26th annual INCOSE international symposium

Edinburgh, UK

July 18 - 21, 2016

On the Nature of Systems of Systems

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The world we're in

Digital technology is transforming the modern world:

- ubiquitous computing and network connectivity
- world-wide availability of time synchronisation and accurate location
- novel sensing systems, drones, geospatial data on demand
- cloud-based computing and services
- systems intelligence, growing automation and autonomy
- social media, web-based tools & applications
- etc…..

- *'Interconnectivity and interdependence will drive future systems design regardless of different markets and application domains'* (INCOSE SE Vision 2025)

However..

- Systems engineering is still largely based on traditional life cycles and processes – TSE – which assume (relative) systems independence
- Systems of Systems Engineering (SoSE) leading our response to dealing with the challenges of the interconnected world
- Best practice emerging

- But..
- Definitions have not necessarily kept pace, and are worth reviewing

Underlying trends

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- Growth of coupling/connectivity/interdependence between the systems we build…
- …and the processes we use to build them…
- …and collaboration between the organisations which build and use them

- Some important classes of systems coupling:
  - Systems which combine in the operational world
  - Systems which share architectures and components (product families)
  - Systems which share enabling systems during development and/or operations
  - Systems which share resources and/or processes

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- Growth of coupling/connectivity/interdependence between the systems we build…
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- Some important classes of systems coupling:
  - ‘SoS’ Systems which combine in the operational world
  - ? Systems which share architectures and components (product families)
  - TSE Systems which share enabling systems during development and/or operations
  - TSE Systems which share resources and/or processes

Definitions

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- Mark Maier (1998): SoS (*Collaborative Systems)*

  Must have both (at least to some degree):
  - Operational independence of components
  - Managerial independence of components
  - everything else is secondary – may have

- *Jamshidi (2005): 'SoS exist where there is a presence of the majority of the following: operational and managerial independence, geographic distribution, emergent behaviour and evolutionary development'*

- Jamshidi (2009): '*A SoS is an integration of a finite number of systems which are independent and operable and are networked together for a period of time to achieve a higher goal'*

- INCOSE (2012): *System-of-systems applies to a system-of-interest whose system elements are themselves systems;* typically these *entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems.*

Difficulties

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- Many exceptions
  - books and articles on SoS and SoSE which don't fit definitions
- Lack of concision - definitions getting more complicated and looser
- Growing number of real-world instances (SoS and SoSE)
- Jamshidi again: *'The SoS literature definitions and perspectives are marked with great variability ……. Viewed as an extension to systems engineering as a means of describing and managing social networks and organisations, these variations lead to difficulty in advancing and understanding the discipline.'*

