32nd Annual INCOSE international symposium

hybrid event

Detroit, MI, USA
June 25 - 30, 2022

If you thought Systems Engineering was fun, you should try System of Systems Engineering!

www.incose.org/symp2022

Duncan's background

Professor Duncan Kemp, CEng FIET, INCOSE Fellow

DE&S Fellow for Systems Engineering
Internal Technical Support Team Leader
Engineering Group
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1984 – Joined MoD as Student Engine
1989 – Graduate E
Technical Discipline Lead for SE
2019 – Senior Fellow for SE
2022 – Digital Engineering Implementation TL

And …

- Chair of the INCOSE System Safety working group
- Published 20 peer reviewed technical papers, including several on System Safety
- Presented DE&S Maritime Safety Refresher, MOD 1* Boot camp
- Guest lectured at Birmingham, Loughborough and Bristol Universities, MIT, USMA West Point
- Visiting Professor for Systems Thinking at Loughborough University
- INCOSE Fellow

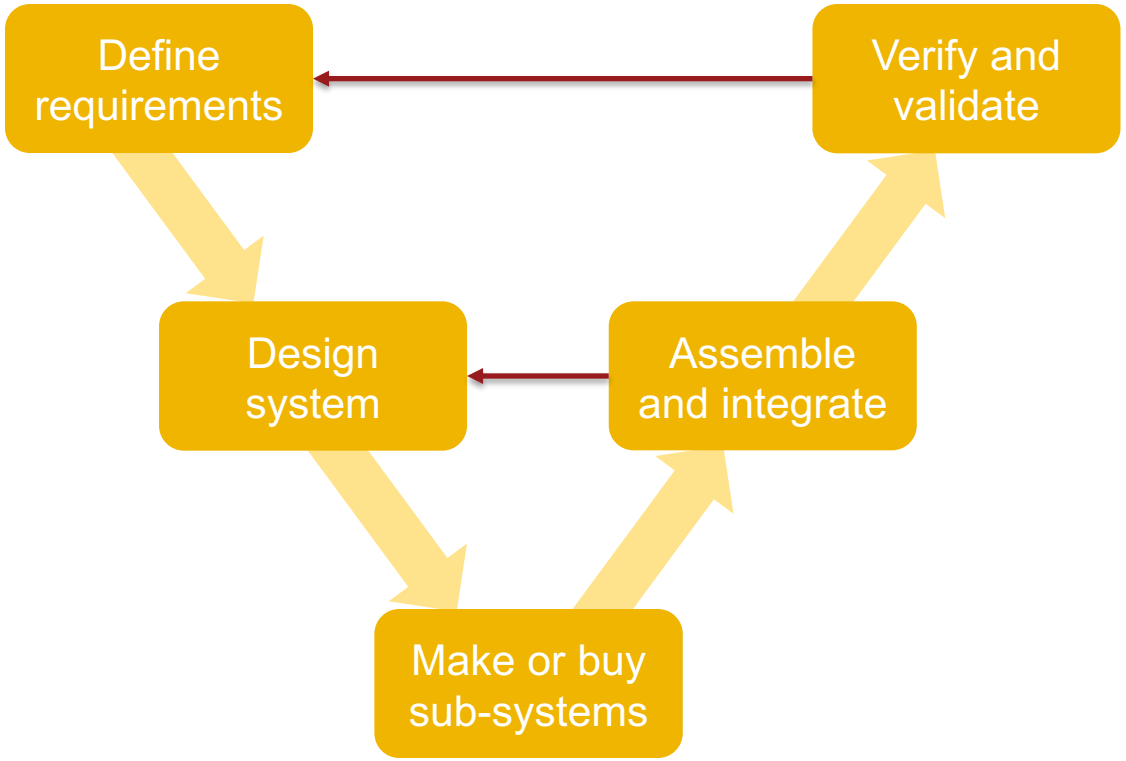
Presentation overview

- Recap on Systems and Systems Engineering
- What is a System of Systems
- System of Systems Engineering Approaches
- Rail and Defence examples
- Summary and conclusions

