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Sandia National Laboratories A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative

Commissioned June 2007 by Stephen C. Roehrig, Director for Energy, Resources & Systems Analysis
At the request of Les E. Shephard, Vice President for Energy, Security, & Defense Technologies

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SANDIA NATIONAL LABORATORIES A ROADMAP FOR THE COMPLEX ADAPTIVE SYSTEMS OF SYSTEMS (CASOS) ENGINEERING INITIATIVE

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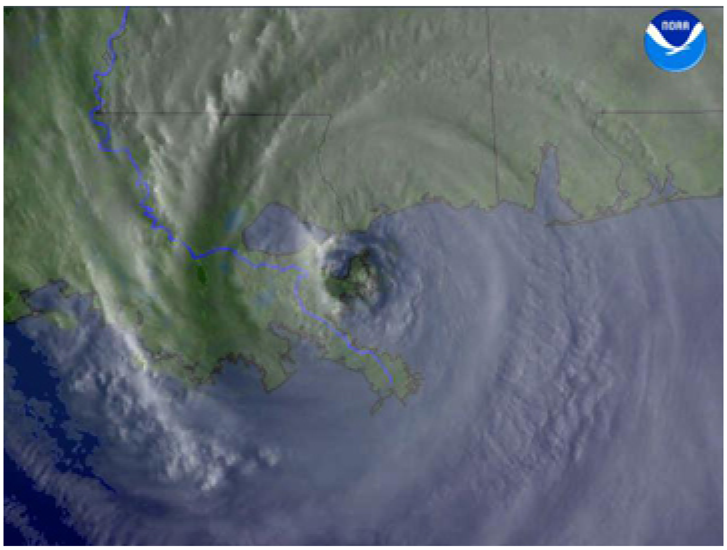
Abstract

Complex Adaptive Systems of Systems, or *CASoS*, are vastly complex *physical-socio-technical systems* which we must understand to design a secure future for the nation. Defining Examples of CASoS encompass humanity's largest problems such as Global Climate Change and Conflict End Games. We argue that while the contexts for various CASoS differ widely, they are all deeply similar; that the theories, technologies, tools, and approaches to enable effective engineering efforts focused on the solution of CASoS problems are the same across all. Elements of a *Winning Initiative* are identified to create the *CASoS Engineering Initiative*. The institutional structure for the CASoS Engineering Initiative is an integrated, outwardly growing spiral with core engineering, theory and experimentation that take place within an expanding analysis and simulation environment. Critical to this structure is the pull of applications: real world problems. As a national laboratory, Sandia has the mandate to solve very big problems of national/global impact. These problems are within CASoS. They will define our future.

ACKNOWLEDGEMENTS

This roadmap for the Complex Adaptive Systems of Systems Initiative was commissioned June, 2007, by Stephen C. Roehrig, Director for Energy, Resources & Systems Analysis (6300), at the request of Les E. Shephard, Vice President for Energy, Security, & Defense Technologies (6000). Feedback along the way from Les Shephard, Stephen Roehrig, John Mitchiner, Rush Robinett III, and Pablo Garcia was essential. Thanks go to the many Sandia staff who participated in the development of this roadmap; those who initiated a 'Defining Example' are included as authors. We are grateful for the opportunity to chart the CASoS Engineering Initiative and hope that it will be used to shape Sandia's future.



Hurricane Katrina landfall, 8/29/2005.
Source: NOAA Satellite Image

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EXECUTIVE SUMMARY

Complex Adaptive Systems of Systems, or *CASoS*, are critically important as we look past the electromechanical systems that have been our traditional focus at Sandia to the vastly more complex *physical-socio-technical systems* we must understand to design a secure future for the nation. We define CASoS through the use of Defining Examples that encompass/embed some of humanity's largest problems (past, present, future). They extend Sandia's traditional emphases on nuclear stockpile management, nonproliferation, and energy systems to global scales and to newly emerging worldwide emphases such as large-scale natural disasters, pandemics, global finance, global economic supply chains, and global climate change. We argue that while the contexts for various CASoS differ widely, they are all deeply similar.

As engineers, we are interested in influencing (designing, controlling, manipulating) a CASoS to *solve a problem, exploit an opportunity, achieve a goal, and/or answer a question*. By combining our understanding of the deep similarity of these systems with a systems engineering focus on influencing them, we can break out of the endless cycle of learning more and more about the details of individual CASoS and differentiate ourselves from other efforts. The influences we want to apply (our *Aspirations*) fall into a set of clearly identified categories: Predict; Prevent or Cause; Prepare; Monitor; Recover or Change; and Control. For each category, there are three emergent issues: *Decision*, *Decision Robustness*, and *Evolution towards Resilience*. All of these have to do with *Informing Policy*. Through systemization, we argue that the theories, technologies, tools, and approaches to enable effective engineering efforts focused on the solution of CASoS problems are the same across all.

We identify elements of a path toward a *Winning Initiative* and outline the *CASoS Engineering Initiative*. From an institutional view, the way we define and solve CASoS problems within Sandia must change to combine the bottom up *Complex Systems* and *Complex Adaptive Systems* view with the top down *Systems Engineering* and *System-of-Systems* view. The envisioned institutional structure for the CASoS Engineering Initiative is an integrated, outwardly growing spiral with core engineering, theory, and experimentation that take place within an expanding analysis and simulation environment. Critical to this structure is the pull of applications: real world problems. The understanding gained from each application is fed back to enhance and grow the core. With each turn of the spiral, the "Practice" of applying the theory to applications spawns new possible applications.

The time is right for a major initiative in this area both in terms of the compelling nature of the problems and in terms of Sandia's need for a challenging future that utilizes its technology, computing power, and modeling approaches, and inspires its unparalleled staff. As a national laboratory, Sandia has the mandate to solve very big problems of national/global impact. These problems are within CASoS. They will define our future.

1. INTRODUCTION

Sandia has long nurtured diverse lines of research and development in Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems. As our capabilities in these areas increase, we encounter problems whose complexity, interconnectedness, and heterogeneous structure challenge current theory and practice. Understanding these *Complex Adaptive Systems of Systems,* or *CASoS* as defined in this roadmap, becomes critically important as we look past the electromechanical systems that have been our traditional focus to the vastly more complex *physical-socio-technical systems* we must understand to design a secure future for the nation. Over the past few years an increasing number of new and ongoing projects, teams and business areas within Sandia are moving to address problems in such systems. CASoS are ubiquitous, including people, organizations, cities, infrastructure, government, ecosystems, the Planet – in short, nearly everything that involves biological and social systems. Sandia National Laboratories too is a CASoS, and can be measured, tested, modeled, simulated, designed, controlled, manipulated, and managed as such.

Quantitative analysis is being applied to CASoS both inside and outside Sandia, primarily through incremental adjustments to current theory and analysis tools. The sheer complexity of CASoS, the subtlety of their adaptive behaviors, the difficulty of running experiments, and the problems of integrating the different analytic frameworks and representations required to understand their component systems underscores the need for new theory, methods and practice. However, this larger field is currently poorly understood, far from integrated, and lacks consistent foundational theory or approaches for either discovery or application.

The goals for this roadmap are to:

1. Define CASoS as a subject of engineering study, determine the nature of theory and practice required to address CASoS issues and actualize solutions, and demonstrate that many of our current and future challenges center on CASoS and that these are and will be the problems of importance crosscutting the Laboratories;
2. Summarize the current state of CASoS research and practice;
3. In context of CASoS problems, create a vision for:
    a. R&D and Application “structure” with core R&D supporting spin-off applications in new areas;
    b. Integration of dispersed Sandia capabilities and external collaborations in R&D&A into this structure;
4. Plot a path forward to achieve our vision that will engage and excite Sandia management, researchers and staff, external collaborators and funding sources.

An invitation to our roadmap has been articulated in presentation form (**Appendix A**). There we begin with an illustration worked by one of us in real time over the past few years on Pandemic Influenza to demonstrate what a CASoS is, how problems can be defined and solved within CASoS, and the use of CASoS principles to actualize these solutions.

2. DEFINING AND INFLUENCING[1] CASOS

Although its subcomponents (Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems) have been defined and form the basis for entire fields of research and application (see **Appendices B and C**), we have found no consensus definition of CASoS itself.[2]

Defining scientific terms for an emerging field is surprisingly difficult. We develop our shared understanding through the use of ordinary language, metaphor, analogy, and social interaction, but the formal definitions that are our goal must be expressed in terms that transcend cultural idioms and individual ambiguities. Two of us, Glass and Engi, have been involved in several attempts to do similar things: Glass has worked on modeling socio-technical systems and combining complex systems with sustainability; and Engi on system of systems definitions, theoretical foundations, applications and issues. They have pursued these topics over the past year in NSF workshops at which, after two days (and several months of group writing), full agreement had not been achieved, and definitions were, at best, fuzzy.[3]

Our approach to defining CASoS was to compile a small set of examples we agreed were CASoS, and then draw a working definition out of their common qualities. This definition went beyond essential qualities to encompass the activities necessary to define CASoS as a field of scientific or engineering study, the actualization of engineered solutions within CASoS (getting them used), and the requirements (theories, technologies, tools and approaches) for enabling the influence of CASoS. We iterated on this process, both deepening our understanding of the examples and tempering the definition. The developing definition itself inspired additional examples and further refining of the definition. **Table 1** gives the final list of CASoS Defining Examples that we considered. Each of these has been given a page within **Appendix D** to illustrate our approach and we encourage the reader to read and explore them for themselves. These Defining Examples cover many of the nation's (and humanity's) most important current and future concerns. They also cover many of the current interests of both staff and business area managers within Sandia. Understanding each of these CASoS Defining Examples is critical to national security, Sandia's mission.

Table 1: Complex Adaptive Systems of Systems considered in this study.