Some ‘Classical’ Systems of Systems

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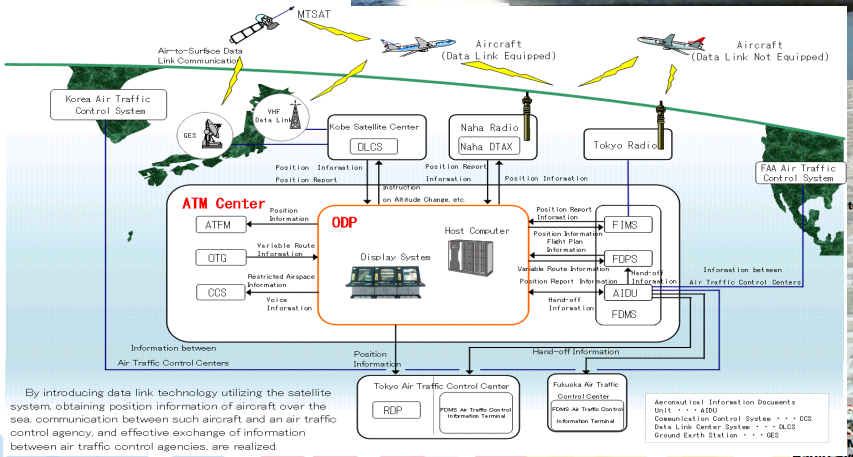
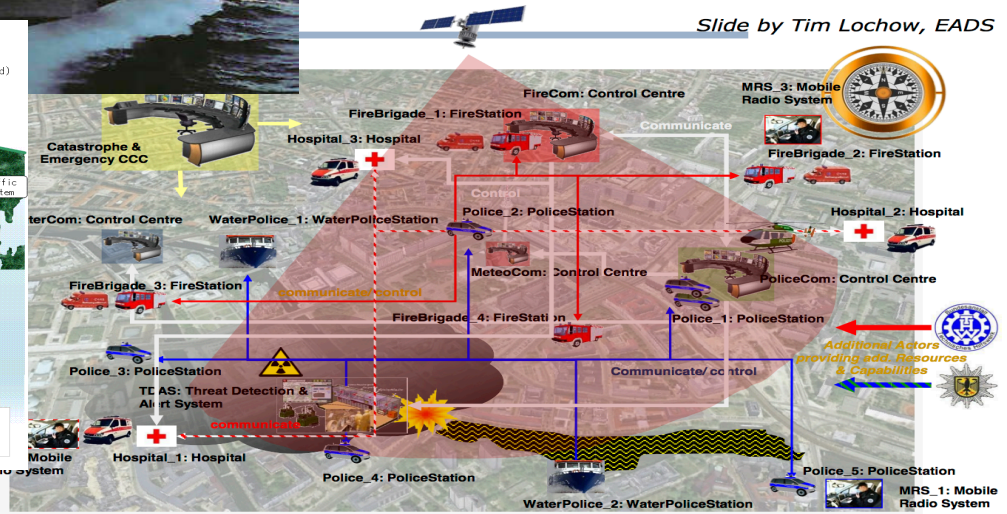
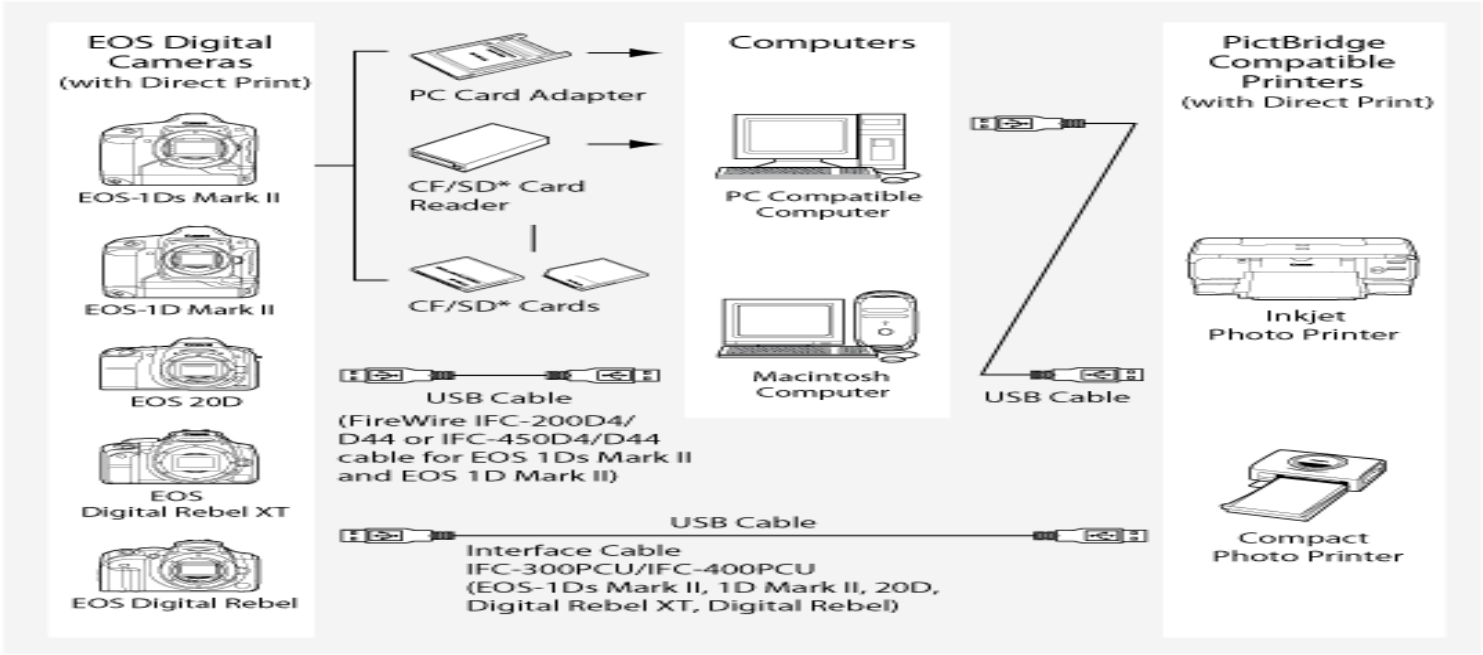




Capability to do Digital Photography



?