Systems refresher

- Performance
- Effectiveness
- Environment
- Emergence
- Architecture
- Hierarchy
- Interfaces

SE refresher



- Basic ‘V’ lifecycle
- Linear process with iteration
- 1 system, 1 lifecycle

System of Systems

- Maier's characteristics
  - Operational independence
  - Managerial independence
  - Geographical distribution
  - Emergent behaviour
  - Evolutionary development

System of Systems

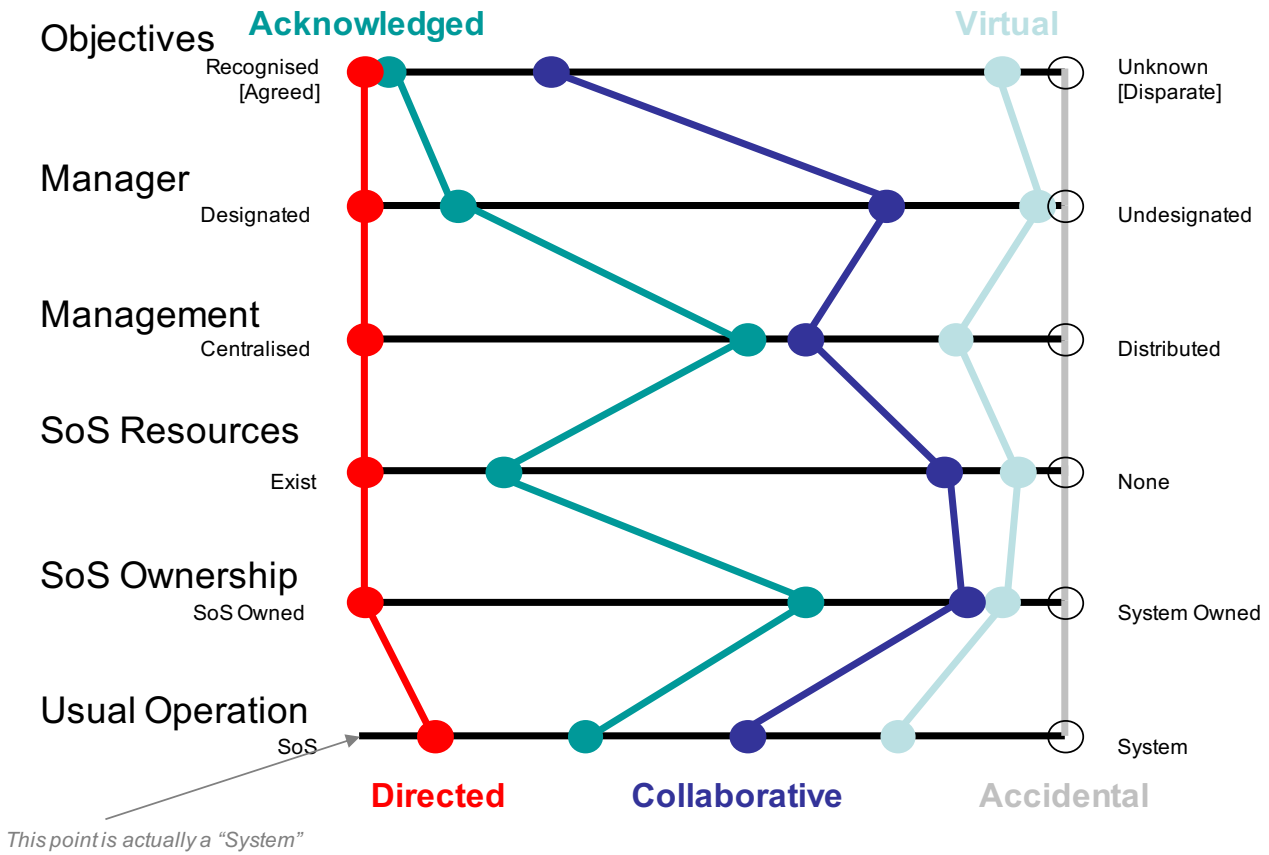
"A system of systems (SoS) brings together a set of systems for a task that none of the systems can accomplish on its own. Each constituent system keeps its own management, goals, and resources while coordinating within the SoS and adapting to meet SoS goals."

