Defining Examples

CASoS is a concatenation of four sub-disciplines or study areas: Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems. "Defining" the system of interest is the first step in the CASoS Engineering Framework process. Definitions of CASoS are accomplished by addressing, at a minimum, the 7 points described below.

A Complex Adaptive System of Systems requires:

- **System:** A system is a set of entities, real or abstract, comprising a whole where each component interacts with or is related to at least one other component and they all serve a common objective. Any object which has no relation with any other element of the system is not part of that system.
    - **Environment:** The system functions within an environment. Interactions with the environment should be less complex than internal interactions and make the drawing of the boundary between them natural
- **System of Systems:** The system is composed of other systems ("of systems"). The other systems are natural to think of as systems in their own right, can't be replaced by a single entity, and may be enormously complicated, or we would be dealing with a single system, rather than a system of systems.
- **Complex:** The system has behavior involving interrelationships among its elements and these interrelationships can yield emergent behavior that is nonlinear, of greater complexity than the sum of behaviors of its parts, not due to system complication.
- **Adaptive:** The system's behavior changes in time. These changes may be within entities or their interaction, within sub-systems or their interaction, and may result in a change in the overall system's behavior relative to its environment.

  This definition of the object of analysis as an object of engineering produces the problem definition needed to articulate the Aspirations for affecting or designing the CASoS.
- **Aspirations:** What are the problems/opportunities/goals/questions?
- **Approaches:** What are the activities (e.g. observation, experiment, design, control, manipulation, modeling) that we might engage in to solve a problem, exploit an opportunity, achieve a goal, or answer a question.
- **Attainability:** How are approaches/aspirations rendered difficult/impossible by the fact that this is a complex adaptive system of systems?

The CASoS for which we developed prototype Defining Examples encompass many of humanity's largest problems such as global climate change, conflict end games, and newly emerging worldwide emphases such as large-scale natural disasters, pandemics, global finance, and global economic supply chains. None of the Defining Examples for any system (as seen below) should be considered complete in any sense; rather, the descriptions are illustrative of the kinds of considerations that should be entertained before attempting to engineer solutions within any CASoS.

DEFINING EXAMPLE: CONFLICT END GAMES

System: The system is two or more entities (e.g. nation-states) embroiled in conflict. Each entity involved in the conflict engages in any activity relating to war. Interactions between the entities can include hostilities, negotiations, trade, etc. Consider unintended as well as intended interactions, spanning at least economic, business, military, diplomatic activities.

Environment: The environment includes the world system within which the conflict is being engaged. World considerations can limit the number of permissible means of engaging in the conflict.

System of Systems: The entities embroiled in conflict are considered here to be aggregate groups of people. Those groups can be further decomposed into governing bodies, combatants, innocents, businesses. Many of these can be further decomposed.

Complex: The interactions between the people involved are complex. Soldiers don't necessarily agree with their leaders; soldiers might be brothers to enemy soldiers; people on opposite sides might share a common religion. These concerns can cause people to act very differently than they are commanded to act. The number and kinds of these interactions are large, so opportunities for complex behavior are large.

Adaptive: Actions vary with the nature of the conflict: when one combatant starts to lose, he may give up, retreat, or he may fight harder. Actions vary due to outside influences: when it rains, the combatants may not come out to fight. Or they may attack *because* it's raining. Actions decided upon are dependent on what worked in the past or what didn't work.

Aspirations: Ending the conflict (cause) can save lives and resources, and removes significant strain from the parties in conflict. Contrarily, continuing the conflict (cause), perhaps at some different level, is an opportunity to make significant profits selling equipment/aid to the combatants. Entities that are cashing in on the opportunity may not think of the conflict as a problem, and may be in opposition to any solution proposed. Another aspiration might be preventing war in the first place.

Approaches: The conflict can be ended by controlling aspects of the game so that all sides (or at least a critical mass) see mutual benefit in ending the conflict that is larger than any benefits they're receiving by continuing the conflict. It could also be ended by preparing parties in such a way that the conflict ceases to affect them – there's no point in continuing a conflict where you're not changing anything or getting anything from it. It is useful to determine how to monitor progress to ensure that the conflict is ending on some schedule; what variables to check is a potentially difficult question. Managing the environmental interfaces is also important (prevent an insurgency).