CASoS Defining Examples	Initial Contributor
Conflict End Games	Arlo Ames
Nuclear Stockpile Management	William Stubblefield
Global Nuclear Nonproliferation	Leonard Malczynski
The Global Energy System	David Wilson, Jeffrey Carlson
Global Climate Change	George Backus
Large Natural Disasters	Robert Glass
Long Term Maintenance of Complex Infrastructures	William Stubblefield
The Global Economy	Mark Ehlen
The Internet	Keith Vanderveen
Sandia National Laboratories	Robert Glass, Arlo Ames

2.1. Qualities of a CASoS

Our process articulated four qualities a system must exhibit to be considered a CASoS. They are all essential – a system cannot omit any of them and still be meaningfully considered a CASoS.

1. **System:** A system is a set of entities, real or abstract, comprising a whole in which each component interacts with or is related to at least one other component.
   a. **Environment:** The system must be understood in the context of an environment, which is not part of the system itself.
2. **System of Systems:** Some of the entities composing the system are themselves systems.[4]
3. **Complex:** The system exhibits emergent behavior which arises from interrelationships between its elements; this behavior is of greater complexity than the sum of behaviors of its parts and not due to system complication.
4. **Adaptive:** The system is adaptive; the behavior of entities or sub-systems and their interaction change in time possibly resulting in a change in the way the entire system relates to its environment.

2.2. Activities necessary to define CASoS as a subject of scientific or engineering study

Our process uncovered three additional activities necessary to define CASoS as a field of scientific or engineering study. We are interested in doing something (designing, controlling, manipulating) with the CASoS to *solve a problem, exploit an opportunity, achieve a goal, and/or answer a question*.

5. **Aspirations:** A set of interesting problems, opportunities, goals, or questions that encompass important things to do with the system, representations of it, or our interactions with it.
6. **Approaches:** There are clearly defined 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.
7. **Attainability:** Some of these approaches or aspirations are rendered difficult or impossible by the fact that this is a complex adaptive system of systems.

Appendix D restates the 7 point definition for CASoS using different words and a rendering of each Defining Example in context of the definition. Again, we encourage the reader to explore the Defining Examples and consider the similarities among them. **Appendix E** elaborates an example Gedanken experiment[5] used to demonstrate the deep similarity in the various CASoS we considered.

From an engineering perspective and across all CASoS considered, *Aspirations* fall into a set of clearly identified categories:

1. **Predict** the evolution of the system and, in particular, the results of events (e.g., perturbations of a variety of qualities and quantities) with direct and consequential changes in system health.[6]
2. **Prevent or Cause** an event to occur.
3. **Prepare** elements of the system for impending events (e.g., minimize/maximize influence).
4. **Monitor** important aspects of a system to record the response of the system to events.

5. **Recover or Change** in response to events.
6. **Control** system behavior to avoid or steer the system towards specified regimes through the design of appropriate incentives and feedback.

Within each category, three sets of similar questions naturally emerge:

1. What are my Choices? What are their intended and unintended costs and benefits? How do I rank them?
2. Can choices be made that are uninfluenced by uncertainties? How different would the system have to be to decide differently?
3. Could we move towards conditions that enable choices to work better or yield better choices and end conditions?

The first of these sets has to do with *Decision*, the second with the *Robustness of Decision*, and the third with *Evolving the System towards Resilience*. All of these have to do with *Informing Policy*.

Important to this systemization is the recognition of *Attainability*, that some problems are too difficult or ill posed to allow solution. To move ahead, they must be restricted with additional constraints, or reformulated so that they are well posed and solutions are indeed reachable. Further, solutions are likely to involve unintended consequences which must be formally considered. It is not enough for a solution to do what it is designed to do; due diligence must be done to ensure that a projected solution does not cause unwanted consequences.

2.3. Actualization of CASoS Solutions

Fundamental to engineering activities is the intent to field solutions – deliver them into the real world so that they contribute value, so that they can be tested against real world requirements and so that they are *used*. We use the word *Actualize*, to refer to this intent in the CASoS context, as it captures the idea of making the solution real, and, in Maslow's terms, becoming complete.[7]

Actualizing solutions for CASoS involves traditional engineering concerns (e.g. thorough testing to requirements, field support) with additional concerns important to getting the solution used:

1. The complex environment in which solutions will be implemented is likely to be incompletely understood, so solutions are almost guaranteed to be incomplete when fielded.
2. The adaptive environment that solutions will encounter will change in response to the implementation of solutions, and might resist, circumvent, or even corrupt solutions. It is also possible for the adaptive system to adapt to the process of delivering solutions – that the solution only works while it is being delivered, and stops once delivery is considered to be complete.

Ultimately, these concerns mean that implementation will likely require more involvement than traditional engineered artifacts, with more requirements for in-the-field modifications and adjustments that embrace adaptation. Critical to this process will be system state measurement and monitoring. The term *actualization* is used to distinguish a solution that works both technically and socially; an actualized solution works as hoped, does not cause unintended consequences, and incorporates the adaptability to continue to work in the long term.

2.4. Requirements (theories, technologies, tools and approaches) for enabling the influence of CASoS

Finally, to enable the influence of CASoS systems, our process considered the required theories, technologies, tools, and approaches that would enable the engineering of CASoS solutions. We did this individually for each Defining Example and then pooled across the set, yielding a lengthy list given in **Appendix F**. This list can be organized into a set of essential categories:

1. Conceptual model construction and representation – enables reasoning about the problem.
    a. Representation of large and widely varying dimensions across sub-systems (time, space, model scope and complexity).
    b. Robust, rapid, thorough, balanced capture of essentials, sufficient to support engineering use.
2. System parameter and state variable measurement – enables measurement of the real world, to correlate model behavior with real behavior.
3. Observational and Experimental design – for discovery, verification and validation (V&V).
4. Pattern recognition and detection in models, data, solutions – enables broader and deeper thinking about problems and solutions through analogy with other complex systems.
5. Policy Investigation – determining rules and incentives to achieve desired behaviors (system control).
6. Engineering processes – enable us to create, test, and deliver solutions.
7. Real-time concerns – problem definition and solution within CASoS that is fast enough to serve policy-makers, especially in times of crisis.
8. Communication of results – recognizing the human factors involved to enable the use of problem solutions to influence a CASoS.
9. Creation of a community of practice in CASoS Engineering – builds the required intellectual critical mass to enable sufficient, sustainable success.

In essence, enabling the influence of CASoS requires that we impose and exercise straightforward scientific and engineering methods, methods which we have yet to apply concertedly to large physical-socio-technical systems. These methods must be applied to the entire problem, from definition to design or solution evaluation to implementation to actualization.

3. CURRENT STATE

To define the current state of CASoS work, we pooled the experience of team members, several past/present road maps on related topics, and some concurrent compendiums of “who is doing what” both internal and external to Sandia.

A number of groups at Sandia and across the world are working on or are moving into CASoS problems, but they are doing so in isolation, using and developing their own tools, each with a problem-specific language, all of which becomes more and more constrained to the particular problem as development continues. This specialization makes it difficult to address new problems whose surface differences mask a deeper structure that is common to all CASoS.[8] Often, the approach to new and more encompassing problems is to glue together several seemingly disparate specific application-based conceptualizations or “models” with a “system of system” (SOS) view (see **Figure “Current State”**). This approach lacks a systemic view of the representational complexities of CASoS, and makes it difficult to fully understand and corroborate the resulting analysis.[9] An essential component of an integrated research program is a unifying body of theory to counter the “butterfly collecting” approach that dominates many current efforts.

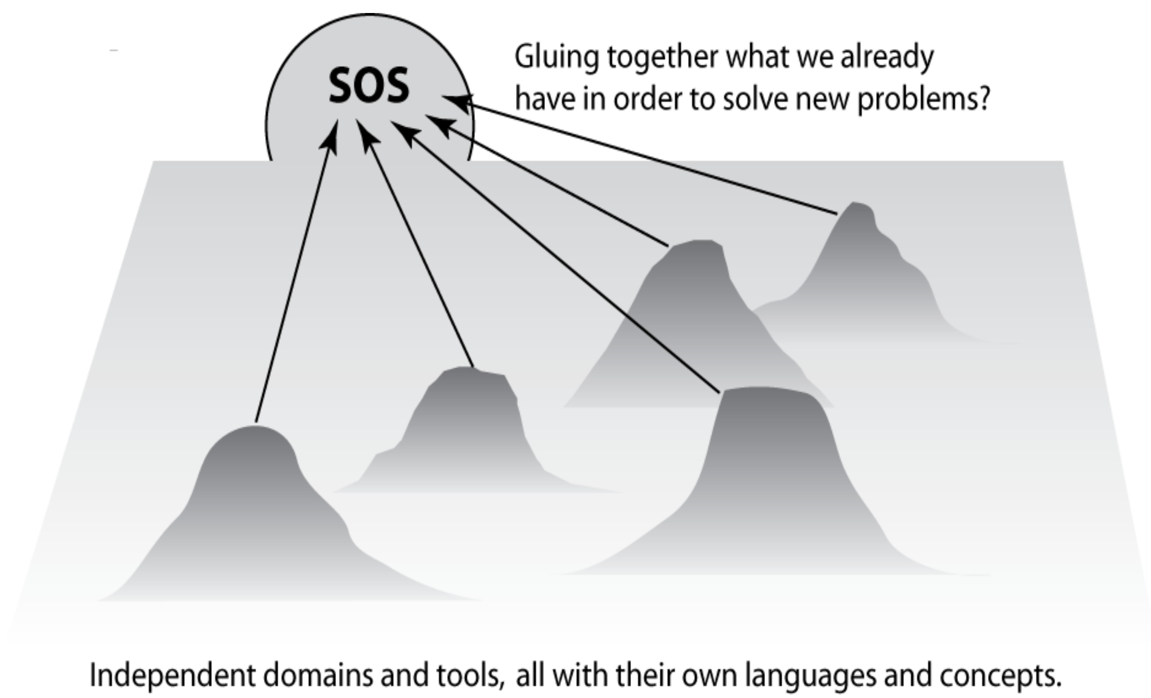


Figure: Current State.

