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System of Systems (SoS) Engineering Problems

SoS as Science? SoS as Fundable? Report to N.S.F.

"Any opinions, findings, conclusions or recommendations expressed in this poster are those of the authors and do not necessarily reflect the views of the National Science Foundation"

The Challenge and Why: Identifying Vital Issues

- A two-day colloquium, sponsored by the National Science Foundation, convened in Chicago to debate about 25 fundamental questions about the emerging field of SoS.
- The underlying rationale for the meeting was to evaluate whether or not a new funding program in the NSF Engineering Directorate or other would be feasible and productive.
- The meeting was organized by the School of Industrial Engineering, U. Oklahoma in collaboration with Sandia National Labs, New Mexico.
- The purpose of this poster and the associated platform presentation is to concisely summarize the interim consensus reported to NSF for each cluster of related questions (blue boxes) and request specific feedback on each from ICCS'07 participants.
- The dozen participants represented a wide range of disciplines and approaches from biology, economics, engineering, history, math,& philosophy. They represented the full range from theoretical and academic approaches to multiple areas of application of SoS.
- One of the strongest outcomes was identification of several "vital issues" that must be solved by advances in SoS theory/tools in order to contribute to solving SoS problems.

What is A System of Systems? SoS Characteristics?

- Hallmark: "hybrid" complex systems of at least two but usually many different types (with e.g. human AND natural system components) whose network topology & hierarchical components of at least three levels are so interdependent that loss of any one component complex system renders SoS behavior substantially different.
- Possesses characteristics such as emergence, multitude of complex interactions, autonomy, resilience, significant cross-boundary influences, learning or intelligence, adaptability, associated large-scale databases, and reverse reductionism
- The team characterized SoS Problems as composed of many non-linear aspects & so were "perplexing, mystifying, elusive, baffling, enigmatic, incomprehensible, & perverse"
- While a large aircraft is a complex system, the entire air fleet supersystem is a SoS
- Must distinguish SoS from "complex system." It is a "complex system" composed of many complex systems whose interaction at the higher aggregate level is also non-linear

- TOPICAL SoS AREAS (societal issues)

Transportation Systems	Educational Systems
Health Care Systems	Warfare Systems
Resource Management	Critical Infrastructures
Homeland Security	National Security

- TOPICAL SoS AREAS (natural sci)

Cell Physiology	Complex Diseases
Any one Cancer	Pandemics
Earth Systems Sci	Global Warming
Systems Biology	Complex Genetic

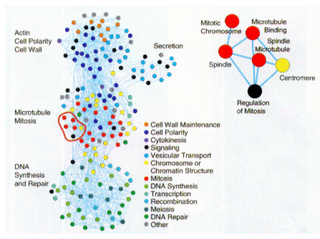
- What SoS is Not: There was a strong consensus that SoS is NOT simply project management with which team members felt SoS is too often equated.
- It is also distinct from natural science studies in its emphasis on social system or engineering system components AND use of reverse-reductionist approaches.

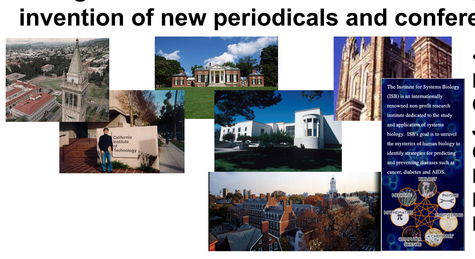
What is the Importance of SoS Studies?

- Consider three recent examples where knowledge and understanding of interacting SoS was missing and "prevented the prediction of now-obvious outcomes with info that was by hindsight clearly available" ……. Consider the immense "costs" of each …
  - Destruction and rebuild challenges of Hurricane Katrina
  - Lack of planning and indecision in the Iraqi Endgame
  - Lack of cooperation among government agencies to prevent and cope with events of Sept. 11th
  - And consider what we are facing as effects of Global Warming as a nation and worldwide

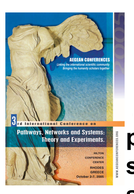
Precedents for SoS Research in Natural Science?