Attainability: Ending the conflict is difficult because this is a complex system – the solution might be as complex as the system itself in order to produce lasting results. The solution might need to include agreements at many levels in order to ensure any kind of complete answer, because disagreements occur at all levels (jealousy across a border about whose grass is greener). Indirect links through the system produce much more opportunity for continued difficulty (e.g. terrorists are still being educated and funded through parties in a different country).

DEFINING EXAMPLE: NUCLEAR STOCKPILE MANAGEMENT

System: When we consider everything affecting the maintenance of the Nuclear Weapons Stockpile (design, manufacturing, surveillance, policy, funding, organization of the laboratory system, etc.), the NWC is a system. There are not only many components, they are also highly interconnected: design affects the efficiency of manufacturing and surveillance; policy constrains funding and design; the organization of the laboratory system determines needed funding and surveillance processes.

Environment: The environment consists of everything outside of the NWC: non-US organizations, non-nuclear-weapon-related US groups (e.g. civilians), non-nuclear US governmental organizations (e.g. DOC, CIA), non-nuclear activities in NWC contractor agencies (e.g. DHS activities)

System of Systems: Each of the major components is itself a system. For example, the design process includes not only technical constraints, but also the organization of technical specialties, supporting infrastructure, stakeholder interactions and requirements, etc. In addition, stockpile management shows other characteristics of a system of systems, including very different time scales: technology changes rapidly, on a time scale of weeks or months; budgets are managed on a yearly cycle; organizational structures change every few years, and major changes to treaties and policy can take decades to complete. Theoretical descriptions of the different components require different ontologies, which must be reconciled in any effort to model the whole system.

Complex: The behavior that results from systems interactions is greater than the sum of its parts. Direct controls on stockpile management, such as budget, requirements, policy, organization, and so forth, constrain the practice of management which is also shaped by unanticipated component failures arising in surveillance, technological progress, and the shifting patterns of skill caused by normal staffing changes.

Adaptive: The system is adaptive and highly goal oriented. The goal of keeping the stockpile safe and reliable is shared by all agents in the system, but its complexity leads to imperfect planning and communication. Consequently, the particular states of the system and their progress toward the goal are determined by loosely coupled efforts of different agents. The system adapts to political and technological change: the end of the cold war and the invention of microelectronics have each caused the NWC to fundamentally change.

Aspirations: Aspirations for the NWC might include protecting it, eliminating it, guaranteeing its viability in the face of fundamental world changes, making it more efficient and robust in achieving its mission, or possibly redeploying it to deal with an expanded notion of world threats.

Approaches: The long term survival of the NWC can be controlled, to a degree, by controlling costs, making the system sufficiently inexpensive to operate. New uses and security needs for weapons might increase funding, but are unlikely. Alternatively, the NWC can be retargeted to additional world problems, which, if sufficiently important, might garner more funding than is currently present.

Attainability: Past activities undertaken within the NWC have created a certain number of enemies, who might choose to hamper efforts to change. People within the system have ingrained behavior patterns that might result in resistance to change. The need to simultaneously maintain current capabilities while reaching for new opportunities exacerbates the problem – it's hard to know whether and when to hold back and when to reach forward.

DEFINING EXAMPLE: GLOBAL NUCLEAR NONPROLIFERATION

System: The system is the international community of nation states. Each participating entity bases its decisions upon the decisions of a subset of all other entities with respect to the decision to proliferate and the actual '*mise en scene*' of proliferation mechanisms. Interaction among entities can occur on planes other than proliferation (conflict, alliances, trade, etc.) all of which may influence formal proliferation decisions.

Environment: A "near" boundary might be drawn around only those entities that currently possess nuclear capabilities; any entity not possessing those capabilities would be in the environment. A further boundary would encompass all the human organizations on the planet that might be or might become involved in things nuclear. The environment would be any human organizations/activities that are not contained, along with the natural world.

System of Systems: The entities embroiled in nuclear nonproliferation include nation states, each of which is itself a system. The entities may have already proliferated, renounced proliferation, considered proliferation, or have indicated no preference. The states can voluntarily form sub-groups where all members take a similar position. The entities may take individual positions.

