System of Systems:

Do We Need a Definition of Definitions?

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Do we need a Definition of Definitions?

A system is... a group of independent but interrelated elements comprising a unified whole…

Which of these are not a system?

- **Computer**
  - CPU
  - Monitor
  - Keyboard
  - Mouse

- **Tree**
  - Roots
  - Stems
  - Leaves
  - Flowers

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Definition of Definitions

- **Where have we come, and are we different?**
  - **Systems**
  - **Complex Systems**
  - **Complex Adaptive Systems**
  - **Enterprise Systems**
  - **System of Systems**

"…the application of conventional systems development for ordinary projects have been found to be inappropriate for complex projects." (Morris and Hough, 1987)

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Systems

- **An assemblage of** *inter-related elements* **comprising a** *unified whole*.
- **A perceived** *whole* **whose** *elements "hand together"* **because they continually** *affect each other* **over time and operate toward a** *common purpose*. **(Senge, 1994)**
- **Two or more subordinate entities that** *interact* **in some fashion to accomplish a** *process* **that transforms a** *set* **of predetermined** inputs **into a set of desired** *outputs*, **in** *time* **achieving a predetermined** *goal*. **(Leach, 2000; Grandy, 2000)**
- **Types of Systems**
  - **Open Systems – influenced by events outside of the declared system boundaries**
  - **Closed Systems – outside events can have no influence**
  - **Dynamic Systems – have components or flows or both, that change over time**

From the Latin and Greek, the term "system" meant to combine, to set up, to place together.

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Complex Systems

- **A *highly structured* system, which shows structure with *variations* (Golden and Kadanoff, 1999).**
- **One whose *evolution* is very sensitive to initial conditions or to small perturbations, one in which the number of *independent interacting* components is large, or one in which there are *multiple pathways* by which the system can evolve (Whitesides and Ismagilov, 1999).**
- **By design or function or both is *difficult to understand and verify* (Weng, Bhalla and Iyengar, 1999).**
- **There are *multiple interactions* between many different components (Rind, 1999).**
- **Systems in process that constantly *evolve* and *unfold over time* (Arthur, 1999)**
- **Complexity in contrast, does not try to breakdown the system but examines the system from a global or *holistic perspective* (Schaef and Bossio, 1996)**
- ***High cost*, engineering and information technology *intensive, customized* products having *large numbers of tailored subsystems* and components (Hansen and Rush, 1998).**

The Latin *complexus* comes from the Greek pleko or plektos, meaning "to plait or twine."

Complex Systems

"Every decade or so, a grandiose theory comes along, bearing similar aspirations and often brandishing an ominous-sounding C-name. In the 1960 it was cybernetics. In the '70s it was catastrophe theory. Then came chaos theory in the '80s and complexity theory in the '90s."

- *Sync* by Steven Strogatz

- **Features:**
  - Emergence – more is different
  - Relationships are non-linear
  - Relationships contain feedback loops
  - Open Systems - influenced by events outside of the declared system boundaries
  - Parts cannot contain the whole
  - Have a history ("Butterfly Effect")
  - Boundaries are difficult to determine
  - Complex networks

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Complex Adaptive Systems

- **A special case of complex systems (Holland and Gell-Mann, Sante Fe Institute):**
  - **Complex in that they are made up of a large number of** *simple*, *autonomous* **and** *richly interconnected* elements**;**
  - **Adaptive in that they have the** *capacity to change* **and** *learn from experience*.
- **A** *dynamic network* **of** *many agents* **acting in parallel,** *constantly acting and reacting* **to what the other agents are doing (Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos*).**
- **Three key principles (Dooley, Arizona State)**
  - **Order is** *emergent* **as apposed to predetermined;**
  - **The system's** *history is irreversible***;**
  - **The system's future is often** *unpredictable*
- **Macroscopic collection of simple (***nonlinearly***) interacting units that are endowed with the ability to** *evolve* **and** *adapt to a changing environment* **(*Complexity in a Changing Science*, European Commission)**

Complex adaptive systems was coined at the interdisciplinary Sante Fe Institute by J.H. Holland, M. Gell-Mann, et.al.

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Complex Adaptive Systems

- **Features:**
  - **Dynamic**
  - **Self-similarity – object is similar or approximately similar to part of itself**
  - **Emergence – complex pattern formation from simpler rules**
  - **Competition and Cooperation between Agents**
  - **Self-organization - internal organization of a system, normally an open system, increases automatically without being guided or managed by an outside source**
  - **Capacity to learn and change**

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Enterprise Systems

- **A notional** *purposive system* **which expresses some** *purposeful human activity*, **activity which could in principle be found in the real world (Checkland, 1993)**
- **The process of** *integrating enterprise systems* **with existing applications (Losavio, Ortega, & Perez, 2002).**
- **Large complex information systems that** *integrate* **and** *streamline* **the** *organization's* **business processes across** *departmental and geographical borders* **(Gulla, 2004).**

This then is the challenge: To design and manage a "human activity system" that comprises a multiplex of autonomous "human activity systems" each which perceives, albeit imperfectly, the benefit of belonging in a meaningful way to a higher level "human activity system."