The roots of this problem run deep in our culture and funding framework, where we continue to manage ourselves (internally and externally) as a collection of independent institutions and projects with no overarching theoretical or methodological drivers. We are managing our theory and tool development like stove-piped, independent processes.

A classical *Systems Engineering* solution to this problem would be the central management of common infrastructure and interactions among various projects. A *System-of-Systems* perspective would note that the projects might be fielded in many different ways, have different lifetimes, and seek some organizing means of interaction that bridges the various differences. A *Complex Systems* perspective would view projects spontaneously growing and dying within energy (funding) gradients, and see any pattern that forms as an emergent property of the system. A *Complex Adaptive Systems* perspective would additionally recognize that individuals as well as groups continuously adapt to secure their places much as species do within ecosystems.

A *CASoS* perspective would combine the bottom up Complex Systems and Complex Adaptive Systems view with the top down Systems Engineering and System-of-Systems view. This is the perspective needed to manage a CASoS Engineering Initiative either at Sandia or across the world. A unified body of theory, research questions, vocabulary, and practice is an essential foundation for solving new problems within wide ranging CASoS effectively.

The time is right for a focus on CASoS problems. Not only are the problems critical and compelling, but we are technologically poised due to the unique combination of 1) computers and the expectation of continuous expansion of speed, memory, and know-how in the future, 2) modeling approaches (ranging from continuous to discrete, agent-based networks) and the expectation of seamless combination of approaches in the future, and 3) data (from satellite imagery showing changing land use to electronic data on the spending habits of individuals) and the expectation that we can find and use the correct data (data mining) in the future. And as a national laboratory, Sandia has the mandate to solve very big problems of national/international impact. We should play a leading role.

4. REQUIREMENTS FOR A WINNING INITIATIVE

Muddling along the current path will not create a Winning Initiative in CASoS Engineering with Sandia as an internationally recognized leader and an essential resource for CASoS related solutions in national security.

A Winning Initiative requires:

1. The building of a multi-institutional community with a shared body of theory, terminology, methods, and corroboration criteria such as is found in mature engineering fields.
2. A definition of a compelling overarching problem or set of problems.
3. An internal structure that is driven by technical vision focused on the overarching problem or set of problems and which recognizes reflexively that it itself is a CASoS.
4. Significant funding.

As an example of a multi-laboratory DOE Initiative that worked reasonably well, consider the Advanced Scientific Computing Initiative (ASCI) which evolved past the Initiative stage to become the ASC program (dropping the I). ASCI built on an existing foundation of physics and physical modeling that had been developed in the larger scientific community. This common language was a pre-requisite for the integration that ASCI required (requirement 1). It began with a compelling overarching problem (requirement 2): How to design and maintain NW without the ability to test. It created an organization (requirement 3) that included the 3 DOE weapons labs, focused on physics solutions and big computers, and imposed a communal structure for computational development and support. The combination of problem, solutions, organization, and technical approach garnered funds (requirement 4) at a significant level for a long time.

ASC stands as a model for part of what we wish to achieve. Before ASC, analysis capabilities the 3 labs were independently developed. Each involved redeveloping a significant amount of functionality: file interfaces, finite element representations, solver technologies, etc. ASC recognized that a significant fraction of the burden of developing a new code could be shared and, further, that the codes would be profoundly more interoperable if they were developed on top of a consistent infrastructure. Pooling of resources enabled the purchase of a series of increasingly powerful parallel computers and the development of codes that take advantage of those machines. Further, ASC linked itself to a DOE weapons Lab mission – stockpile stewardship. That link provided a significant measure of funding stability. ASCI, and now ASC, has received significant funding for many years and has provided leverage for developing many new capabilities.

ASC is not without problems. The common infrastructure is not necessarily as efficient as previous implementations, nor is it necessarily easy to work with. Efforts are underway to replace the infrastructure – to start again. Further, the large size of the ASC program means that larger numbers of people can be negatively affected by funding problems than would be affected by a smaller program. However, because of its success, a thorough study of ASC seems warranted, to maximize potential benefits of patterning work after it while avoiding potential pitfalls. One such pitfall is not recognizing that large initiatives are themselves Complex Adaptive System of Systems and must be managed as such.

5. THE CASOS ENGINEERING INITIATIVE

Given that CASoS issues are real; that they represent important issues challenging the establishment of a safe, secure world; that we want to address these issues; and that there are technological needs that must be met in order to address them, an Initiative in CASoS Engineering is crucial.

Applying the four requirements for a Winning Initiative to the development of the CASoS Engineering Initiative leads to the following actions.

5.1. Build a multi-institutional community with a unified body of theory, terminology, methods, and corroboration criteria

We must focus on the development of theory, terminology, methods, and corroboration criteria (verification and validation or "V&V") that define a mature engineering discipline. It is not enough to cobble together a point solution to a given problem – all participants must focus on advancing the larger state of the art and developing a community of practice in doing so. We envision a community that crosses organizational lines, is multi-institutional, and is held together through collaboration on projects, the sharing of tools built for community use, and communication (newsletters, presentations, conferences, and workshops). We also envision spending significant effort on making sure that anything built in the community (understanding, methods, code) is general, well documented, discussed among the members, and used to ensure that we leverage each other's work.

5.2. Define a compelling overarching problem or set of problems

In a sense, problem definition is the essential counterpoint to the theoretical focus in requirement 1. It is what keeps us from solving a series of artificial problems simply to advance theory for its own sake. CASoS Engineering, in particular, demands this grounding in real problems since the constructed problems science often addresses cannot capture the full complexity of the real world. We identified a set of compelling problems in the Defining Examples above (**Table 1**) which are detailed in **Appendix D**. Sandia has experience in addressing problems of this kind; the analysis documented here initiates the process of formalizing, systematizing, and expanding our capabilities (development of strategically-targeted technical approaches) to work on such problems. The undeniable importance of this problem set and our intent and ability to address them need to be communicated to critical people; ultimately, to the key set of Senators and Representatives in Congress whose support will be needed to provide the significant funding required to establish this as a Winning Initiative. The overarching problem and our potential for addressing it need to be presented simply and compellingly enough to focus attention (and resources) on discovery of applied solutions with life-changing practical benefits. These are the kinds of problems people trust us and depend on us to solve.

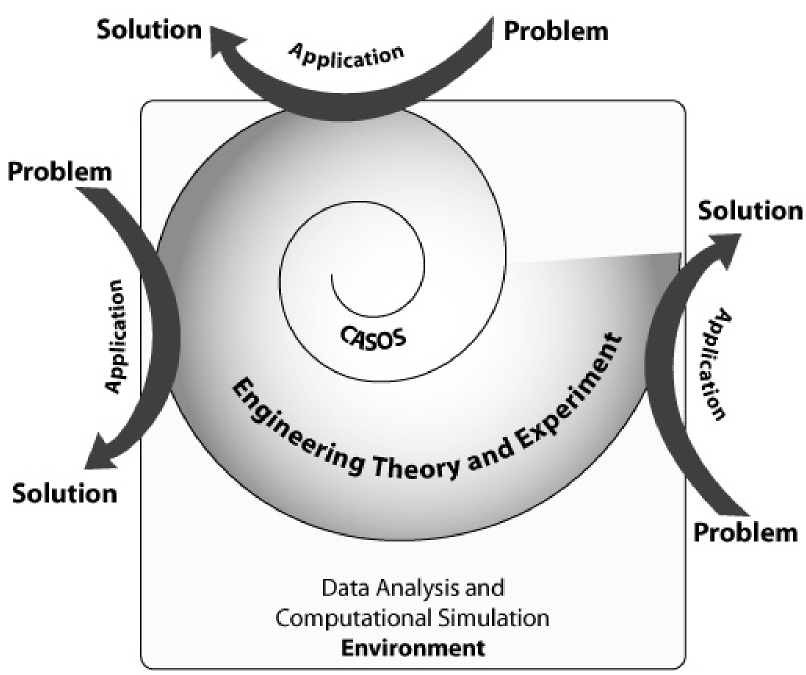
This effort is analogous to the Manhattan Project in which strong theoretical work from the laboratory was coupled with a compelling need to find a game-changing solution. Even rough solutions to any of the CASoS problems have the potential to strengthen and secure humanity. Sandia and other institutions are seeking compelling new missions, ones as important as that of fighting the Cold War. With CASoS Engineering, we may have found just such a worthy mission.

5.3. Drive Initiative structure by technical vision focused on the overarching problem(s) and by recognition that the Initiative itself is a CASoS

We believe that CASoS Engineering theory and practice must be conducted together to develop a discipline that is both grounded in reality and works to extend our understanding and control of that reality. This, in fact, is the ideal marriage of science and engineering. We envision an integrated, yet distributed initiative in *CASoS Engineering* that involves the National Laboratories, academia, and industry. At Sandia, the fit would be strong because:

1. As a National Laboratory, our focus is on solving problems of interest to National Security, not the theory of CASoS for its own sake;
2. We can focus on what we do best: the engineering aspects of design, control, manipulation, mathematical modeling, computational simulation, and decision support;
3. We should be able to make progress rapidly by solving a sequence of well defined staged problems across a variety of CASoS;
4. New applications will emerge continually and funders of engineering R&D are most interested in solutions.