?

Generic SE challenges for SoSE

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- Rapidly changing working environment
- Asynchronous life cycles for constituent systems
- Multiple ownership/management of constituents
- Arbitrary mix of new and legacy systems
- Continuous technological change
- Unpredictable emergent behaviour as systems join and leave

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- But these factors can be in play for all systems and all SE

Can this be fixed?

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- By (re) - addressing 3 inter-related questions:
  - What is a SoS?
  - How does a SoS differ from a system?
  - What sorts of SoSs are there and how do they differ from each other?
- Caveat: *What follows is speculative and intended to provoke debate, all conclusions are tentative and evolving*

Back to basics

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- One way of solving definition problem is to make the concept of coupling the *defining* factor
  - everything else becomes secondary, eg operational and managerial independence, geographical distribution, heterogeneity, etc etc:

- Possible new definition: *'SoS is a System which results from the coupling of systems at some point in their life cycles'*

- SoSE becomes: *'The Systems Engineering of Coupled Systems'*

Also – two viewpoints in play:

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- Systemic: concerned with how a system behaves as a whole and how it interacts with its environment

- Systematic: concerned with the details of how a system is made up, how the parts interact, are developed and integrated and work together

Using viewpoints

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- From a *systemic* point of view, a SoS is 'just' a system when it is operating in a steady state
  - SoS classes are the same as system classes, eg open, closed, etc

- From a *systematic* point of view the differences between systems and SoS appear to be large and deep-seated

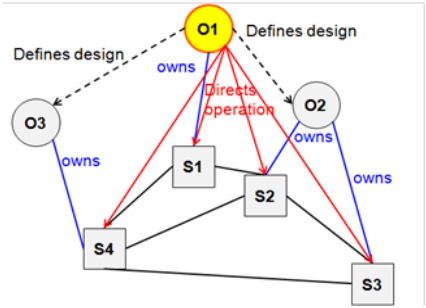
- These viewpoints matter in classification

Systematic (?) Classification

Type	Definition
Directed	Directed SoS are those in which the SoS is engineered and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the centrally managed purpose.
Acknowledged	Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, development, and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the system.
Collaborative	In collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed-upon central purposes.
Virtual	Virtual SoS lacks a central management authority and a centrally agreed-upon purpose for the system of systems. Large-scale behavior emerges—and may be desirable—but this type of SoS relies upon relatively invisible, self-organizing mechanisms to maintain it.

Classification

Directed



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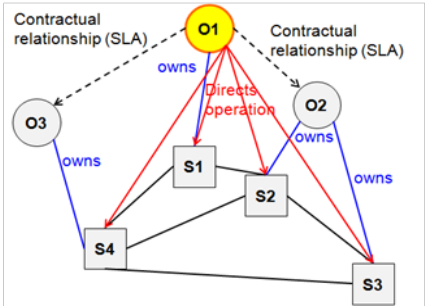
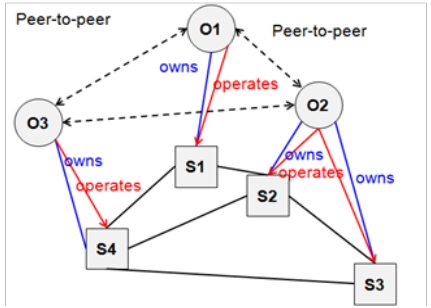
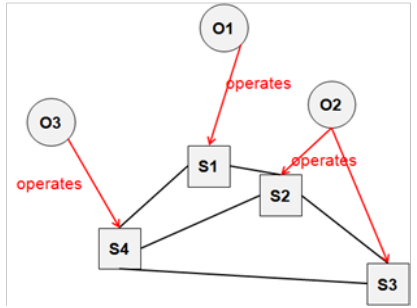