Boardman and Clegg, 2001

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System of Systems

Over 40 independent definitions…

- **System of systems problems are a collection of trans-domain networks of heterogeneous systems that are likely to exhibit operational and managerial independence, geographical distribution, and emergent and evolutionary behaviors that would not be apparent if the systems and their interactions are modeled separately (DeLaurentis, 2005).**
- **System of systems are meta-systems that are themselves comprised of multiple autonomous embedded systems that can be diverse in technology, context, operation, geography and conceptual frame (Keating, et al., 2003).**
- **SoSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure (Luskasik, 1998).**
- **A system-of-systems is a set of collaboratively integrated systems that possess two additional properties: operational independence of the components and managerial independence of the components (Maier, 1998).**
- **Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development (Sage and Cuppan, 2001).**
- **An array system (system of systems) is a large widespread collection or network of systems functioning together to achieve a common purpose (Shenhar, 2001).**

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System of Systems: a computer architecture term that started in the US military

Who is doing what?

- Purdue University – System of Systems Cluster within the School of Engineering
- Carnegie Mellon Software Research Institute
- Old Dominion University - The National Centers for System of Systems Engineering
- Cranfield University (and Univ. Manchester, Univ. Cambridge, Univ. Sheffield, Univ. College London) - Complex Systems Management Centre
- New England Complex Systems Institute and MIT – Managing Complex Organizations

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What is Stevens doing?

- **The distinction between a system and SoS lies in the meaning and significance of 'gathering together', teasingly hidden in the meaning of *of*.**
  - **What the two have in common is being gathered together which is why it is proper to refer to a SoS as a system.**
  - **However a SoS is much more because its parts, acting as autonomous systems, forming their own connection and rejoicing in their diversity, lead to enhanced emergence, something that fulfills capability demands that set a SoS apart.**
  - **We summarize our thinking in the following Table which also includes a set of cross references from our literature research where we believe others are articulating our chosen differentiating characteristics.**

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Systems vs System of System

Element	*System*	*System of Systems*	*Cross References*
Autonomy	Autonomy is ceded by parts in order to grant autonomy to the system	Autonomy is exercised by constituent systems in order to fulfill the purpose of the SoS	Directed [Eisner, 1993], Planned [Eisner, 1993, Lane and Valerdi, 2005], Embedded [Keating, Rogers, et al., 2003], Autonomy [Monarch and Wessel, 2005, Keating, Rogers, et al., 2003, Bar-Yam, 2004, SoSECE, September 2003]
Belonging	Parts are akin to family members; they did not choose themselves but came from parents. Belonging of parts is in their nature.	Constituent systems choose to belong on a cost/benefits basis; also in order to cause greater fulfillment of their own purposes, and because of belief in the SoS supra purpose.	Enterprise [Carlock and Fenton, 2001, Lane and Valerdi, 2005, SoSECE, November 9, 2005], Shared Mission [Holland, 1995, Shenhar, 2001, Crossley, March 31, 2004], Sharing [Lane and Valerdi, 2005]
Connectivity	Prescient design, along with parts, with high connectivity hidden in elements, and minimum connectivity among major subsystems.	Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possibly via a net-centric architecture, to enhance SoS capability.	Interdependence [Cook, 2001, Eisner, Marciniak and McMillan, 1991], Distributed [DeLaurentis, 2005, Eisner, 1993, Keating, Rogers, et al., 2003, Lane and Valerdi, 2005, Sage and Cuppan, 2001, Shenhar, 2001, Maier, 1998], Networked [Lane and Valerdi, 2005, Shenhar, 2001, DeLaurentis, 2005], Multiple Solutions [Eisner, Marciniak and McMillan, 1991], Loose Coupling [Monarch and Wessel, 2005], Integration [Luskasik, 1998, Maier, 1998, Pei, 2000], Interoperability [Pei, 2000, Manthorpe Jr, 1996, Carney, Fisher and Place, 2005], Synergism [Manthorpe Jr, 1996, Bar-Yam, 2004]

J. Boardman and B. Sauser
The full paper to appear in
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April 24-26, 2006, Los Angeles, CA, USA