Figure "Future State" sketches the envisioned structure for the *CASoS Engineering Initiative*. It shows a spiral development model for CASoS engineering, theory, and experimentation that take place within an integrative analysis and simulation environment. Critical to this structure is the pull of applications, real world problems that give momentum to the Initiative. Understanding gained from each application is fed back to enhance the core. The "Practice" of applying the theoretical approach to applications feeds the development of core and environment. Each turn of the spiral improves the foundational core, and adds energy and momentum, generating new applications at an increasing rate



Critical national problems drive the research engine

Figure: Future State

This envisioned CASoS Engineering structure is composed of a set of 5 continuously expanding critical components:

1. **Theory**, which is generic and applicable to the seemingly disparate problems that share the deep structure of CASoS. Advanced development will involve ongoing efforts by a multidisciplinary community of scientists, engineers, applied mathematicians, social scientists, epistemologists, and other specialists:
    a. Conceptual Modeling and Representation (system identification);
    b. Analysis and Computational Simulation;
    c. Integration of a variety of ideas from sub-disciplines, such as non-equilibrium thermodynamics, that include self-organization, adaptation, networks, and robustness/fragility/resiliency;
    d. Design and Control: approaches to encourage or eliminate complex and/or chaotic behavior, depending on design requirements.

2. **Experiment**, including approaches, systems, and test-beds for both discovery and the testing of theory (V&V). Performance will involve ongoing efforts of scientists, engineers, technicians:
    a. Observation methods for use in real systems;
    b. Measurement and design of required “sensors” (data collection);
    c. Experimental design, testing and other forms of corroboration.

3. Data analysis and computational simulation **Environment** that would require ongoing efforts of computer scientists, interaction designers, statisticians, human-factors specialists to include:
    a. Generic data and simulation analysis and visualization;
    b. Integration of systems that are under independent/interdependent development, embody multiple, interdependent capabilities, and support multiple missions.

4. **Applications** for a wide range of stakeholders with continual spin-offs. Applications will pull rather than push the Theory, Experiment and Environment and will employ engineers, analysts, and designers to create solutions involving:
    a. Vast systems that apparently defy analysis by conventional methods;
    b. Collaboration with application-specific stakeholders;
    c. Commitment to solutions throughout actualization process.

5. **Reflexive Management** of the Initiative as a CASoS: testing the theory and practice will require ongoing efforts of managers and staff involving:
    a. Applying CASoS theory to the process of inventing the theory and practice
    b. Discovery of new ways of finding opportunities in the social and technological networks surrounding CASoS practice.

The five components are intimately intertwined. As one example, consider Verification and Validation (V&V). The use of CASoS analysis for high consequence decisions requires a rigorous and defensible process for V&V. If V&V is part of the analysis from its inception, analysts can reformulate the problem characterizations and the approach to modeling its solution such that confidence in the model results/implications is built-in, rather than added-on. Because CASoS efforts are distinctly different from conventional modes of analysis, unique V&V methods will need to be developed.[10]

5.4. Find significant funding

In recognition that we work within a CASoS, it is appropriate to consider funding opportunities in a CASoS-theoretic way. We examine here a few top-down and bottom-up funding approaches, approaches for leveraging them against each other, and opportunistic processes. At this time, our investigation into possible funding approaches is incomplete, but it follows a collection of plausible scenarios, many of which have worked well in the past. All should be combined and pursued simultaneously.

First is to harness the energy (funding, excitement, compelling nature) of existing and new CASoS applications in the future. This model would make use of CASoS Engineering principles to grow the core naturally and in context. Current applications feed its development allowing future applications to be landed and worked more effectively. This bottom-up path would require a top-down initial investment likely in the form of multiple LDRDs ($300-600K each) or a Grand Challenge LDRD (several million $) to achieve the activation energy required to create the necessary structure (**Figure Future State**) and begin to build a multi-institutional community.

Second is to redirect or entrain the paths of currently developing initiatives. There is at least one developing initiative currently within the DOE Office of Science that could be directed towards CASoS. Three DOE energy labs Argonne, Oak Ridge and Lawrence Berkeley have produced a draft "Report on the Advanced Scientific Computing Research Town Hall Meetings on Simulation and Modeling at the Exascale for Energy, Ecological Sustainability and Global Security."[11] This effort addresses an intrinsically CASoS problem. Within Sandia, there are several developing initiatives within the energy arena such as the National Energy Innovation Initiative (NEII) and its sub-component, the Transportation Energy Innovation Hub (TEIH). These also are CASoS.

Third, along the lines of ASCI development, is to convince Congress and the administration to fund the CASoS Engineering Initiative directly. This would require the directors of several national labs to combine forces and push for its creation. However, the timing may be just right. The Congress and the administration are considering cuts to the nuclear weapons complex and, consequently, NNSI sponsored work at SNL, LANL, and LLNL. What better Initiative than CASoS to augment it?

For all of these approaches, working the social and constituency network is critical. There are numerous potential champions at all levels (management and staff) within Sandia as well as external to Sandia throughout academia, industry, other national labs and government. Each connection in the social/constituency network is an opportunity to open up new connections. Being opportunistic is critical. Opportunities will most likely be topical. Our Defining Examples are topical. Each funded opportunity must produce effective answers – they are paths to further opportunity if done well, and barriers if done poorly.

6. THE PATH FORWARD

The path forward for the CASoS Engineering Initiative must include a blend of bottom up self-organization (researchers and their ideas), top down direction (incentives, funds), and a cultural commitment to risk-taking that is increasingly rare in government or industry sponsored R&D. The Initiative must grow to be big and multi institutional (labs, industry, government, academia). We will have to convince Sandia small staff that this is our future and entrain them in the process to achieve the appropriate scale with commensurate funding.

As a first key step along the path, LDRD projects should be orchestrated to bring together a core group of CASoS Engineering researchers, articulate an overarching CASoS Engineering Framework, begin the process of developing core theory and technologies, and demonstrate the application of this theory and technology to several CASoS of critical importance. This step should be followed closely by the design of a Grand Challenge LDRD in CASoS Engineering that would establish the future state structure shown in the **Figure Future State** and accomplish a turn or two along the spiral.

Around the nucleation provided by LDRD projects we must:

- Expand CASoS Engineering components within current funding from existing customers: DOE, DHS (NISAC[a] in particular), DoD, GM, other
- Integrate current work across groups doing CASoS Engineering: break down project/ department/business-area/center/directorate stove-piping with cross-teaming.
- Develop new funding in CASoS Engineering: PD, external funds from new clients with new applications.
- Organize CASoS Engineering workshops/conferences: both internal and external to Sandia (such as a Gordon Conference).
- Build a Community of Practice: brown bags, workshops, chat sites, co-location.

As we accomplish the above we will use CASoS Engineering principles reflexively to manage the Initiative:

- Contextualize work (setting Sandia work in context of CASoS Engineering concepts).
- Identify niches (setting Sandia work in context of other work, guild identification).
- Render the network of interdependencies (recognition of how work fits together, e.g., the food web, economic supply chains, etc.).
- Identify fertile areas for growth (combination of fundamentals and business).
- Design practices and configurations to best accommodate growth (strengthening the core while enabling agility, cross-fertilization to create new areas, guided self organization).
- Internalize the life-cycle of individual applications (define and accept when projects are complete, doing our job right means that we move on to new applications).

Additionally, we must work towards creating and doing something *significantly different* (at least different for Sandia) that would bring national recognition in this area and significantly boost our effort. We envision at least three potential efforts that we expand upon below: 1) An internal/external *CASoS Engineering Institute*; 2) *Curricula in CASoS Engineering* through the CASoS Engineering Institute; and 3) *Engineering Corporate Excellence at Sandia*.

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[a] Composed of analytical staff at SNL and LANL, the National Infrastructure Simulation and Analysis Center (NISAC) provides support for mitigation and policy planning to DHS.

6.1. A CASoS Engineering Institute[12]

The CASoS Engineering Institute would combine Sandia researchers with researchers and practitioners from industry, government, and academia as well as other national labs. The institute would form an umbrella for a wide variety of activities such as workshops, conferences, and curricula with the goal of developing fruitful collaboration in CASoS Engineering research and practice. Researchers and practitioners would belong to the Institute in addition to their current home institution. They would become members by applying to the Institute and being accepted for a period of time (say 1-5 years) with review and renewals contingent on furthering the goals of the Institute. Roles in the Institute could be paid or unpaid. The Institute could be real or virtual; both states have pros and cons. Institute funding could come internally/externally through Sandia or have sources and management independent of Sandia. Belonging to the Institute would confer status and would be rewarded through standard performance review at home institutions. CASoS Engineering principles would be reflexively applied to the management of the Institute.

6.2. Curricula in CASoS Engineering through the CASoS Engineering Institute

The industry/government focused curriculum would combine intense periods of full immersion at the Institute with individual practice (application) back at home institutions. This will engage corporations/departments in our approach, instigate change in their institutions and across the institutional landscape, and develop application-focused collaborators who become members of an expanding community of CASoS Engineers.

6.3. Engineering Corporate Excellence at Sandia

We have identified Sandia as a CASoS through a Defining Example within **Appendix D**. The reflexive management principles articulated for the Initiative would be applied to Sandia at large to Engineer Corporate Excellence. If Sandia’s state as characterized through its organizational, influence, expertise, communication, and constituency networks, was measured autonomously, then every future perturbation (internal or external) yields insight into system behavior. Conceptual models that capture this insight can then be applied to design changes in corporate practices and organization that would meet a set of objectives and achieve a given state. Designs could then be implemented and tested experimentally to see if they achieve the desired objectives and state. For example, define processes, incentives, and organizational structures that work interdependently, have high repurpose-ability, and address potentially indefinite as well as cradle-to-grave-to-cradle lifecycles. Then initiate activities (at strategic and tactical level) and determine, as objectively as possible, how successful the new structures are at achieving guided yet agile and adaptive self-organization. Cooperation among technical staff and management in design and testing would ensure buy-in from both sides, permitting management to leverage state-of-the-practice with CASoS Engineering theory to Engineer Corporate Excellence. Recognizing Sandia as a CASoS would also empower staff to define and take responsibility for the processes that affect their professional lives.