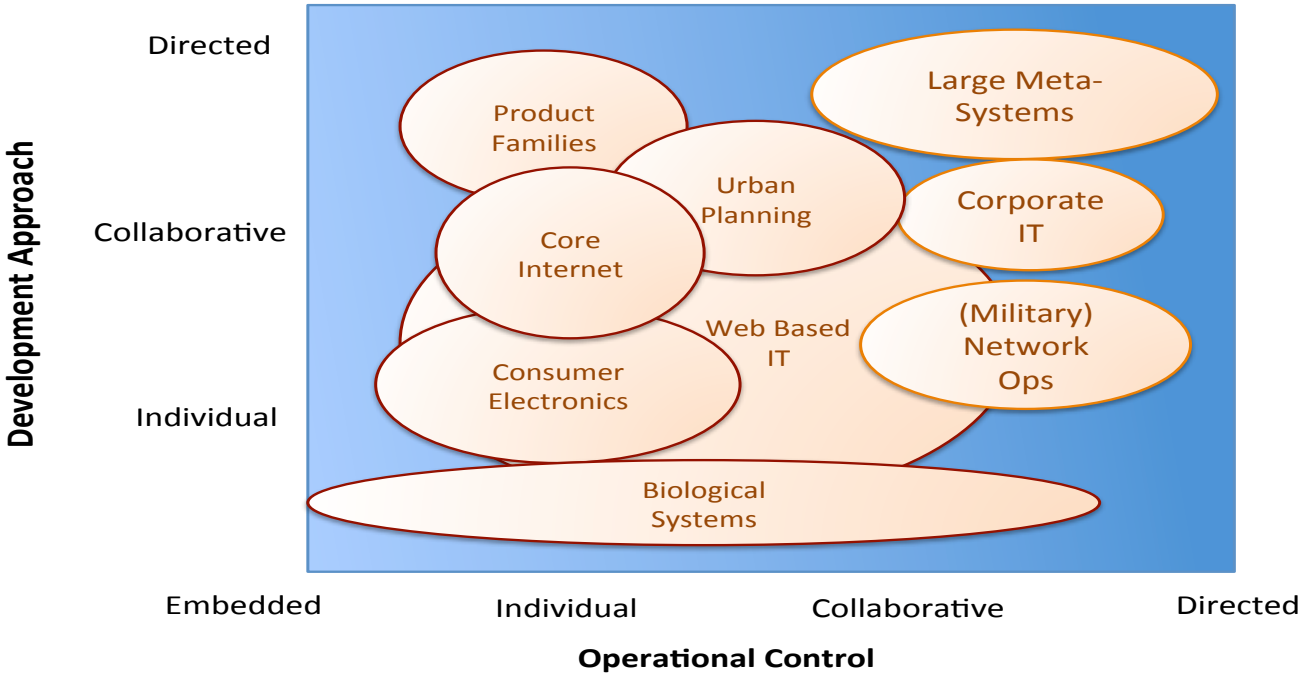
Collaborative



Virtual

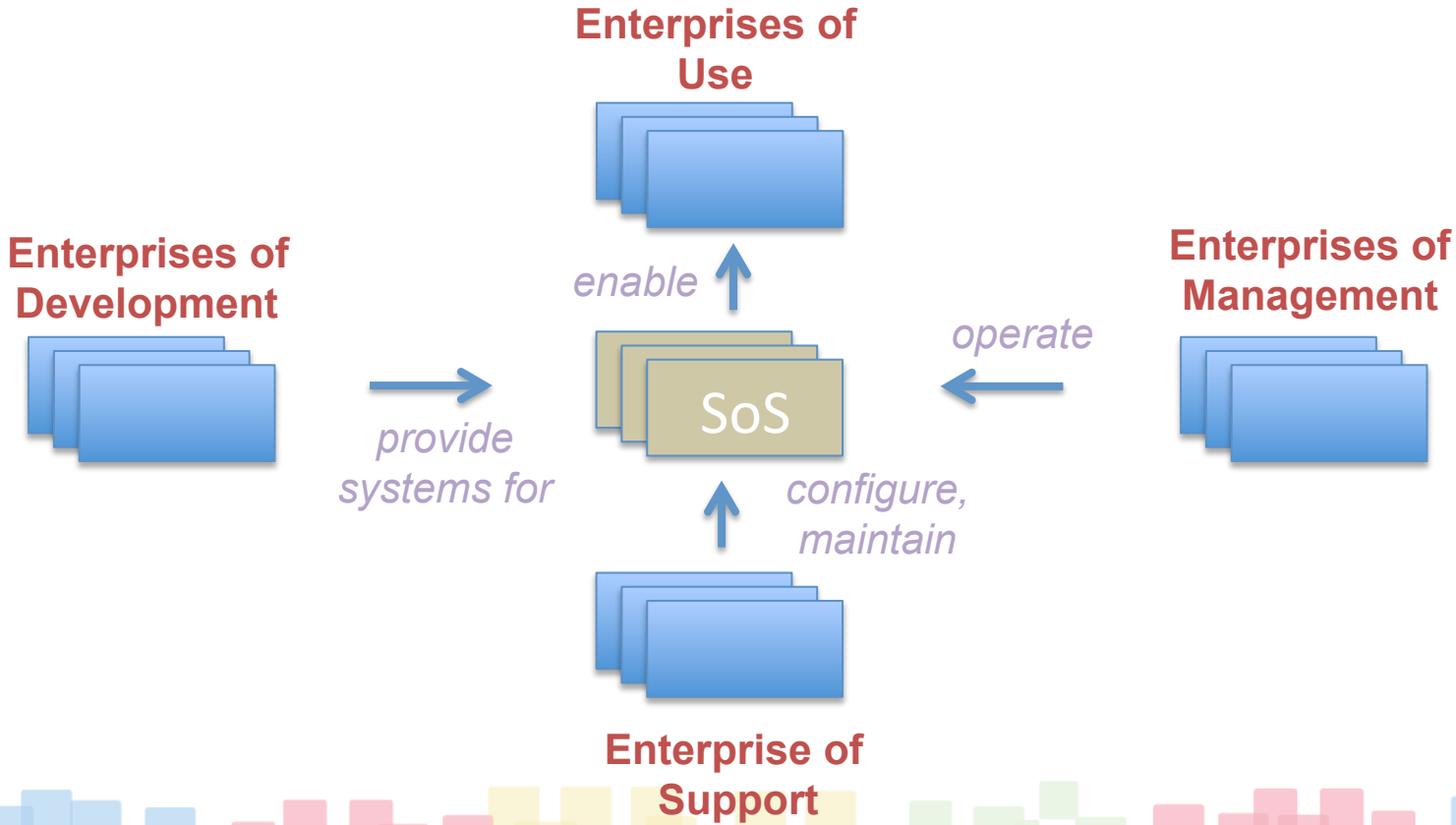


A 2-dimensional View