- The team agreed that many of the natural sciences inevitably explore aspects of SoS, but using reductionist methods. E.g. cell & molecular research on the cell now involves detailed investigation of hundreds of genes/products & their interactions for any of dozens of key, cellular, systems-level phenomena (apoptosis, cell division, etc.) or cell subsystems (nucleus, chromatin, mitochondria, etc.). Huge data bases, literatures, & simulations exist for each. So the success at reductionism is pushing them to SoS.
- SYSTEMS BIOLOGY: Is a good example of SoS-related research in a natural science. While pursuing better understanding of the way a cell works on a systems level (as shown at right) , SB does not develop systems tools and techniques for studying systems as systems per se. Still its findings become part of the overall knowledge base of systems. Further SB would benefit directly from enhanced SoS; an insight important to NSF funding. SB is a also good model for SoS due to its ability to attract funding & stimulate invention of new periodicals and conference series as shown below.



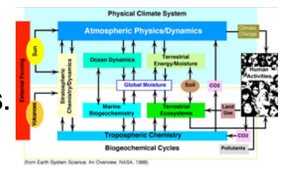


- ~Left to right ……..
  Berkeley ($100M)
  Caltech ($100M)
  Johns Hopkins ($34M)
  Claremont ($50M)
  Princeton ($70M)
  Harvard ($50M)
  Hood's ISB ($140M)
- SYSBIO Funding: Over the last few years, the range of major universities shown have committed ~$550M of their own endowments to begin new SB programs showing the wide appeal & timeliness of SoS approaches. Meanwhile, NSF and other agencies support mostly the reductionist-level (non-syn) of SB.
- SYSBIO Periodicals: As in general systems science, there is a proliferation of new journals on Systems Biology or special issues of Science & Nature on complex systems ……..



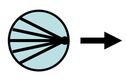
……..SYSBIO Conferences: And a proliferation of new international conference series, Cold Spring Harbor, Keystone, ICSB series, Aegean Series, etc.

- Earth Systems Science: As in biology, conventional geology programs, curricula, UG majors, & K-12 programs, funded by NASA or internally, are multiplying rapidly. Several alliances of 20+ universities exist that study all earth subsystems as an SoS.



Is there a Science of SoS? Can One Emerge?

- If so, what are its foundational axioms, hypotheses, theories, laws? What is it's knowledge base? The team recognized past work on complex systems, intelligent systems, adaptive systems, systems theory, systems science, systems analysis, systems methodology, and systems simulation has resulted in many schools of thought & independent theories, but noted that there was not yet an established consensus that integrated these areas. That is what is needed for a science of SoS to emerge. The following other knowledge base or methodological needs were discussed as essential to SoS becoming a science:
  - Pleoetiology: SoS needs a better understanding of extensively non-linear /or/ network /or/ "nested" /or/ "quorum" *causes* as well as the effects of having *multiple causes* of different weights being simultaneously active. Conventional sci has a mindset of linear causality.
  - Pleotrophy: SoS needs a better understanding of *multiple effects* of causes whether linear or non-linear. Conventional sciences like genetics have studied this feature (as in penetrance, variable expressivity, cohorts of genes causing a cellular phenomenon, etc.).



- Better Recognition of Appropriate "Knowledge Units" for SoS: Perhaps new constructs beyond axioms, hypotheses, theories, & laws are necessary for SoS. SSP (this poster) posits "linkage propositions"
- Systems-Level Correspondence Principles: CP in normal science is reductionist as in e.g. like spectral lines in astronomy, or fluid dynamic equations to explain ultracentrifuge bands. SoS needs "macro" CPs.
- Reproducibility/Repeatability: If non-linear, how can SoS fulfill these science requirements? Alternative?
- Methods of Falsification: How can SoS falsify a hypothesis if "equifinality" characterizes SB and SoS?
- Organized Feedback: How can SoS improve its knowledge base unless there is a way to determine which "knowledge units" are more reliable than others? What would an SoS experiment look like?
- Emphasis on Alternative Scenario Building: Conventional science is used to defining a system the way that it is - a singular description. But in SoS, especially with hybrid human-natural complex systems, the "ideal" is defining & validating a series of possible future scenario's - much like hurricane-path prediction
- New SoS Tools for: Hypothesis-generation, synthesis, abstraction, de-abs, discrimination, discinyms …

What is Needed to Manage Major Examples of SoS?

