is still part of the on-going Universal evolution, the ontogenesis and development of things. But with the human mind and especially the social mind, we replace the chance and necessity dynamics of auto-organization with what we have called ‘intentional’-organization; the bringing together of components to form a whole artifact intended to solve a problem.

Artifacts are objects or processes that come into being as a result of intentional construction (conception, design, and implementation), be this by non-human animals (chimpanzee modifying a twig for the purpose of ‘fishing’ for termites) or human artifice. We normally think of the latter as being of ‘artificial’ origin, but here we consider a larger scope of how things come into existence in reflection of the ontogenic process described in Chapter 2. However, in our current sense, we consider a new process involved in bringing things together in new configurations. Instead of auto-organization, or the stochastic coupling of entities with predisposed personalities and the energy sources to achieve those couplings, we introduce the notion of the organization of an artifact resulting from the construction of a mental model in which an overall function that is desired can be simulated[21]. This is the bringing together of entities for a purpose or the shaping of systems to solve a problem. This is what human beings have brought to the ontogenic table.

But no artifact is ever born in some kind of final state. We know that artifacts themselves evolve over time, incremental improvements in form and function continually reshape the artifact so that it serves its purpose better (e.g., more efficient, more capacity, more esthetic). If an artifact type is considered useful, then that type, like a biological genus, is kept in play (is fit). Over time, as humans discover ways to modify the artifact to be better at serving its function it morphs and may eventually give rise to a whole new kind of artifact that, perhaps, serves a different or expanded purpose. Just think of the evolution of the automobile over the century.

Occasionally wholly new artifacts do come into existence. From time to time we are faced with a new problem that cannot be addressed merely by modifying an existing artifact. Or, somewhat more rarely, someone serendipitously discovers (invents) something that allows performance of a task that has rewarding consequences. In the former case, the mind is challenged to envision some kind of artifact (and remember, artifacts are not just instruments but also procedures and other abstractions) that could possibly be used to solve the problem. Necessity is the mother of invention, after all.

[21] Today, these mental models are most often transferred via a formal language into a computer-based mathematical model for greater precision. Even so, the model originates in the mind of one who can envision how a construction could solve the problem at hand.

13.3.1 Solving Problems, Expanding Capabilities

In what follows we use a single word, 'problem', in a more generic sense than in more common usages. A problem exists whenever a cognitive entity seeks a goal state for themselves that is different from the current state or from a likely or possible future state. This definition differs from standard dictionary definitions but covers the range from mathematical problems, in which the mathematician seeks to, for example, prove a theorem, or social problems in which a group perceives that they are not able to achieve a desired condition under the current state of affairs. Individuals are almost constantly presented with problem situations from, for example, navigating through a complex terrain, getting from point A to point B, to finding food, to obtaining a sufficient education in order to get a good job. Most of the time individual problem solving involves the application of learned procedures, such as following a trail through the terrain, unconsciously. But frequently enough the problem solving involves conscious and cognitive processes, such as with the mathematician.

One particular kind of problem can be characterized as 'a desire to be able to do something not previously possible to do'. Another variation on this is 'a desire to be able to do something faster or more efficiently (or both)'. We call this 'expanding capabilities' and it seems to be a universal drive in human beings. Whereas all other non-human animals seem content, generally, to live easily within their econiches and never do much in the way of invention of artifacts that would 'improve' their conditions, early human species began on an evolutionary course based on altering aspects of their environments to gain some kind of advantage, become more fit, as it were. Starting with the control of fire to reshape landscapes and later actively reshaping stones to serve purposes like butchering carcasses, they continued to seek ways in which they could be better off. And this invariably involved the creation of artifacts.

There are three main factors driving this tendency that need to be considered. These are the underlying motivations of a human or group of humans to want 'improvement,' the capacity to recognize and grasp a 'problem,' and the autonomy of thought and imagination to formulate a solution in the form of an 'invention' of an artifact. We will examine each of these briefly.