Many SE approaches in play

Enterprises and Systems of Systems



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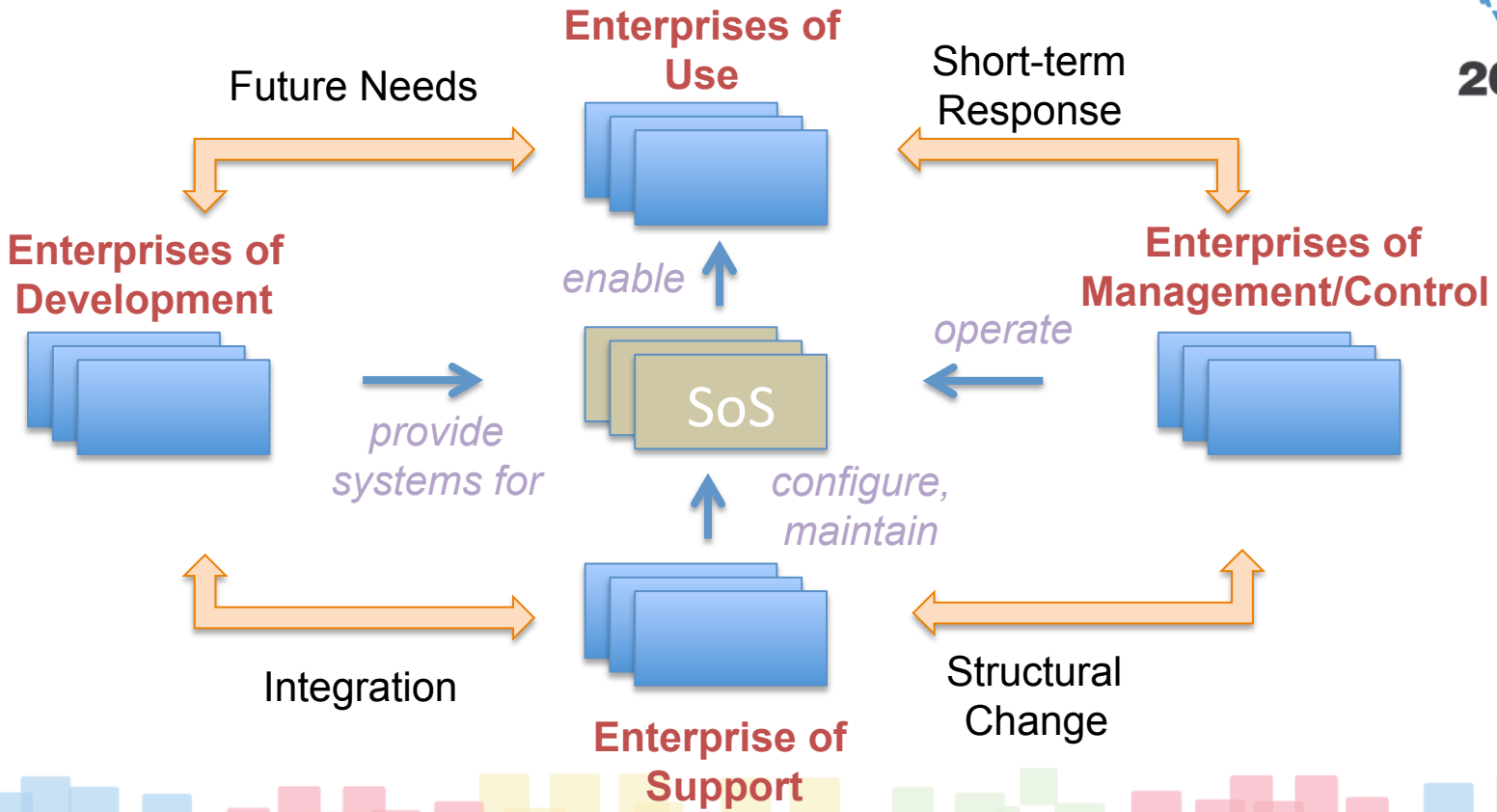