7. A CALL TO ACTION

What seemed to be the "normal" condition throughout the 20th century, governance by central authorities whose decisions, alignments, and interactions dominated and oriented social endeavor, can now be seen as an exceptional, and transitory, state. In today's environment of rapid reconfiguration of lines of communication and shifting patterns of interaction and responsibility, there is no locus of authority for the class of problems currently presenting the greatest threats to today's societies. We must provide the perspective, leverage, and tools to manage the risks within our chaotic and uncertain environment. Through the CASoS Engineering Initiative, we can develop the required theory, technology, tools and approaches, apply them to humanity's largest problems now and in the future, and actualize the solutions so that they are used by society. This effort is analogous to the Manhattan Project in which strong theoretical work from the laboratory was coupled with a compelling need to transform to yield a game-changing solution. Even rough solutions to any of the CASoS problems have the potential to strengthen and secure humanity. The time is right for a major initiative in this area both in terms of the compelling nature of the problems and in terms of Sandia's need for a challenging future as important as that of fighting the Cold War that utilizes its technology, computing power, and modeling approaches, and which inspires its unparalleled staff. As a national laboratory, Sandia has the mandate to solve very big problems of national/global impact. These problems define our future.

APPENDIX A: POWERPOINT PRESENTATION AND INVITATION TO THE ROADMAP

Engineering Solutions in an Interdependent World: The CASoS Engineering Initiative

The CASoS Team:

Robert Glass, Arlo Ames,
William Stubblefield, Stephen Conrad, Louise Maffitt,
Leonard Malczynski, David Wilson, George Backus,
Keith Vanderveen, Mark Ehlen, Dennis Engi

Commissioned by Stephen Roehrig, 6300

At the request of Les Shephard, 6000

*An **invitation** to our Roadmap.*

Sandia National Laboratories

First, A Story

To illustrate

- What a **CASoS** (complex adaptive system of systems) is
- Defining **problems within** CASoS
- Engineering **solutions** using a generic component based approach to modeling
- Using CASoS principles to **influence policy** (get the solution used within the CASoS)

Pandemic Influenza: Halloween 2005

Sandia National Laboratories

The Situation

Two years ago on Halloween NISAC got a call from DHS. Public health officials worldwide were afraid that the H5NI "avian flu" virus would jump species and become a pandemic like the one in 1918 that killed 50M people worldwide.

DHS asked NISAC to put together a briefing package to prepare DHS Sec Chertoff for a White House table top exercise the second week of December.

Chickens being burned in Hanoi

Our Applications at the time…

- We were applying a generic CASoS approach to **power grids**, to the movement of funds from bank to bank within the FED's **Fedwire** system (2+$T a day), to the contagious transfer of ideas and action in settings of **civil disobedience…**
- In these systems we see **cascades** of activity, **emergence** of **power-laws** for distribution of event sizes vs event frequency, **fractals**, all the hallmarks of Complex Systems
- In context of these systems, we were interested in questions that had to do with **keeping a system from cascading** and if it did, defining the right **corrective action** to dissipate the cascade.

Pandemic? No Vaccine, No antiviral.
What could we do to avert the carnage?

Seeking Solutions by Analogy with other CASoS

- **Forest fire**: You can *build fire breaks* based on where people throw cigarettes… or you can *thin the forest* so no that matter where a cigarette is thrown, a percolating fire (like an epidemic) will not burn.
- **Power grid blackout**: The spread of a pandemic is a cascade that runs on the interactions among people, the social network, instead of the wires of a power-grid.
- Could we target the social network and thin it?
- Could we thin it intelligently so as to minimize impact and keep the economy rolling?

PROBLEM DEFINTION: *stop an epidemic with the least social burden*

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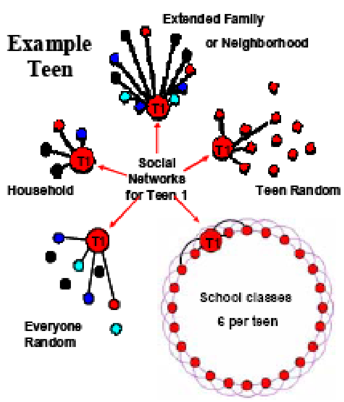
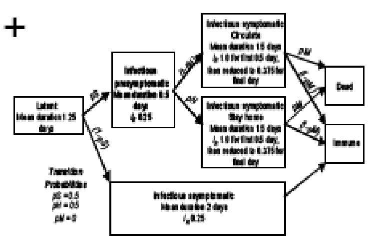
Application of Generic CASoS Approach to Influenza



Stylized Social Network
(nodes, links, frequency of interaction)

\+

Disease manifestation
(node and link behavior)



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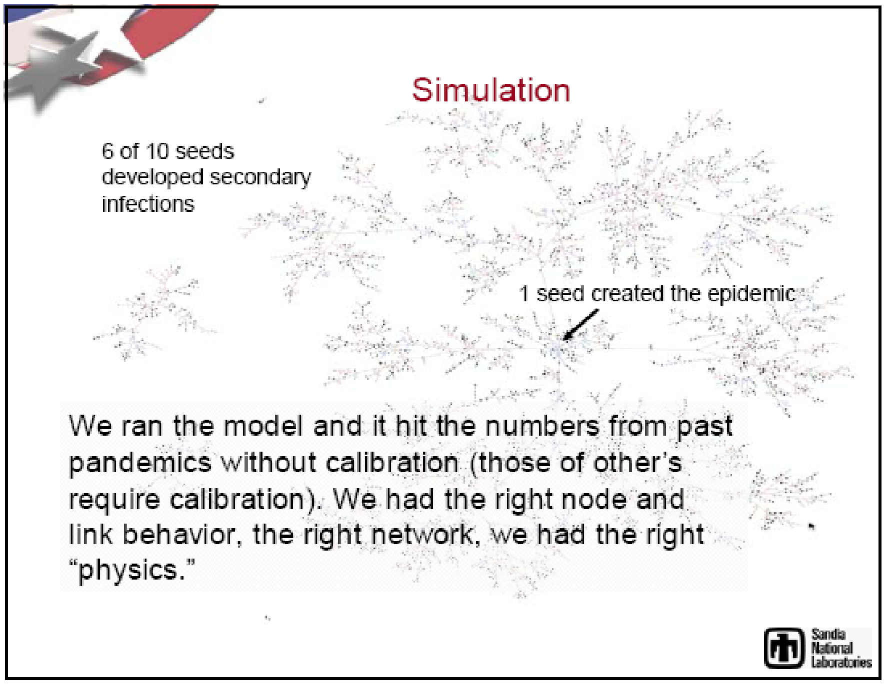
Simulation
6 of 10 seeds developed secondary infections
1 seed created the epidemic
We ran the model and it hit the numbers from past pandemics without calibration (those of other's require calibration). We had the right node and link behavior, the right network, we had the right "physics."
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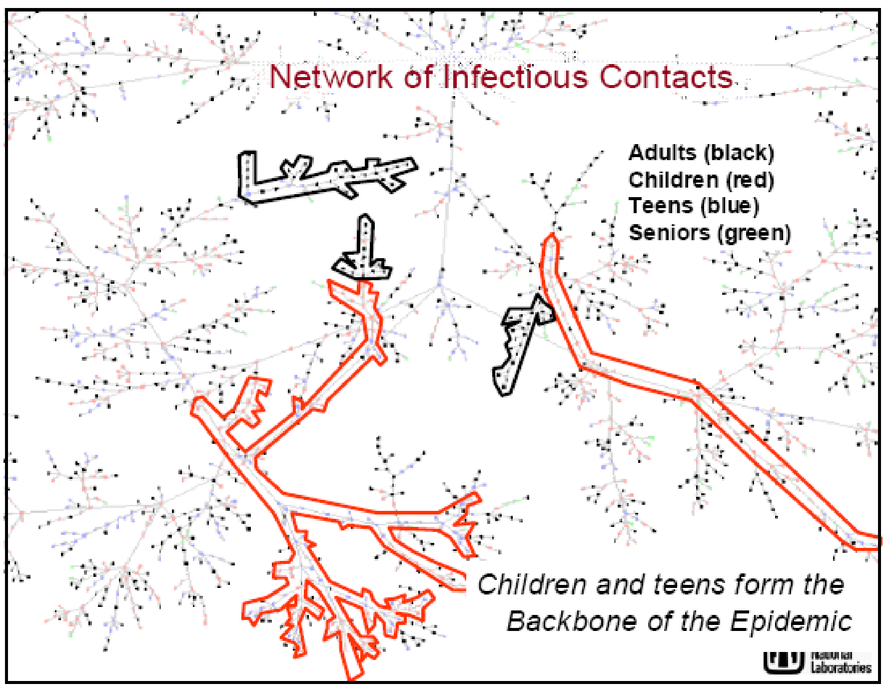
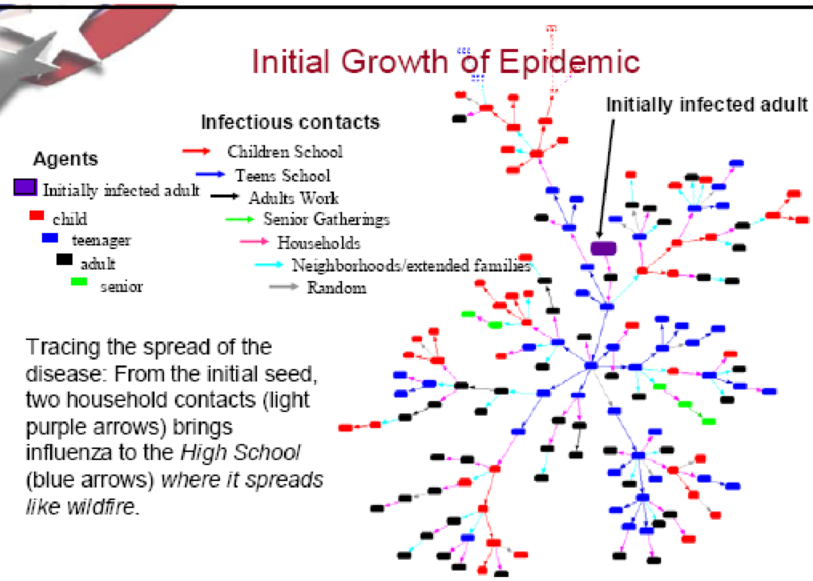