13.3.1.1 Motivations

All animals possess innate drives to perform behaviors that support their living, reproduction, and, in many cases, supporting their offspring until they are able to do so on their own. These drives are motivation to action and to make decisions accordingly. Animals that have rich social lives, such as most primates, have evolved more complex behaviors to enable the maintenance of that social life. Humans have evolved extremely complex behaviors and conceptual modeling, e.g. having a theory of mind (Tomasello, 2019).

As we saw in Chapter 8, a main motivation for human beings is to obtain resources (as supplies to their ability to satisfy the drives/needs they experience) at the least cost in terms of energy and time. That is, they are always looking to 'pick the low hanging fruit' in the fastest time possible.

One reason that this might be the case, as opposed, for example to the motivations of other great apes with more-or-less stable (and steady-state) lifestyles, is that from the initial emergence of the genus *Homo*, there appears to have been a tendency to expand territory and numbers. It is not clear why this is the case, however it is clear that the species (indeed the genus) is incredibly adaptable. The genus is marked by a significant increase in brain size relative to body size as compared with other apes. This may have contributed to an ability to conceptualize living in new kinds of environments and experimenting with new kinds of foods. We also see, not long after the advent of the genus, the ability to use fire which, through cooking foods, provided more energy per unit weight of foodstuffs and setting up a positive feedback to supporting the further evolution of brain size. In any case, *Homo* began to explore more broadly and showed a tendency to be more acquisitive than their cousin genera.

Once this tendency started the genus became motivated to 'find more.' The basic animalistic balance between exploitation of existing resources and exploration (e.g. a predator trying to find a new waterhole to stake out for prey) had shifted toward higher exploration. As a consequence, early humans expanding outward from their origin region in East Africa kept encountering new challenges and thus had to develop the capacity to overcome them in order to survive and thrive. Clearly, they became very successful at doing so. So much so that the motive to expand and explore became the main theme of life.

13.3.1.2 Recognizing a Problem

A problem exists when a human mind recognizes that a drive cannot be satisfied readily, or it could be satisfied at a lower cost, IF ONLY…

Another form of this problem recognition takes the form of: "I see X and recognize X as a useful resource but I am blocked from acquiring X because…" A problem, in the abstract, is a situation that blocks one from achieving a goal state, fulfilling a need, or more generally, a want.

Given the nature of the motivations described in the prior section, human beings immediately set out on a quest to discover a means for "solving the problem." Given great cleverness, resourcefulness, and desires to conquer obstacles (which seems to include other humans) members of our species seek to solve the problem.

When problems were basically simple (where can I find more food?) solutions were relatively easy to come to mind. As culture evolved and societies became more complex, as with the advent of machinery and the Internet, problems were still 'felt', but not necessarily recognized for what they were. Complex problems are often not well understood; they are often seen as open-ended or wicked. As a result, the rush to find a solution to a poorly understood problem generally leads to new problems (Tainter, 1988) and the cycle perpetuates.

As a rule, the failure to understand complex problems is the result of not recognizing the 'problems' are really just parts of a larger embedding supra-system. What needs to be done is to treat the 'problem' as the system of interest and then use the reverse recursive analysis of Chapter 5 to better understand the environment in which the problem exists (often giving us a clue as to why it is a problem in the first place). This almost never happens. Most problems, even complex ones, are seen as local phenomena and short-term solutions are sought to speed the results. Inventors are often individuals that operate in this mode (usually with a reward in mind).

When groups are involved in recognizing (and working toward solving) a problem the focus tends to shift from local and short-time scales due to the introduction of multiple perspectives having to be considered and integrated. This is a good thing, though it often drives diehard progressives insane since it tends to enforce a more conservative dynamic on the process. So too, marketing managers are frustrated by the perceived 'slowness' of projects carried out by large teams where those projects are part of the profit-making goals of the organization. Even so, groups too often ignore important environment dynamics when seeking a solution.