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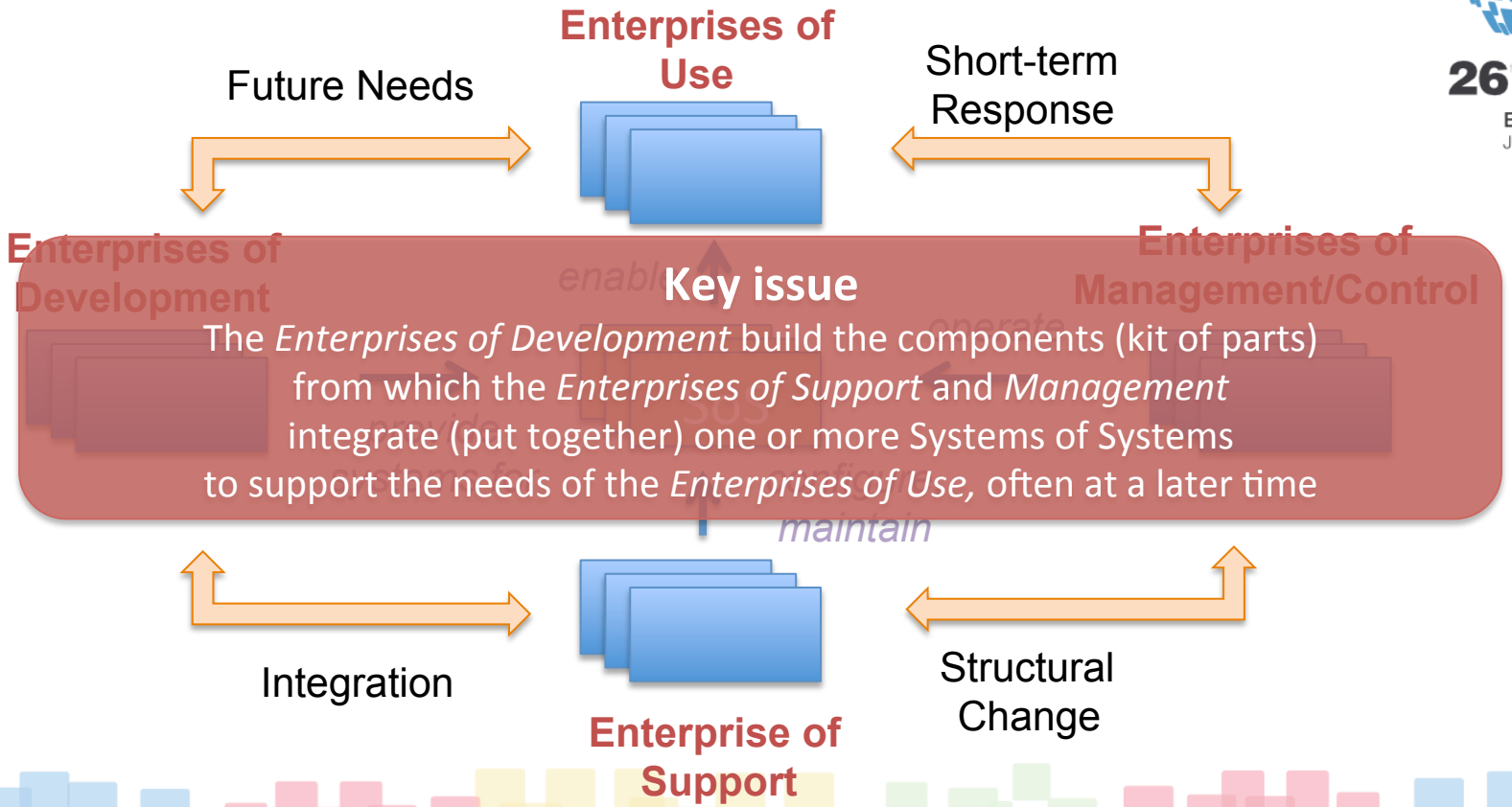