Network of Infectious Contacts
Adults (black)
Children (red)
Teens (blue)
Seniors (green)
Children and teens form the Backbone of the Epidemic

Initial Growth of Epidemic



Tracing the spread of the disease: From the initial seed, two household contacts (light purple arrows) brings influenza to the *High School* (blue arrows) *where it spreads like wildfire.*

PROBLEM SOLUTION: *Close the schools AND keep the kids & teens at home*

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The Clouds Thicken…

- Sec Chertoff briefed, open release SAND report written.
- White House table top: everyone several steps behind our thinking, fixated on closing borders, etc. Closing borders = building fire breaks. *They don't solve the problem.*
- Big names in epidemiology modeling the movement of the disease across the US with massive models at LANL and in Great Britain (published rapidly in Science and Nature) suggested there was little that could be done. The pandemic would wash over the US without antivirals.

But their tools were not built to consider the intricacies of the underlying social network on which the pandemic would spread in a local community.

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Getting our results used…

- We needed to **INFLUENCE PUBLIC POLICY** and quickly.
- We used the *informal social-influence network* instead of the command and control hierarchy to get our work to the critical nodes with control.
- We sent our SAND report to a colleague at the VA who sent it to a colleague who was the VA's rep on the Homeland Security Council (HSC) Pandemic Implementation Plan Writing Team, who sent it to the team lead who sent it to the Senior Director for Biodefense Policy, HSC.
- Glass got on a plane and after a 4 hour presentation-interrogation-brain storming session, he had *changed the course of public policy.*
- We had started another kind of cascade. The story goes on and illustrates other critical features such as collaboration, reaction, adaptation, consensus building… and the continued use of *CASoS principles to affect system behavior*, but this is enough for our illustration today.

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Summarizing the main points

- We were dealing with a large complex adaptive system, a CASoS: a global pandemic raging across the human population within a highly connected world (social, economic, political)
- By similarity with other such systems, their problems, their solutions, we
  - defined **THE CRITICAL PROBLEM** for the pandemic
  - applied a **GENERIC APPROACH** for simulation and analysis
  - came up with a **ROBUST SOLUTION** that would work with minimal social and economic burden independent of decisions made outside the local community (e.g., politics, borders, travel restrictions).
- Through recognition that the **GOVERNMENT's** global pandemic preparation was a CASoS, we
  - used CASoS concepts (social net, influence net, people) to **INFLUENCE PUBLIC POLICY** in short time. These concepts continued to be used by the HSC folks over the past 1.5 years to implement the policy that we identified. And work continues…

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So…

- We have prototype theory, practice, and examples for solving CASoS related problems, *independent of domain*, that is focused on applications
- We know that we can expand to new applications, and we can hone our skills, but we will have to "do the science"

Questions:

- Can we do it generically?
- Can we do it across Sandia in a way that increases leverage and impact?
- Can we become the "go to" place for the problems of today and the future?

The CASoS Engineering Initiative

Sandia National Laboratories

Can we do it generically?

- CASoS are similar
- The engineering problems of CASoS are similar
- The questions for each problem are similar and of are of three classes:
  - What Decision?
  - Is the Decision Robust?
  - How can we Evolve towards Resilience?

We believe the answer is YES
But we need to fund and do the science

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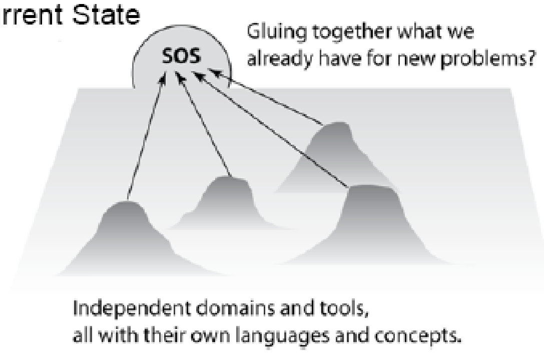
Can we do it across Sandia in a way that increases leverage and impact?

Current State



Maybe, but we would have to move from the Current Stove-piped Structure to…

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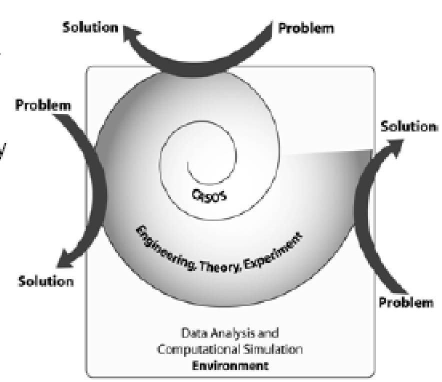
An Integrated Structure

- ***Theory:*** generic, applicable to the seemingly disparate problems that share the deep structure of CASoS
- ***Experiment***: approaches, systems, and test-beds for both discovery and the testing of theory
- Data analysis and computational simulation ***Environment***
- ***Applications*** for a wide range of customers that pull rather than push the Theory, Experiment and Environment
- ***Reflexive Management*** of the Initiative as a CASoS



Customer problems drive the research engine

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Example CASoS problems we would like to solve/engineer:

- What do we do about Iraq? Afghanistan? the Kurds? Dafur? the Sudan?
- What do we do about Iran/Syria/North Korea…?
- CO2 emissions?
- Dependency on foreign oil?
- Katrina like events?
- Sub-Prime Credit Crisis and CDOs? (weaponized financial instruments?)

The New Problems of National Security

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Can we become the "go to" place for the problems of today and the future?

Only if we have the courage, wisdom, commitment, and will to begin… the Roadmap for the ***CASoS Engineering Initiative*** points a direction.

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APPENDIX B: TERM LIST

Some of these terms and concepts seem trivial to define, but many people use them to mean something very different than we may intend. Some of these have been defined below; the list and definitions are incomplete. We began our process collecting terms and found ourselves struggling for definitions. We moved to thinking about problems and solutions, which we found much more productive and satisfying, and settled on a working definition. The following glossary may remain incomplete; we are more interested in defining and solving problems (rather than terms and concepts).

noise

control

pattern

chaos

complexity

organized

self-organized

criticality

self-organized criticality (SOC)

complex system: A complex system is a system whose properties are not fully explained by an understanding of its component parts. Complex systems consist of a large number of mutually interacting and interwoven parts, entities or agents. They are woven out of many parts, the Latin complexus comes from the Greek pleko or plektos, meaning "to plait or twine." (Gell-Mann).

adaptation: requires spontaneous, self-organized response that is new (not part of the script for the system)

complex adaptive system

system of systems: A System of Systems is a set (say A) of entities satisfying three conditions; namely, each of the entities in set A (1) interacts with at least one other member of set A, (2) can be characterized in the context of a set (say Bi for entity i in A) of entities each of which interacts with at least one other member of that set (Bi), and (3) can be eliminated from the set A without causing the resulting System <of Systems> to exhibit behavior that is substantively different than that the original System of Systems. (Engi)

complex adaptive system of systems

networks (nodes, links, rules…)

interdependencies

competition

redundancy, efficiency, effectivity

vulnerability, robustness, fragility, resilience

well posed vs ill posed problems

wicked problems: problems that have incomplete, contradictory, and changing requirements; and solutions to them are often difficult to recognize as such because of complex interdependencies. While attempting to solve a wicked problem, the solution of one of its aspects may reveal or create another, even more complex problem. (Rittel)

highly optimized tolerance (HOT)

complexity such as found in DNA or in a living organism or in a society

emergence

scaling

percolation, invasion percolation, modified invasion percolation

markets

non-equilibrium systems, far from equilibrium systems, thermodynamic principles

energy gradients

order on the edge of chaos

fractals in time, space (phase space?)

sustainability

indefinite (infinite) product lifetime

independent, interdependent development

system boundaries changing over time

overlapping (possibly conflicting) spheres of influence

APPENDIX C: BACKGROUND FOR DEFINITION OF CASOS

CASoS is a concatenation (or combination) of a series of words. These words may be defined independently and combined to constrain/specialize the definition of any one.

Definitions of individual words from the Cambridge Advanced Learners Dictionary:

complex (HAVING MANY PARTS)
adjective

1 involving a lot of different but related parts:

a complex molecule/carbohydrate

a complex network of roads

a complex procedure

The company has a complex organizational structure.

2 difficult to understand or find an answer to because of having many different parts:

It's a very complex issue to which there is no straightforward answer.

The film's plot was so complex that I couldn't follow it.

adaptive
adjective SPECIALIZED

possessing an ability to change to suit different conditions

system (SET)
noun [C]

1 a set of connected items or devices which operate together:
a central-heating system

2 a set of computer equipment and programs used together for a particular purpose:
The system keeps crashing and no one is able to figure out why.

3 a set of organs or structures in the body which have a particular purpose:

the immune system

the nervous system

4 the way that the body works, especially the way that it digests and excretes:
A run in the morning is good for the system - it wakes the body up and gets everything going.

Definitions of sub disciplines:

Three combinations of the terms that make up CASoS have meanings that are greater than their sum of parts: Complex System, Complex Adaptive System, System of Systems. In addition to Systems, this yields four independent sub-disciplines or study areas. Extensive literature exists for each of these subsystems and can be skimmed through look-up in Wikipedia.