- MORE SoS CASE STUDIES:
- WWII industrial mobilization (*)
- World hunger (x) AIDS Epidemic (x)
- Autoimmune Diseases (x)
- Transition to Alternative Fuels (+)
- Health Care Systems (+)
- Social Services Systems (+)
- Shifts in Global Economy (+)
- Species Extinction (+)
- European Union (other incipient) (+)
- World Terrorist System (+)
- National Mortgage System (x)
- Challenges to National Education Sys (+)
- Commercial Aircraft (*)
- Computer Chips & Microprocesors (*)
- Founding Fathers & Constitution (*)

….. Some of these represent very challenging social conditions (x), some unintended consequences (+), & a few that have been addressed successfully? (*)

- Key Need: Recognition that SoS requires vigorous multi-, inter-, & trans-disciplinary approaches/tools. Improvement of those tools.
- Key Need: These are large-scale problems that will cause vast costs for our society, yet there is not yet a funding source for evolving the tools to solve these problems. Why must a crisis occur before act?
- Key Need: Beyond the technical challenges, a way to solve the bureaucratic, human barriers to SoS.
- Key Need: Teams need sufficient size & diversity to match the problems addresses.
- Key Need: Pick one or a few SoS Problems to use to advance SoS tools & methods, both hard & soft, for highest return on investment by later extension.

What are the Most Vital SoS Development Needs?

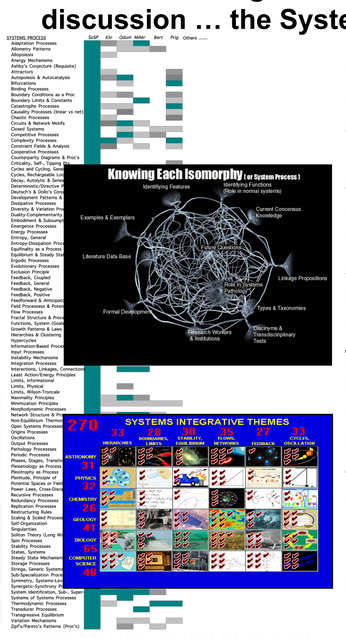
- Central Problem1: SoS are "hybrids" of human and natural systems and the best current simulations of each of these are incompatible and do not communicate. Often social sys are modeled using "agent-based" approaches while the natural system parts of the same SoS problem are modeled using empirical & equation-based models. Both are vital to understand future scenario's of any SoS. How can these partial models "talk" to each other to render results of use to decision-makers.
- Central Problem2: Integration of the tools in the toolbox. Analysis tools such as systems dynamics, stochastic, econometric, & social networking models, network & Monte Carlo theory exist, but have not been adequately coupled.
- SoS Needs a Consensus Exemplar that has solved these problems.

Where Will SoS Knowledge & Tools Be Taught?

- How different is SoS from earlier attempts such as OR, general systems theory, various systems analyses? Experience with these suggests that the stovepipe, specialty focus of conventional academia may inhibit development of adequate SoS education.
- Small initial enrollments, limited funding, non-science aspects, political resistance, as yet incomplete knowledge base, shaky academic homes, indecision of educational level for SoS education, need for consensus on what would be taught, with what degree or job goal, insufficient journal & conference focus on SoS especially on educational aspects, all contribute to the slowing of the urgently needed development and evolution of SoS.