Fundamental bi-directional relationships

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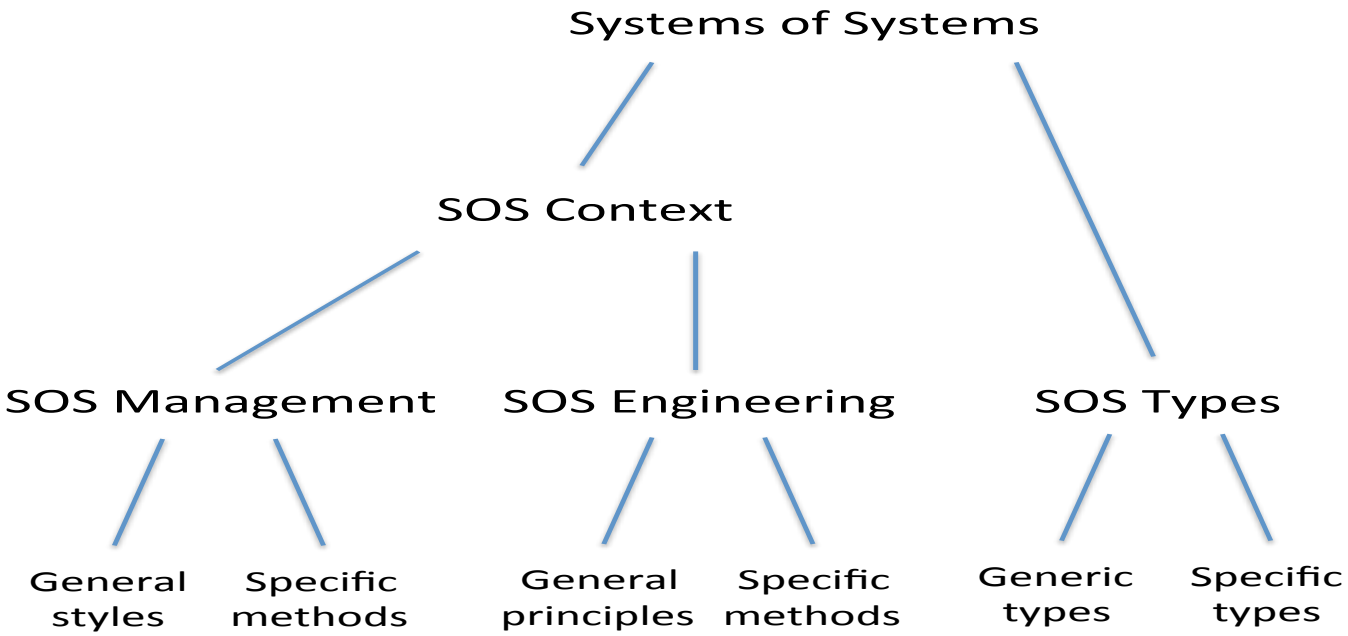
- Enterprises may collaborate to build, operate or use SoS:
  - Multi-company, multi-project developments
  - Working across life cycle, linking developers, operators and users

- SoS may be needed to support Enterprises – especially when they come together:
  - Company mergers, requiring underpinning IT
  - Military operations
  - Civilian/Domestic uses

Systems of Systems Taxonomy



General (Systemic) Classification

Systems of Systems Types	
Generic Types	Specific Examples
• Open • Closed • Semi-open	• Natural systems • Social Systems • Cyber physical systems • Families of systems • Military capabilities • Information systems • Internet of things • Enterprise systems