13.3.1.3 Autonomy

The human mind may be constrained to thinking in certain ways by virtue of its design and its life experiences, but the imagination is incredibly free to pursue seemingly boundless possibilities. Consider, for example, the nature of language. With a limited set of phonemes (or written characters) a human can invent an uncountable number of words, especially if there are few constraints on the length requirements. Every time a human mind encounters a 'new' semantic, it is possible to name it. It is true that random combinations of phonemes do not work for a variety of reasons and so the actual number of 'legitimate' words is probably countable, even so, a likely infinite number of sentences can be constructed from those words.

So, it is with the combinations of things, or procedures. Initially, we imagine humans only sought to combine things that were at hand, sewing skins together, attaching a stone ax to a wooden shaft. But as humans learned to shape those things-at-hand so that they fit together better we were off in the adventure of exploratory invention coupled with intentional organization.

Human beings have an unprecedented level of mental autonomy in the construction of concepts (those mental models that turn into artifacts). This can be seen as a good thing when looking through the lens of innovation today, with the sentiment leaning toward novelty and serving wants. It is definitely a positive factor in the exploration of possibility space; some amount of exploration is needed to prevent getting stuck in a local and non-optimal minimum. But, on the other hand, without constraints that reflect reality it can lead to creations that have numerous and negative unintended consequences. It can be argued that we are seeing many more of these kinds of artifactual creations today. Autonomy in individual and group problem-solving cannot be unlimited or unconstrained by taking into account the larger supra-system. The embedding governance system must establish some rules by which exploration is kept in keeping with the nature of reality. The overarching question is: "Just because we can do a thing, does that necessarily mean we should do that thing?"[22]

13.3.1.4 Mental Affordance

We've used the term 'affordance' to mean a potential interaction between two components or systems. The human mind has proven supreme in recognizing affordances in objects and methods and is the basis for the capacity to recognize a potential solution to a problem by using an artifact. But it goes far beyond mere recognition. A chimpanzee can recognize the utility of a stick for fishing out termites. With human cognition we find an ability to construct an artifact in our minds, a mental simulation, and check its affordance against the problem we are trying to solve.

Mental affordance is the phenomenon, coupled with the autonomy of mind covered above, which is at the base of intentional invention and design. We humans are certainly not the only problem solvers in the animal kingdom. Crows and octopuses have been able to cleverly solve problems (puzzle-boxes) involving obtaining food. But it is not contested that the human capacity for recognizing other kinds of problems and then considering new ways to solve those problems seems limitless. However, it may be that it only *seems* so. There exist physical constraints on the feasibility of potential solutions. One might imagine a lever (having the affordance of lifting a heavy weight) that could lift the world. But where would one put the fulcrum?

13.3.1.5. Constraints

It is incumbent on us to recognize that our ability to imagine artifacts (and artifactual systems) that solve some particular problem has to be constrained by the laws of nature and situational realities.

For example, currently humanity is recognizing that the burning of fossil fuels has led to the untenable situation of global warming leading to climate chaos. We burned fossil fuels to solve one kind of problem – driving economic growth. But now, faced with the existential predicament that this has caused (not just for the human species but for the vast majority of other species) some of the more physics-naïve of us have locked onto a "solution" that involves transferring to so-called renewable energy sources and a phase-out of fossil fuels. This is based on the assumption that we can and should continue the kind of industrial civilization that we have had and that all that is necessary is to transition to "clean" energy sources. This is woefully ignorant of physical realities. The power factor of fossil fuels far exceeds that of solar energy, for example. Even though the total energy in sunlight that falls on the Earth daily exceeds that of that available in the daily burning of fossil fuels currently, the power density of sunlight is so

[22] This version of the question may be attributed to the Star Trek movie, The Undiscovered Country. It is one of many variants on the ethical dictum: Just because you can do something doesn't mean you *should* do that thing.

small that we would have to convert enormous tracts of sunlit land areas to provide an aperture large enough to collect the same amount as well as a method of concentrating that relatively low-power energy into the high-power form that is needed to drive the economy. Alas, the "Green New Deal" has not really taken into account this thermodynamic fact. It is more wishful thinking than aspirational.