ISO 15288

An SoS is a system, with
- Performance
- Effectiveness
- Environment
- Emergence
- Architecture
- Hierarchy
- Interfaces
- Lifecycle

But, each sub-system is also a system with its own
- Lifecycle
- Operational control
- Management control

What types of SoS are there?



- **Accidental** – oh we have an SoS!
- **Virtual** – lets use this SoS
- **Collaborative** – lets work together on this SoS
- **Acknowledged** – lets work together, and Mary can decide when we disagree
- **Directed** – Mary sometimes lets me use my system on its own

But, beware the emperors new clothes

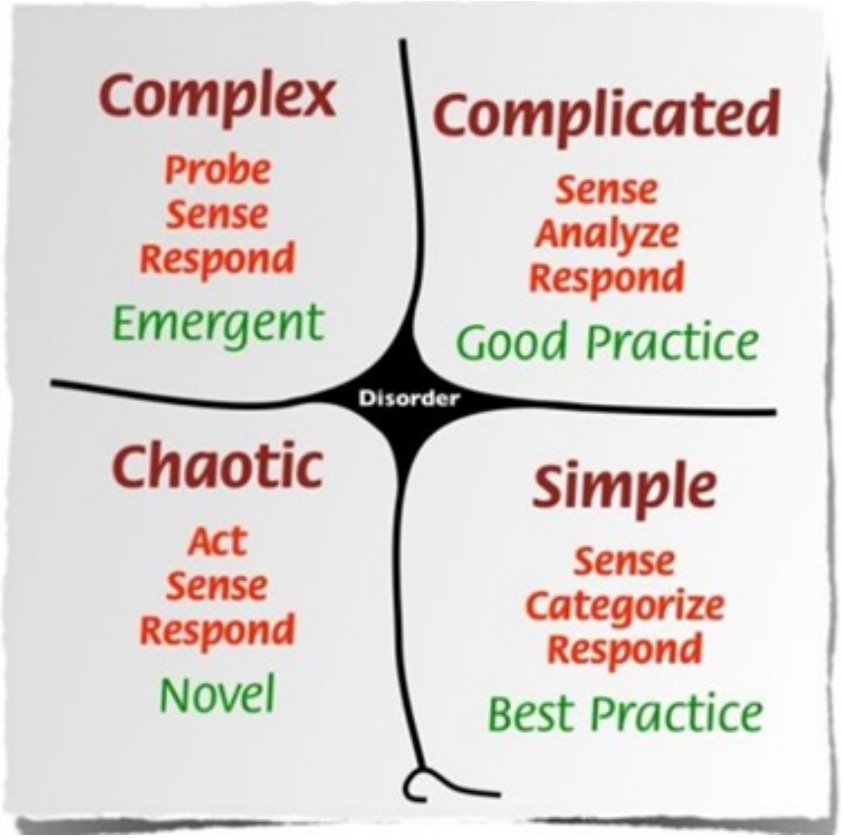
System of Systems pain points

- Authority
- Constituent systems
- Capabilities & Requirements
- Autonomy, Interdependencies & Emergence
- Testing, Validation & Learning
- Leadership
- SoS Principles

How to cope with no one 'in charge'