Context for Engineering and Managing SoS

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Systems of Systems Context	
General Scenarios	Nature of Coupling
• SoS designed as a whole • System (or SoS) joins an SoS • SOS evolves as a whole • Existing SoSs merge • System (or SoS) leaves an SoS • SoSs demerge	• Type • Depth • Duration • Life cycle timing

How SoS are managed

Systems of Systems Management (SOSM)	
General Styles	Specific Methods (examples)
• Directed • Collaborative • Acknowledged • Virtual	• Portfolio Management • Programme Management • Capability Management • TOGAF ADM (management and governance) • Joint Operational Control

How SoS are engineered

Systems of Systems Engineering (SoSE)	
General Principles	Specific Engineering Methods (examples)
• Modularity • Frameworks • Open systems • Patterns • Composability • Component reuse • Service Orientation	• ISO 15288 • DANSE • EA, for example TOGAF (Architecture Design Method)

Some loose ends

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- Intentionality
  - TSE is based on premise we know what a system is for *ab initio*
  - SoSE requires different approach to requirements
  - Intentionality as a continuous variable?

- Scale
  - Why do we call big systems SoS when they don't fulfil the Maier criteria?
  - Complexity of interaction in the enterprises, not systems

Some loose ends

- Hierarchy
  - The term SoS implies ‘systems composed of systems’
  - TSE covers development of hierarchically-coupled systems rather well
  - Point of integration crucial

- *All systems are SoS during development, when viewed systematically*

- *All SoS are systems during operation, when viewed systemically*

Return to Maier

- Private correspondence (April 2016)
  - ‘we have different viewpoints’
  - regrets having used the term ‘Systems of Systems’
  - prefers now to discuss: *‘Systems that agglomerate for a purpose’*

- This is not unhelpful to the current debate

Summary

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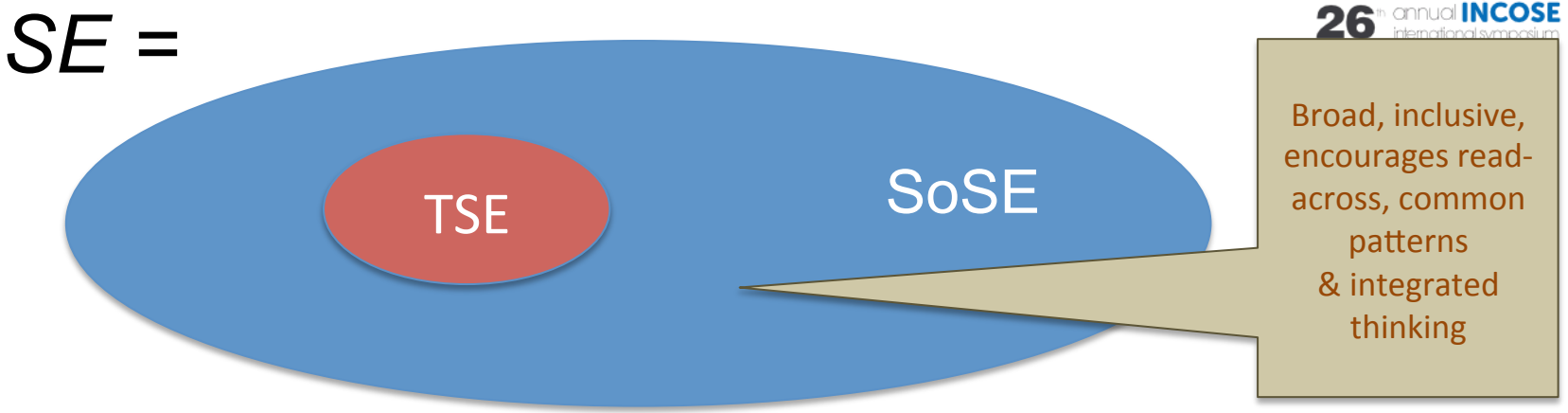
- We've taken a broad look at coupled systems in general
- It's getting harder to fit definitions to modern examples
- One option is to open the scope of the definition to describe all coupled systems as SoS and look for broad common principles as well as specific methods
- Implication is that SE = TSE + SoSE, the latter covering the whole of the interconnected world identified in INCOSE SE Vision 2025

Implications



- SoSE (or the engineering of coupled systems) becomes the predominant concern of INCOSE in 21st Century
- Timely to reexamine how the interconnected world can be classified as a whole – and best practice codified
- And to tackle other questions, eg: relationship between SoSE & ESE

Questions?