But, there is no definition of “Complex Adaptive System of Systems.”

APPENDIX D: CASOS REQUIREMENTS AND DEFINING EXAMPLES

CASoS is a concatenation of four sub disciplines or study areas: Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems. Definitions of CASoS are accomplished by addressing, at a minimum, the 7 points described below. A Complex Adaptive System of Systems requires:

1. **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.[13] Any object which has no relation with any other element of the system is not part of that system.
   a. **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
2. **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.
3. **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.
4. **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.

We are interested in problems regarding CASoS.

5. **Aspirations:** What are the problems/opportunities/goals/questions?

We are interested in doing something (designing, controlling, manipulating) with the system to solve a problem, exploit an opportunity, achieve a goal, or answer a question:

6. **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.
7. **Attainability:** How are approaches/aspirations rendered difficult/impossible by the fact that this is a complex adaptive system of systems?

Defining Examples:

The CASoS that we considered for Defining Examples cover many of the nation's (and humanity's) most important concerns now and in the future. This example set also covers many of the current interests of both staff and business area managers within Sandia.

CASoS Defining Examples	Initial Contributor
Conflict End Games	Arlo Ames
Nuclear Stockpile Management	William Stubblefield
Global Nuclear Nonproliferation	Leonard Malczynski
The Global Energy System	David Wilson, Jeff Carlson
Global Climate Change	George Backus
Large Natural Disasters	Robert Glass
Long Term Maintenance of Complex Infrastructures	William Stubblefield
The Global Economy	Mark Ehlen
The Internet	Keith Vanderveen
Sandia National Laboratories	Robert Glass, Arlo Ames

It is important to note that, for the purpose of this study, we were interested in proving (and improving) our definition of CASoS and in showing that the systems above meet necessary conditions for being considered CASoS. None of the Defining Examples for any system 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

1. **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.

    a. **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.

2. **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.

3. **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.

4. **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.

5. **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.

6. **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).

7. **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

1. **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.
    a. **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).
2. **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.
3. **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.
4. **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.
5. **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.
6. **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.
7. **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

1. **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.
   a. **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.
2. **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.
3. **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.
4. **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.
5. **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.
6. **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 customers/suppliers/partners).
7. **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 power capability, which is readily promoted, can provide resources for weapons proliferation).

Defining Example: The Global Energy System (GES)

1. **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.

    a. **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.

2. **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.

3. **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.

4. **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.

5. **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-CO_2 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.

6. **Approaches:** Potential responses range within the socioeconomic-technical realm from the socioeconomic (e.g., negotiation of global and national targets for CO_2 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, CO_2 capture and storage).

7. **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

1. **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.
   - **a. 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).
2. **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.
3. **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.
4. **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.
5. **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.
6. **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.
7. **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

1. **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.

    a. **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.

2. **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.

3. **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.[14]

4. **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.

5. **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.

6. **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)

7. **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

1. **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.
    a. **Environment**: The environment would be the collection of entities (people, governments, businesses) that create, maintain, use, and damage these infrastructures.
2. **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.
3. **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?
4. **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.
5. **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.
6. **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).
7. **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

1. **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.

    a. **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.

2. **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.

3. **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.

4. **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.

5. **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.

6. **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.

7. **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

1. **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.
    a. **Environment**: The internet is embedded within modern society to such a degree that it can be accessed from nearly anywhere within the developed world.
2. **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.
3. **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).
4. **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.
5. **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.
6. **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.
7. **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.

Defining Example: Sandia National Laboratories

1. **System**: Sandia National Laboratories is a system, whose components include problem/product-oriented groups (projects), line-oriented groups (e.g. departments), subject-matter-oriented groups (e.g. engineers, scientists, managers), a communication network, an influence network (including network incentives and regulations), and support systems (infrastructure).
    a. **Environment**: A near environment would be delineated as those who receive a paycheck from Sandia, and includes the following: U.S. Government (DOE, DOD, DHS, etc), other funding sources, competitors, academia, home environments of the staff. A far environment, delineated by those who directly interact with Sandia, would include foreign countries, companies that don't interact with Sandia, academia in non-scientific fields.
2. **System of Systems**: Individuals and groups have a wide variety of dynamically changing interactions. The organizations within Sandia are frequently self-organizing and autonomous, perhaps more so projects than line organizations, but they must be considered systems in their own right. Independent action and interdependence are both possibilities, and coordinating the development of multiple organizations simultaneously is tremendously difficult. Finally, the component systems are not independent; many individuals are connected to a variety of component subsystems.
3. **Complex**: There are a wide variety of mechanisms for interaction among the various components of the system: social interaction, funding interaction, space interaction, etc. Further, the component systems change on a variety of time scales, from seconds to years.
4. **Adaptive**: Certainly, Sandia adapts to changes in the environment. The end of the cold war and the establishment of telecommuting and CRADAs are among the forces that have changed the way the elements of the system interact.
5. **Aspirations**: A critical aspiration is to evolve to be robust and resilient. A first step is to define/characterize the state of the system so that it may be evaluated relative to robustness and resilience. This includes a characterization of SNL's internal structure and function, as well as a characterization of SNL's external interactions
6. **Approaches**: A first step is to produce a real-time-updating model of the interactions, and seek metrics for measuring health, productivity, etc. Following that is to model policy changes and their effects on the state of the system. A next step would be a thorough study of the overall behavior space of the system to seek opportunities for leverage and better system behavior.
7. **Attainability**: Sparseness of data and complexity of the organization are the largest immediate hurdles in addressing Sandia as a CASoS. Beyond that, there are questions of obtaining acceptance, in the near term of analysis tools, and in the far term of the attempts that would make the system more robust and resilient (resistance stemming from turf considerations being a significant concern).

APPENDIX E: GEDANKEN EXPERIMENT

We can share the flavor of our iterative approach to the definition of CASoS and the intuitions it fostered through a small Gedanken experiment involving two of the Defining Examples. Although "Global Nuclear Nonproliferation" and "Large Natural Disasters" are very different disciplines, looking at them in light of our definition of CASoS reveals a common deeper structure, which is an important way clear definitions add value to an inquiry. Our thought experiment is simply to swap terms in the example definitions and see if each still reads intuitively. The experiment was performed on earlier versions of the defining examples and has not been updated.

Substituting Large Scale Natural Disasters terms in the Global Nuclear Nonproliferation discussion:

- Substitute "community" for "nation state"
- Substitute "invest to protect the community" for "don't proliferate" and "ignore preparation" for "proliferate"
- Substitute focus on prevention to focus on disaster and aftermath (highest leverage time intervals differ between the two, but each is plausible)
- Substitute "contracts, agreements, political power, funding base" for "treaties, alliances, military capability, economic might"
- Substitute "support of not preparing" for "support for nuclear tests"
- Substitute "agreement to prepare" (a less formal device) for "CTBT".
- Substitute "preparing for a disaster" for "constructing nuclear weapons"

Substituting Global Nuclear Nonproliferation terms in the Large Scale Natural Disasters discussion

- Opposite substitutions as before
- "Physical infrastructures" is a new consideration, but not unimportant in nonproliferation considerations
- LSND considers a wider range of entities and infrastructures than GNN discussion. They are reasonable for nonproliferation – they are part of what makes the problem difficult. Individuals (e.g. scientists) can commit acts in both directions – towards nonproliferation or proliferation.
- Substitute "try to capture proliferated devices" or "clean up fallout" for "stop bleeding and mend bones"
- Substitute "encourage nonproliferation activities" for "reinforce for next disaster"

It is interesting that most of the differences are merely substitutions of terminology, suggesting these problems do indeed share a deeper structure. We do see some differences in scope or point in the timescale, but examining each problem within the others' scope is an opportunity for broadening understanding, a potential for finding more ways of addressing the problem. We chose these two examples randomly; examination across the board shows similar results.

The process for defining CASoS involved searching for a set of criteria that separate CASoS from non-CASoS, then testing that definition by determining that there is strong similarity in example CASoS problems. In the process, we determined that there is interesting deep structure in CASoS problems – we learn significant things about our problems by considering mappings between apparently different problems.

APPENDIX F: REQUIRED THEORIES, TECHNOLOGIES, TOOLS AND APPROACHES THAT ENABLE CASOS PROBLEM SOLUTION

For each of our Defining Examples, we considered how we currently solve problems, and what we would need to solve the problems *right* – that is, what bodies of theory and practice would make our solutions more correct, easier to obtain, more tractable, more easily retargeted to the next problem that comes along. The list below is a union of those solutions. Theses solutions were checked against all of our example problems, and they appear to be universally applicable. While we cannot claim that the list below is in any way complete, it's a good start for CASoS activities.

1. Model construction
    a. Techniques and languages to enable low cost, rapid construction and use of models. Possibilities exist in game theory, control system identification, system dynamics.
    b. Model construction in regimes where no data is available – how do you gain confidence that your parameters and model structures are adequate, or determine what to do if you can't make them so? Possibilities exist in phase space mapping, model checking, and sensitivity analysis.
    c. Modeling where the scales are vast, or vastly varying (e.g. huge numbers of people, long time scales, long and short time scales combined). Multigrid approaches and strong integrators might help pave the way here.

2. Effects of long and widely varying time scales on the things we're modeling
    a. Specific R&D in aging processes (in humans, machines, and durable infrastructure)
    b. R&D in understanding the effects of changing technologies on maintenance of capabilities
    c. Languages and tools for modeling systems of systems that include widely varying rates for change across components (e.g. both seconds and centuries in a single system).
    d. History. Many modeling approaches create agents with behavioral rules but no history of how those rules developed. The behavior of many systems (e.g. design processes) can be as much a function of the manner in which rules change as of what they are.