Complex: Given that nuclear weapons are considered dangerous and 'bad,' recently citizens of some proliferation-inclined states have staged public demonstrations in support of nuclear tests. These demonstrations could potentially be more in support of national capability and pride than in support of, or even in spite of, the destructive power of the nuclear bomb per se. Cases exist in which capable nation states have begun, then renounced, proliferation efforts.

Adaptive: Individuals and nations adapt in their approaches to attempting to proliferate and attempting to control proliferation. Any approach to limit proliferation (high security, treaties, etc) can be adapted to and possibly circumvented by sufficiently persistent individuals.

Aspirations: Typical aspirations involve attempts to prevent or control attempts to proliferate. The CTBT is suggested as a way to eliminate proliferation through a ban on testing of nuclear devices; achieving its promised benefit is difficult. Alternate aspirations might be to devise a robust world system in which there was no incentive to proliferate (either through sufficient penalties, lack of resources, lack of imbalance in world society), no means of proliferation (expertise removed from the earth), or a means of controlling use of weapons so that possession of the technology or devices isn't sufficient to enable their use.

Approaches: While guards, fences and treaties continue to play their part, there are other approaches to the problem. Transparency of government activities (possibly encouraged through media/intelligence community cooperation) would reduce opportunity to divert assets to weapons development. Greater shared benefit from global economy might reduce the value of a nuclear threat (it's hard to want to bomb your markets/suppliers/partners).

Attainability: Ending proliferation is difficult because this is a complex system – the solution might be as complex as the system itself in order to produce lasting results. Some entities will not relinquish their current capabilities, thus causing trust issues. The solution might need to include agreements at many levels in order to ensure any kind of complete answer, because disagreements occur at all levels. Indirect links through the system produce opportunity for continued difficulty (e.g. the existence of a civilian nuclear energy capability, which is readily promoted, can provide resources for weapons proliferation).

DEFINING EXAMPLE: THE GLOBAL ENERGY SYSTEM

System: The Global Energy System (GES) encompasses the physical components of the atmosphere, lithosphere, and hydrosphere, as well as the components of the biosphere which prominently include human economic and socio-political activities, in addition to energy generation, storage, control, and interdependent global distribution networks. For humans, the most important function of the GES is its contribution to the sustenance of life on Earth.

Environment: The boundary of the GES has often be drawn at the interface between human-created energy systems and natural systems; however, ignoring natural systems has proven short-sighted, e.g., greenhouse emissions. A more encompassing boundary considers all sources and sinks for energy, natural or man-made, and their effects in both physical and social realms (for example, the economy, air and water quality, war, etc); the environment includes the physical world beyond, as well as aspects of human life that aren't work-energy related.

System of Systems. Each of the components is a system in its own right; many are poorly understood. For example, weather prediction (atmosphere) is extraordinarily difficult, and weather events have powerful and poorly understood influences on the other components of the GES.

Complex: Each component system constituting the GES can exhibit complex or chaotic behavior. Interactions between these component systems are subtle and pervasive. Extreme variations in temporal scales (effects from nanoseconds to eons) and spatial scales (effects from microscopic to solar system) add to the intricacy of interactions. Large numbers of interactions at many different scales guarantee complex behavior for the GES.

Adaptive: The physical components of the GES are constantly changing: solar activity, continental drift, volcanic activity, climate, ocean levels, constituency of water and air, weather phenomena. Species evolve within this changing environment and, at shorter time scales, so do human civilization and needs. All of these changes impact our ability to extract energy from the environment and put it to use. In response, we adapt/evolve our designed energy systems and our lifestyles.

Aspirations: Our nation and others require secure, reliable, sustainable, and cost effective supplies of energy to support economic development and to maintain a high standard of living. At present we have high-CO2 emissions, dependence on foreign petroleum for many critical activities (e.g., transportation fuels), and inadequate investment in energy source diversification. All of these consequences are now a threat to national as well as global security. Aspirations focus on rectifying this situation to build a robust and resilient energy policy with supporting infrastructure that is global in scope.

Approaches: Potential responses range within the socioeconomic-technical realm from the socioeconomic (e.g., negotiation of global and national targets for CO2 emissions, incentives/restrictions, technology and fund transfer, war) to the technical (e.g., renewable energy sources, next generation distributed energy grids, energy storage systems, new transportation fuels, CO2 capture and storage).