An Example SoS Synthesis: The SSP Model

- What would a SoS research and education program look like? There are many different schools of thought. One was presented at the Colloquium as a strawman to promote discussion … the System of Systems Processes model of the I.A.S. (see above & next 3 posters)



- SSP is based on "integrative eclecticism" - trying to synthesize the many results of research from old general systems to modern complex systems approaches enshrined in a dozen categories (left, black) of information on >100 systems processes, which are the unit ideas of SSP; they explain how systems work. SSP maintains it integrates more systems processes than any other current school of thought (white excel chart at left).
- The main goal of the SSP is ID & documentation of the interactions between systems processes in great specificity and quantity, allegedly in much greater detail than other systems theories.
- We call these interactions "Linkage Propositions" (hereafter LP's) because they tie together (unify, synthesize) the systems processes (linkages) & because they are not proven in the scientific sense in every system yet, so remain as only partially proven "conditionals." They are stronger than conjectures in math because some proof exists in some phenomena studied empirically by the natural sciences.
- To become a candidate LP, strong evidence has to be documented for the interaction in some range of well-studied particular, real systems (see blue at left for example). But the full range of their transdisciplinarity need not yet be determined. Their specification will help do this as LP conjectures to pursue.

- GRAPHIC SUMMARY: The network graphic at the right shows a subset of > 90 linkage propositions that describe mutual influences among only 4 systems processes common to many systems. These are only a sample; not even the full set of interactions among these four processes. This SSP "system of systems processes" sample already shows why complex systems behavior and systems dynamics are non-linear. It would be very difficult to "trace" completely stand-alone or independent cause and effects in this network. Many alternative paths are possible. Controlled experiments would leave out many key paths & confound results. That is why Systems Biology and modern science disciplines must turn to systems science for methods and help. Conditions and solutions evident in one may not be as evident in another, and so both can contribute to each other's development.

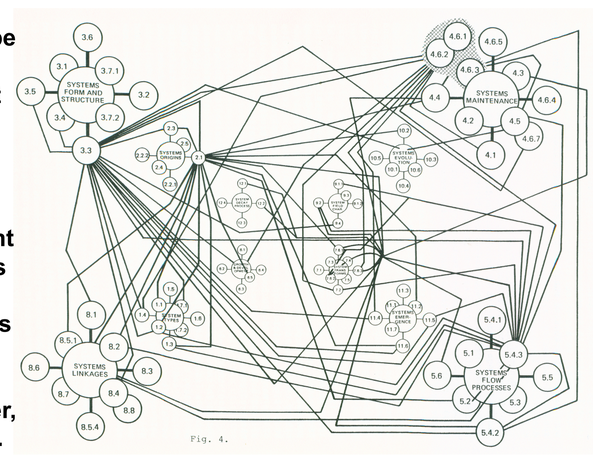


Fig. 4.

Suggested Sponsors of SoS Research & Development

- Given the range of SoS Problems and Examples, the team suggested the following possible agencies that might consider supporting future SoS synthesis and research:
  - NSF (National Science Foundation
  - NIH (National Institutes of Health
  - DARPA (Defense Advanced Research Projects Agency
  - CIA (Central Intelligence Agency)
  - U.S. Department of State
  - Noted difficulty of large-scale, interdisciplinary funding
  - DOE (Department of Energy)
  - NIST (Nat'l Institute of Standards & Technology
  - DOD (Department of Defense)
  - U.N. (United Nations)
  - Private Research Foundations & Philanthropies
  - State and Local Governments (sustainability)

Conclusions & Recommendations

- An SoS unintegrated Knowledge Base at a very early stage of maturity already exists.
- See urgent need for a more integrated, mature SoS set of methods, tools, & techniques because problems they would address are themselves so urgent
- If funding targeted at synthesis of the wealth of current systems-level results and needed techniques & methodologies is not forthcoming, then the SoS will not be ready to help solve the major SoS problems facing our nation and our species (at great cost).
- Team reluctant to create unreasonable expectations; where are the Ph.D. Theses? Inst's?
- Future work: "Retrospective analysis of two past, independent SoS-level studies to see how they might have benefited from advances in SoS methods & integrating approaches.

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