How to cope with a large complex system with 'uncontrolled' changes

How to lead and manage in this environment

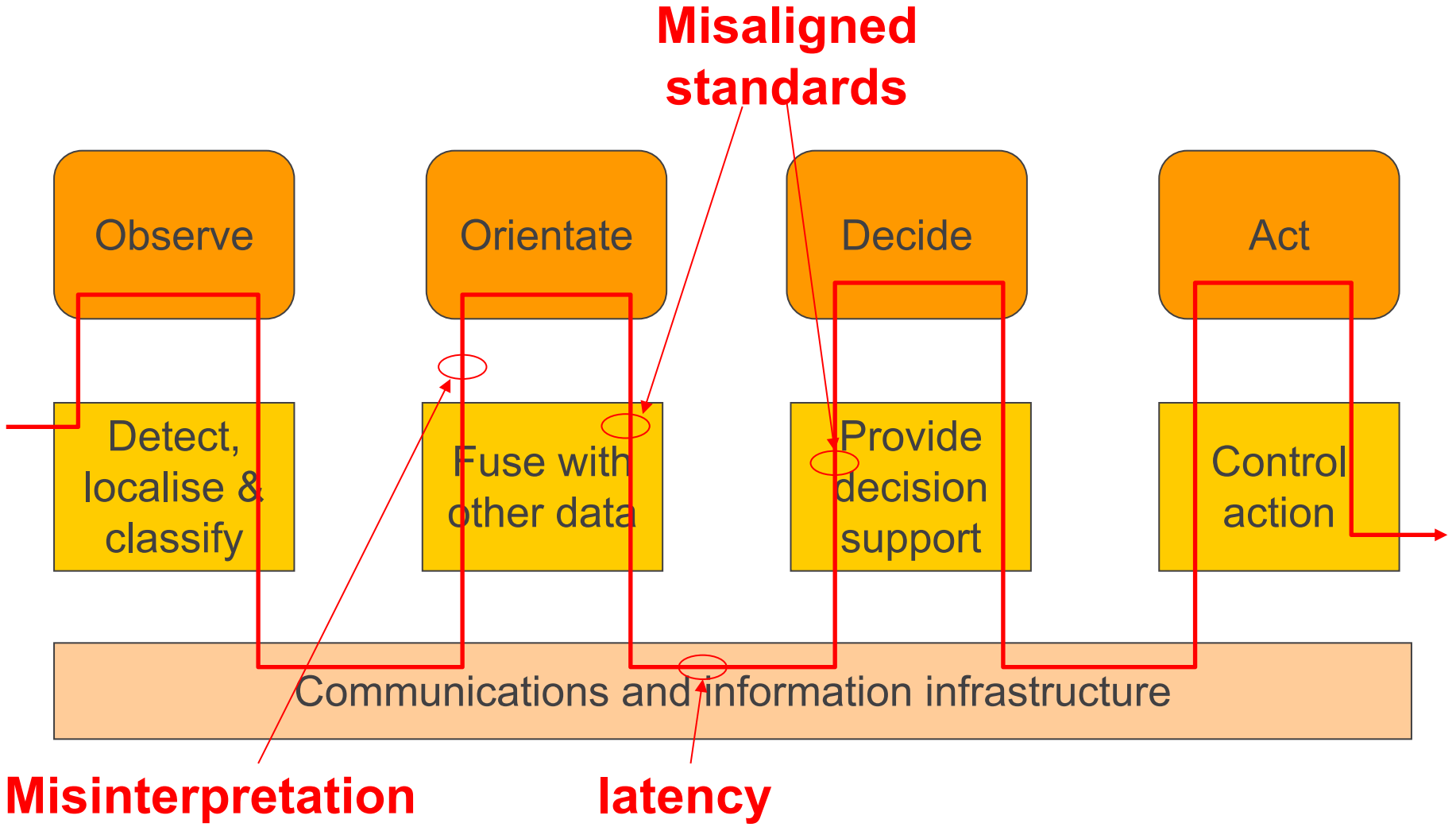


Steampunk SoS Engineering

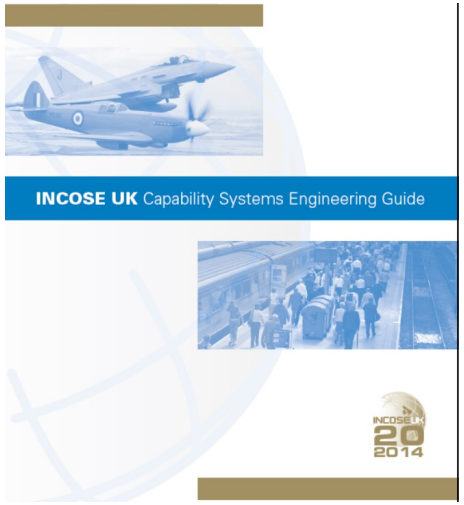
- GB rail evolved from
  - 150 individual railways in 1840s
  - Collaborative SoS in 1870s
- Required standard
  - Time
  - Timetables
  - Ticketing
  - Revenue sharing
- Driven by economic reality that collaboration was better than competition