Attainability: The GES is one of the largest, most complex, and most interdependent CASoS. Opinion differs widely on what the problems are, how big the problems are, and how to go about solving them. Defining problems that have feasible solutions, that can be shown to be robust, and that can be actualized to enable system resilience within the GES will be a huge challenge due to its combined technical, economic, social, and political realms.

DEFINING EXAMPLE: GLOBAL CLIMATE CHANGE

System: The system is composed of interactive atmosphere, land, and water components that affect and are affected by human institutions/societies. Local and global climate condition changes due to human activities lead to unequal sharing of burden and opportunities which, in turn, lead to conflict affecting nation states and multi-national corporations, and, in turn again, the climate. The dynamics are intrinsically chaotic but dominated by negative feedback, which tends to balance the system. Human activities tend to alter natural balancing forces; it is imperative to understand the controls within the system to manage risk from unbalancing activities.

Environment: Since the system includes nature and human activities that affect nature, the environment must be nature beyond earth (space exploration is moving this boundary), and human activities that have no environmental impact (if such exist).

System of Systems: This system of system includes all the disparate aspects of nature and all the earth's peoples in an evolving set of interrelationships and dynamics.

Complex: The behavior of individual components (e.g. humans, weather) has been shown to exhibit complex/chaotic behavior. The number of components and their interconnections guarantee the possibility of complex system behavior.

Adaptive: The climate-earth system is a feedback process that evolves and adapts. Humans excel in adaptation (and mis-adaptation). We must learn to adapt to climate change at a simultaneously global and local level. Humanity has never faced this challenge before.

Aspirations: Recent studies indicate that over 2.7 billion people will be within the turmoil of war and nation-state destabilization over the next few decades. In addition to the already crisis-laden extreme weather events caused by global warming, accelerating changes in the Arctic will impact the world economy, global ocean currents, and the world's weather patterns. Aspirations include controlling the system to achieve global stability and international security, adapting to climate-constrained resource production levels, and restabilizing climate conditions impacted by human activity.

Approaches: Approaches include technological changes in sources of energy and efficiency of energy use, behavioral changes to reduce energy waste, social attitude change regarding standards of living, instituting controls, possibly economic, that affect energy use.

Attainability: Fundamental issues include disagreement about the severity of the problem, issues of achieving behavioral change at international, national, corporate and individual levels, technological challenges to seek less-impacting, more efficient solutions. Interestingly, there is a trivial solution to the problem if we don't solve it, nature may just solve it for us. We may not like the answer.

DEFINING EXAMPLE: LARGE NATURAL DISASTERS

System: The system is the set of communities and physical infrastructures affected by the natural disaster (both local and remote to the disaster), first responders, and government and private aid organizations, including those involved from the initial event on through reconstruction.

Environment: The system is embedded within the national or international community; this environment supplies "energy" and resources to the system (e.g., funds, raw materials, people), which expand and contract across time.

System of Systems: The system is composed of entities which are themselves systems ranging from individuals, families, neighborhoods, businesses, and local, regional, and national governments to infrastructure systems for the flow of life support such as water, food, sanitation, communication, and power.

Complex: Communication/interaction (and miscommunication, errors) between entities at all scales (individual to national government) and between entities of all types and status (e.g., businesses, industry, utilities, law enforcement, national guard, first responders, self organized groups of affected individuals) will occur. Entity behaviors differ and thresholds for behavioral (state) changes of an entity (passive to active or vice versa) are history dependent (hysteretic). Both heroes and devils, or mass obedience and disobedience can emerge. Such emergent behavior is contingent on the interaction of the all the sub-systems and cannot be predicted.

Adaptive: The behavior of all entities at all scales evolves as a function of external influences, internal interactions, and experience (both general and specific). Experience grows in time over the course of the Disaster and influences action. The physical infrastructures change as they are stressed, repaired, and subsequently improved, and this, in turn, changes the actions of people. Experience from one disaster to the next also changes communication/interaction behaviors, entity actions and decisions, and the response of the surrounding environment that supplies energy and resources.