3. Representation
    a. Modeling CASoS may require very different representation languages for different component systems. How do we integrate model results when the component languages may function at different levels of abstraction, time scales, or even incommensurable ontologies?
    b. In what ways can the underlying commonalities of structure we believe exist across CASoS be captured in generic representation languages? Are there at least reasonable mappings between model representations that we can take advantage of?
    c. Adaptation in CASoS can reflect multiple states of knowledge, perception, and ranges of action across the population. For example, during Hurricane Katrina, the perceptions that shaped the response of citizens in the flooded area were very different from those of first responders, and even further removed from those of policy makers in Washington. How can we represent the effects of different perceptions and assumptions on adaptation in a CASoS? How can we understand how they interact and change each other?

4. Recognizing patterns in solutions – enables "pre-determining" solution possibilities, engineering controls on system behavior, investigating policies.
    a. Analytically mapping solution space so direct simulation is unnecessary. Phase space analysis and mapping to a finite state machine are two related technologies.
    b. Algorithmically mapping out ties in the solution space (regions where nobody wins) can provide a means of determining ways to always win. This is called the "Game of

Kind” in Differential Game Theory, and similar notions are used in hybrid control systems theory to define controllers that prevent systems from entering dangerous operating regimes. These approaches would be quite suitable for investigating possible policies.
   c. Control Theory. Control of chaotic systems is profoundly different from classical control or hybrid control. How do these control system approaches change if we are trying to control a complex adaptive system?

5. Taking advantage of patterns and solutions from other problem domains
   a. Examining problem in bigger context by detecting, mapping, and extending analogies. Analogical reasoning, inductive learning, and knowledge-based learning could contribute to this.
   b. Linking solutions from other domains. Some terminology mapping, work in linking multiple models from differing modeling paradigms. Modeling paradigm mapping?
   c. Repurposing solutions from other domains. Verifying that solution structure is appropriate is difficult. Pattern matching between solutions (e.g. subgraph isomorphism in state space) is a means of comparing solutions and determining what differences to focus on. Principled documentation and testing can help, but is at best a partial solution.

6. Model size questions
   a. Models can grow too large to get good answers, or to even be able to understand answers. Devise a means of automatically simplifying models.
   b. Devise a means of determining how much model behavior is likely to change for increases in model complexity.

7. Increasing model scope
   a. As scope increases, the need for software engineering/systems engineering/system of systems engineering tools increases, to ensure that models interact with each other in a reasonable way. How can we take advantage of the particular structure of CASoS modeling to create powerful, CASoS specific engineering tools?
   b. Increases in model scope require commensurate increase in number of domain specialists. How to manage communication across disciplines? Areas we can find solutions include ethnographic field methods, social theory, and knowledge engineering.
   c. Model larger scope by implementing replicated structures, even if they are not necessarily a strong match for the systems being modeled (increased maintainability at the cost of local fidelity).

8. Policy Investigation – determining rules and incentives to achieve desired behaviors.
   a. How do I prevent or encourage behaviors (chaos, complex behavior, stability, panic) in a CASoS where I can’t change the subsystems? Hybrid control systems theory is a start. Phase space and model checking analyses are helpful in locating helpful basins of attraction. Stronglink/weaklink-like notions might help – targeting components that will not fail or will fail first – as a simple means of cutting through complexity.
   b. How do I determine what unintended consequences might occur in attempting to field a solution? The system is complex and adaptive, so I might not have modeled the potential causes for such effects, and might not be prepared to recognize them when a solution is fielded.

9. Real-time concerns – how do we do all of this fast enough to serve policy-makers, especially in frantic times of crisis
   a. Modeling, simulation, analysis before the crisis – have canned solutions in hand. Difficult if we don’t know how broad the domain might be. This is another form of analogical reasoning where we map <scenario, result> from previous runs onto a <scenario, ?> for a new problem.

b. Fast computing
c. Lean models
d. Rapidly-constructible models. Work in higher-level languages, logic programming, etc. could provide a basis for this.

10. Building Confidence in Results
    a. Software engineering models of V&V assume unambiguous requirements, control over testing, and stable interpretation of requirements, and system performance. This may not be adequate to large-scale CASoS where requirements are difficult to state, and testing is practically impossible. It is also unclear that the complexity of interactions between components of a CASoS will fit the unit/integration testing model of software V&V. Sources of potential solutions include philosophy of science, especially post-positivist models of confirmation, consilience, and other qualitative supporting elements, sensitivity analysis and other quantitative methods, and Knowledge Management to handle large bodies of evidence and analysis.

11. Engineering Processes
    a. Capturing requirements in a system that is complex.
    b. Defining solutions for systems that might adapt to circumvent or corrupt them.
    c. Testing solutions against critical systems
    d. Continuous improvement
    e. Product lifecycle processes.
        i. Conceptual design
        ii. Design
        iii. Build
        iv. Test
        v. Delivery (Actualization)
        vi. Disposition

12. Managing this effort

The environment in which this is developed is a CASoS. Managing of the theory, tools, solutions, and practices needs to be performed in a principled way. We envision using some of the same engineering practices we develop for modeling, and applying them to the tools we invent.

APPENDIX G: END NOTES REFERENCED IN TEXT

[1] We choose the term influence as opposed to other possible terms, such as solving problems, fixing or affecting, as a reminder that CASoS problems are big, that we might be limited in engineering problem solving to only influencing the system to change.

[2] Googling the phrase "Complex adaptive system of systems" produces a mere 13 unique results. It is unclear why the notion of CASoS has failed to receive attention. This lack of attention may be because "System of systems" tends to treat complex adaptive systems or because CAS treats SOS systems; but we see such incomplete attention paid to the overall problem that we believe at this writing there is much room for developing CASoS theory.

[3] Complex Engineered, Organizational and Natural Systems, March, 2007 (attended by Engi) and Complex Interacting Systems for a Sustainable Future, June, 2007 (attended by Glass).

[4] Possibly the most apparent difference between Systems Engineering and System Of Systems Engineering would be the question of scale – the components of the overall system-of-systems are generally thought of as being sufficiently large and heterogeneous to merit treatment as systems themselves, while in Systems Engineering, systems are composed of "subsystems" or "components". In addition, the component systems of a CASoS typically require different languages for their analysis (as in combining the languages of social science and engineering in socio-technical systems work), or involve radically different time scales (as in understanding a forest ecosystem, which requires integrating geological time with the brief life spans of insects and microbes). While this distinction is, perhaps, vague, we need to establish that we're not dealing with ordinary Systems Engineering problems. An equivalent means of distinction is that Systems Engineering seeks to control interfaces and behaviors (the subsystems and components are fully designable) while System Of Systems Engineering seeks to deal with systems where interfaces and behaviors may not be capable of being manipulated, and the subcomponents may exist outside of the scope of the containing system (they effectively have lives of their own).

[5] Thought experiment - Wikipedia, the free encyclopedia: A thought experiment (calque of the German term Gedankenexperiment, coined by Hans Christian Ørsted) in the broadest sense is the use of a hypothetical scenario to help us understand the way things actually are. There are many different kinds of thought experiments. All thought experiments, however, employ a methodology that is a priori, rather than empirical, in that they do not proceed by observation or physical experiment.

[6] We specifically avoid including "understand" as a category because "understanding" by itself is open-ended, can become an end unto itself, and doesn't focus on solving problems. Also, prediction can be difficult in other ways: understanding can be limited to behavioral and structural considerations (determining the nature of interactions), while prediction expands to include understanding of current state, careful calibration of parameters, etc.

[7] For a good discussion of Maslow's concept of self-actualization see Frank G. Goble's book "The Third Force, the Psychology of Abraham Maslow", 1970.

[8] Locally, it has recently been a revelation to apply phase-space analysis from the field of Dynamic Systems (DS) to the practice of Verifying and Validating System Dynamics (SD) models. The analysis is classical, known for decades in DS, but largely unused in SD. Imagine the difficulty for more disparate fields.

[9] As one of many examples, over the past 3 years, a new problem, the evaluation of the influence of pandemic influenza on national infrastructure and the design of optimal mitigation strategies, was analyzed with a set of models (epidemiological, economic, infrastructure, behavioral) none of which were built to work together. Progress was slow, painful, uncreative, difficult to evaluate, and it was impossible to model the full problem

with all the appropriate interdependencies correctly. While significant results were obtained, in the end, only a small fraction of what should have been done was done (Glass).

[10] Many techniques exist to produce high confidence results despite the lack of data and the uncertainty in system performance. The extensive SNL-lead efforts in ASC V&V methods and emerging efforts can readily act as a foundation for the CASoS V&V, and ensure that SNL develops a highly respected trust capability in the mission critical use of CASoS analysis.

[11] See http://www-unix.mcs.anl.gov/~insley/E3/E3-draft-2007-08-09.pdf

[12] It is important to note that such an institute would differ from ACG or Santa Fe Institute in seeking practical applications – in doing the work. The institute differs from the Santa Fe Institute in seeking more than theory – seeking theory, tools, practice and solutions, and understanding the interplay between them.

[13] We need to avoid getting hung up on the phrase "common objective;" its use is to focus attention on the boundaries of the system. For example, two warring parties have the "common objective" of fighting/ending/winning a war; they may have very different personal objectives regarding the final outcome, but the overall "fighting a war" objective is useful in deciding (defining?) what is outside of the system

[14] Benjamin Franklin's *Poor Richard's Almanac* (published in 1757), retells an ancient ditty as follows: "A little neglect may breed mischief. For lack of a nail, the shoe was lost; for lack of a shoe, the horse was lost; for lack of a horse, the rider was lost; for lack of a rider, the message was lost; for lack of a message, the battle was lost; for lack of a battle, the war was lost; for lack of a war, the kingdom was lost; and all because of one horseshoe nail."

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