Systems vs System of System

Diversity	Managed i.e. reduced or minimized by modular hierarchy; parts' diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of the hierarchy	Increased diversity in SoS capability achieved by released autonomy, committed belonging, and open connectivity	Independence [Crossley, March 31, 2004, DeLaurentis, 2005, Eisner, Marciniak and McMillan, 1991, Maier, 1998, Sage and Cuppan, 2001], Diversity [Keating, Rogers, et al., 2003, Crossley, March 31, 2004, Sage, 2003], Heterogeneous [DeLaurentis, 2005, Purdue, 2005]
Emergence	Foreseen, both good and bad behavior, and designed in or tested out as appropriate	Enhanced by deliberately not being foreseen, though its crucial importance is, and by creating an emergence capability climate, that will support early detection and elimination of bad behaviors.	Evolving [Cook, 2001, DeLaurentis, 2005, Lane and Valerdi, 2005, Luskasik, 1998, Monarch and Wessel, 2005, Sage and Cuppan, 2001, Maier, 1998], Intelligence [Lane and Valerdi, 2005], Sum is Greater than Parts [Eisner, Marciniak and McMillan, 1991], Behaviors [Parks, Jung and Ramotowski, 2004], Emergence [DeLaurentis, 2005, Lane and Valerdi, 2005, Monarch and Wessel, 2005, Sage and Cuppan, 2001, Maier, 1998, Bar-Yam, 2004], Dynamic [Lane and Valerdi, 2005], Adaptive [Carney, Fisher and Place, 2005, SoSECE, November 9, 2005]

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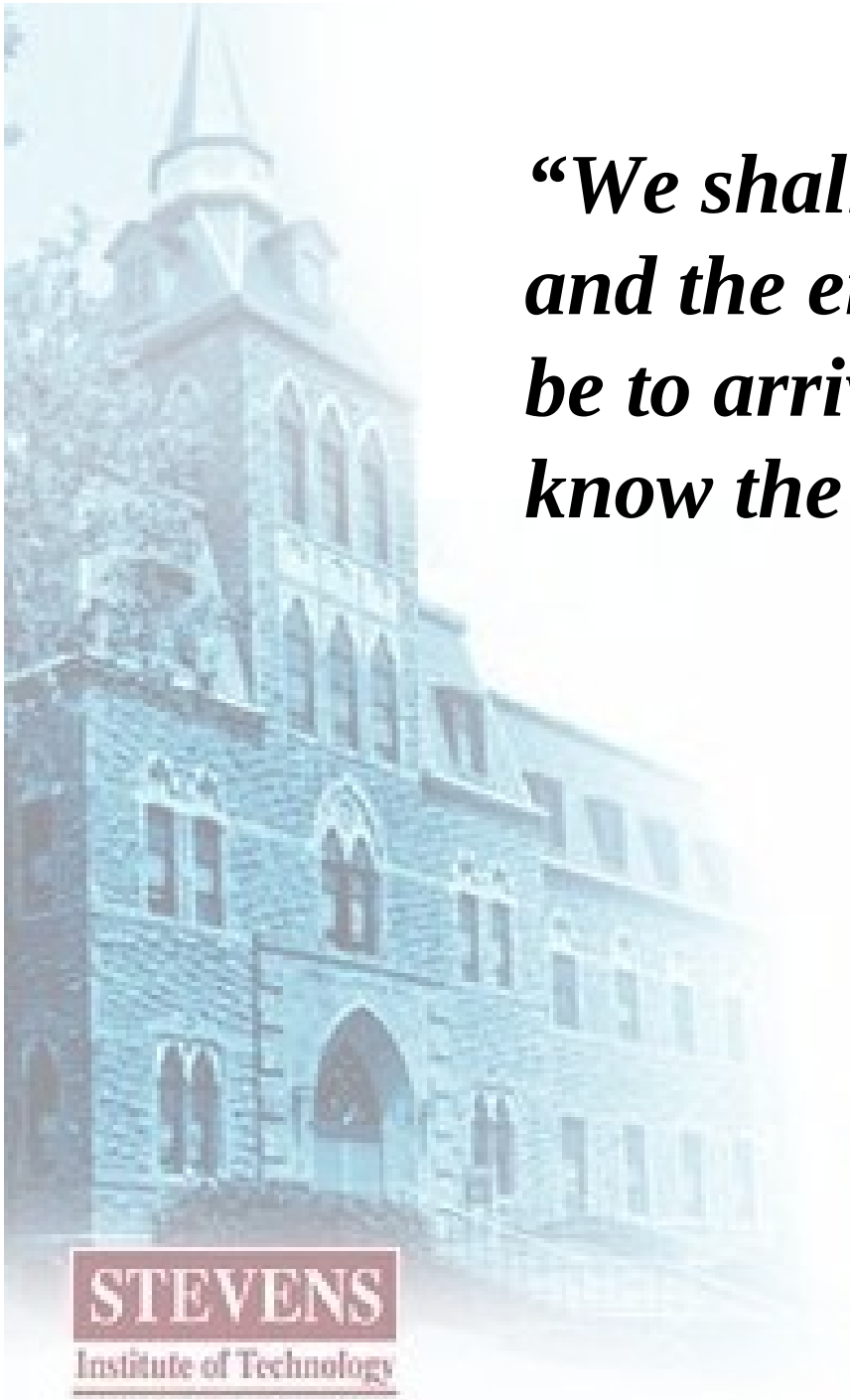

"We shall not cease from exploration and the end of all our exploring will be to arrive where we started and know the place for the first time."

-T.S. Eliot

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