Aspirations: A robust and resilient system-of-systems in which planning, reengineering, and reinforcement occurs naturally to limit the cost (life, disruption of services, funds, resources, recovery) of large natural disasters. A means of predicting or preventing/attenuating them.

Approaches: Evaluation of actions/decisions (before, during, and after) to rank their benefit, their robustness to variation of fundamentals and in initial/boundary conditions, the identification of critical enablers for their benefit, and design of systemic resiliency. Evaluation would use 1) historical events, 2) parsimonious models of the interdependent CASoS, and 3) systematic variation of parameters. Design of monitoring systems that allow measurement of critical state variables during events and the control of action/reaction. Better weather prediction could help with some weather-related disasters. Technology to prevent disasters would likely be disaster-specific (e.g. one technology for earthquake, another for hurricane).

Attainability: The manifestation of the natural instigator (physical extent, intensity, and type of perturbation) and the state of the system (individuals to systems-of-systems) when the instigator hits (initial condition) are always different and unpredictable. Guided emergence (control) of human organization that is helpful (rather than harmful) may be unique to each situation.

DEFINING EXAMPLE: LONG-TERM MAINTENANCE OF COMPLEX INFRASTRUCTURES

System: The system could be any major infrastructure (all are complex) or a set of interdependent infrastructures. Since the Minneapolis Bridge collapse is fresh in our minds, we can go with transportation as an example, although this would apply to any and all infrastructure systems.

Environment: The environment would be the collection of entities (people, governments, businesses) that create, maintain, use, and damage these infrastructures.

System of Systems: Large-scale infrastructures are, out of engineering necessity, composed of complex subsystems which themselves may be infrastructures. Transportation, for example, includes bridges, rail, roads, air, fuel, etc.

Complex: The problems of long-term maintenance involve interrelationships between elements. There are a number of such effects: repairs to one piece of infrastructure may only be effective or economical if a related piece is fixed; taking one piece of infrastructure off-line to do maintenance may move traffic to another area, causing the other piece to fail; money spent fixing one thing cannot be spent on another; new technologies may make certain infrastructures obsolete; catastrophic events can completely reshape the infrastructure and our ability to use it; social changes can reshape the environment in which the infrastructure exists. What is society's maintenance responsibility on sunset infrastructure, and what complex effects can occur due to retiring an infrastructure?

Adaptive: The system's behavior changes relative to its environment or as a result of internal interactions. Here the behavior we care about results from the cumulative effects of normal wear and damaging events, and how agents in the infrastructure adapt to those effects.

Aspirations: Aspirations include maintenance, replacement, and development of new technologies (not just old components) that allow us to improve the robustness and resilience of existing infrastructure. We desire to increase system awareness, anticipate long term problems, and proactively manage infrastructures, rather than react as they fail. Infrastructure should be cheap, robust, adaptable, repairable, easily replaced, disposable.

Approaches: Approaches include focusing engineering activities on wider concerns (more robust, less sensitive to technology change), behavioral change (be kinder to it so it lasts, construction near bodies of water is risky).

Attainability: Maintaining complex infrastructures is difficult because: The complexities make prioritization difficult; Public perception of risk makes funding difficult; and Effective decisions about maintaining large scale infrastructures, like transportation, should address longer time spans than we are used to thinking about. Engineering activities are increasingly focusing on the larger scope (e.g. "green companies" are focusing on wider issues of construction, use, disposal).

DEFINING EXAMPLE: THE GLOBAL ECONOMY

System: The global economy is composed of a system of entities including: raw resource providers that provide "out-of-ground" resources (e.g. mining, labor); resource converters who convert one set of resources into another (e.g., automobile manufacturing, labor); resource movers who transfer resources from one to the other (e.g., firms, markets); and resource consumers who use resources for personal consumption (e.g., households). These entities rely on a set of enabling sub-systems that include: physical infrastructure systems (e.g., power, communication, and transportation networks); economic market systems providing the structured mechanisms for linking providers, converters, and consumers with each other; financial and monetary systems providing the store of value, medium of exchange, and lines of credit necessary to operate and make structural changes to the economy; and intra- and inter-government political policies and agreements providing short-run and long-run government incentives and constraints with sweeping impacts on how a country's economy operates both domestically and internationally.