There are real and necessary constraints on human invention and artifact creation when it comes to solving societal problems. But at the same time, we need to recognize that the recognition of a problem is often an arbitrary situation. Humans, on the whole, want progress and see anything blocking their path forward as a problem. So part of the "problem" is actually human perception of the situation and the needs for the future. Suppose humans recognized that continued growth (population and consumption) were not desirable. Then the loss of high-powered energy from fossil fuels would no longer be a problem, but a limitation on the numbers and permitted consumption per capita. We could seek other solutions to the problem of sustainable existence than trying to grapple with maintaining our current requirements.

13.3.2 Incremental Improvement as Evolution

Even the human endeavor to imagine a new artifact or a significant improvement on an existing design is part of an evolutionary process. As in biological evolution, the process involves incremental innovations over existing structures and functions and not, as might be sometimes imagined, the whole cloth invention of something completely new. Even the electric light bulb was proceeded by various fuel-burning methods of supplying concentrated light. So, the notion of providing a point-source of lighting was not something Edison came up with out of the blue. What he did was, knowing that electric current flowing through a resistive filament induced high heat and radiation of light as a result. Putting together the idea of, say an oil lamp wick, and an electric filament to produce a useful source of light was the act of intentional-organization. After that he had to begin a search for a filament that had the right properties and longevity to count as an economic replacement for the oil lamp, an act of intentional selection. He had not been living in a world where the darkness of night was never chased away by some kind of intense energy illumination and then suddenly thought of inventing a point-source of lighting. His ideas were based on previous inventions, a series of them, in fact.

Biological evolution demonstrates how incremental improvements on designs works in general. Variations in physiology, anatomy, or behaviors that get selected because they are fortuitous to fitness generally account for the majority of improvements. Occasionally, a major innovation in either form or function (or both) proves to be very favorable and slowly takes over in the gene pool. But more generally genetic drift[23] guides the pathways followed in speciation.

Human innovation follows a similar pattern. Most advances in culture take the form of incremental changes in existing designs that are then subject to selection in the noosphere.

[23] See the Wikipedia article: https://en.wikipedia.org/wiki/Genetic_drift for explanation. Accessed 1/27/2020.

13.3.3 Admitting Evolution into the Design and Engineering Process

The engineering tradition has placed a lot of weight on the notion of formal design processes that essentially ignored the idea that DE was really an exploratory, evolutionary process. The worldview of DE has largely been derived from scientism and positivism, the traditions, themselves derived from the Enlightenment, which held that the world could be understood in strictly deterministic terms as long as we could measure the states of the world absolutely. Over the last half century of experience, and especially over the last few decades, the realization that we really can't know anything absolutely has entered both scientific and engineering thinking. In Sanskrit, from the Vedic tradition, there is a term, "Lesha Avidya," which means the remains of ignorance that persists after learning (or even enlightenment!) takes place. In Mobus & Kalton (2015), Figure 7.2 we show how knowledge grows only asymptotically toward absolute (K = 1). The implication is that a human mind may get marginally closer to the "truth" but will always have some uncertainty about what that might be.

There will always be room for some uncertainty in any model of real systems. And, with respect to CAES designs we have to be ready to admit that uncertainty about the future should be accounted for in our DE processes. We have to admit evolution into our DE process so that our artifacts can change themselves to meet previously unrecognized needs within the artifactual system.

Designing for evolvability begins with the identification of component subsystems that are candidates for structural/functional modifications should the environment change in unanticipated ways that exceed normal adaptive response. Of course, with intentional selection in mind, the kinds and ranges of modification would need to be anticipated and, in effect, designed into the component subsystem. The CAES in Chapter 9 included a module that is capable of taking in a problem statement and construct a new component. In the next chapter we will show how this can be done in the design phase employing evolvable simulations[24].

[24] For example we will look at the field of genetic algorithms and evolutionary programming as early examples of this kind of problem solving applied to the DE process.

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