Environment: The environment includes the natural world from which resources come and to which spent resources ultimately go; the social and political realms of the human sphere may be relegated to the environment or not, depending on the problems of interest.

System of Systems: Each of the entities that compose the global economy and each of the enabling sub-systems upon which they rely are systems in their own right.

Complex: Each entity in the global economic system makes independent decisions about its use of enabling sub-systems, whether it be sectorally (which specific resource), inter-temporally (acting now or acting later), or regionally (which provider). These decisions directly and unilaterally affect the internal operations of enterprises and households, regional and national markets, and the behavior of the subsystems that support the economy, in ways that, due to this high-level of autonomy, yield emergent behavior.

Adaptive: To remain economically viable, enterprises and households must constantly adapt their use of resources, their purchasing behaviors in markets, their use of financial assets and liabilities, and their response to actions of governments. Because many economic resources are easily transferable (regionally, sectorally, and inter-temporally), the prices of these resources (cost of gasoline, cost of food, interest rates) generally serve as critical public information that travels through the economy very rapidly, potentially broadly affecting the economy in the matter of hours to days.

Aspirations: A global economy that is agile, responsive, and "self-healing" to man-made and natural disasters, i.e., resilient; where the standard of living over the course of individuals' lives improves; the removal of poverty.

Approaches: Institutions working to establish economic resiliency have a limited set of tools for deploying public economic policy (e.g., using the national federal funds rate to control national unemployment), but have few if any tools for understanding how national and global economies are affected by domestic disruptions. Application of all possible approaches, from observation, experiment, design, control, and manipulation to modeling, is needed to gain perspective on this system.

Attainability: The tremendous scale of this CASoS will require an enormous effort to collect and normalize data, build and validate models, etc. Because person-to-person influence is an undeniable local mechanism that affects economic actions at the lowest scale (the individual), some aspirations at higher scales may not be attainable (such as some forms of predictability). Management of the global economy to yield global benefit will require application of incentives and constraints at all scales and across a diverse set of local to national entities.

DEFINING EXAMPLE: THE INTERNET

System: The system consists of the network of hosts, routers, and other devices connected to the Internet. People interact with the devices connected to the Internet and, through them, with each other. Software runs on the devices. Web sites, service providers, and other organizations exist at higher levels of aggregation of people, devices, and software.

Environment: The internet is embedded within modern society to such a degree that it can be accessed from nearly anywhere within the developed world.

System of Systems: The hosts, routers, devices and the people, organizations, infrastructure that use them may all be viewed as complicated and complex systems in their own right.

Complex: The interactions between entities in the Internet give rise to behaviors that can not be predicted simply from knowledge of the properties of the entities themselves, even assuming that were possible in principle. New innovations in software/devices or small changes in state, such as whether a particular user clicks on an e-mail attachment infected with a virus or not, can lead to large changes in Internet state (and large-scale observables such as traffic patterns).

Adaptive: Software, devices, and organizations undergo adaptive change constantly, either in response to competitive pressures, as a result of failures of components that require replacement, or simply in response to changes in traffic patterns (e.g. to avoid congestion). People are inventing and using the system; people learn.

Aspirations: Security is difficult owing to the complex interactions between different components of hardware and software even at the level of individual hosts and devices. Control systems for vital installations such as power plants are connected to the Internet for ease of administration and to facilitate collection and processing of data, but this introduces vulnerabilities. Other critical infrastructures, such as financial organizations and governments, maintain connections to the Internet to facilitate their operations, which also exposes them to attacks that originate on the Internet. Ideally, we aspire to protect the privacy of individuals and organizations, the integrity of financial and other transactions, and the vital installations and systems that use the Internet.

Approaches: The internet is constantly evolving; all possible approaches can and must be applied to this system across the spectrum from observation, experiment, design, control, manipulation, to modeling.

Attainability: At present, it is very hard to analyze the security properties of systems that maintain connections to the Internet due to the large number of interactions between software and hardware on these systems and other software and hardware entities on the Internet. In addition to the increasing numbers of entities and interactions among them, the growth in software and hardware complexity over time exacerbates the difficulty of ensuring secure connectivity. This growth in complexity, on the other hand, is being driven by competitive pressures to make hosts and other devices more useful and flexible.