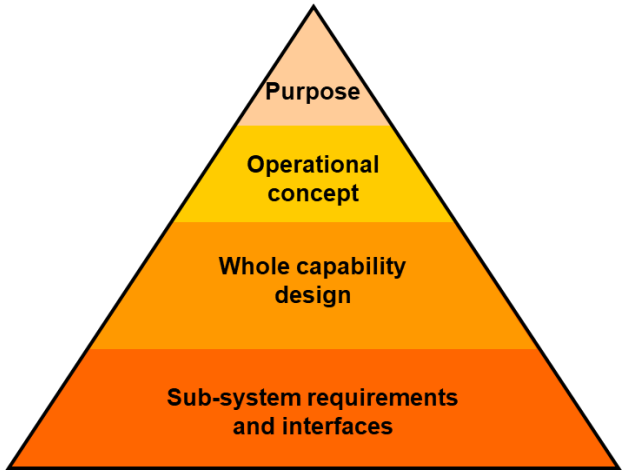
Accidental **Virtual** **Collaborative** **Acknowledged** **Directed**

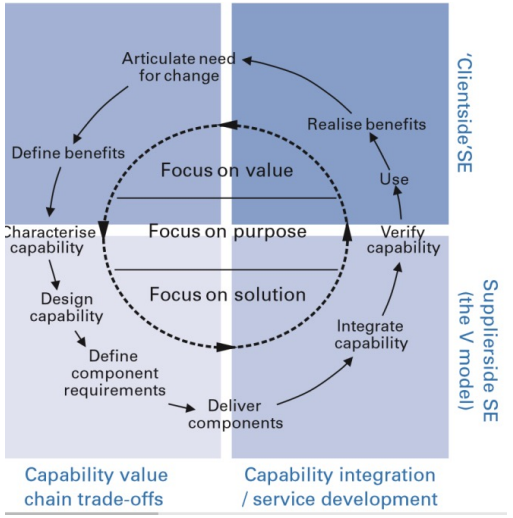
Typical defence information service

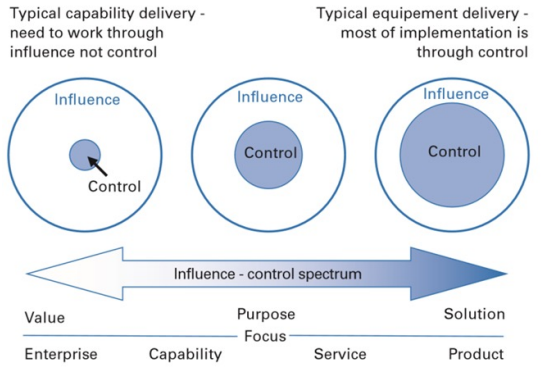


Capability SE

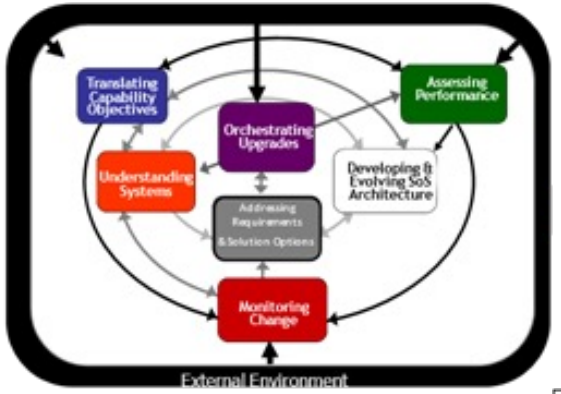


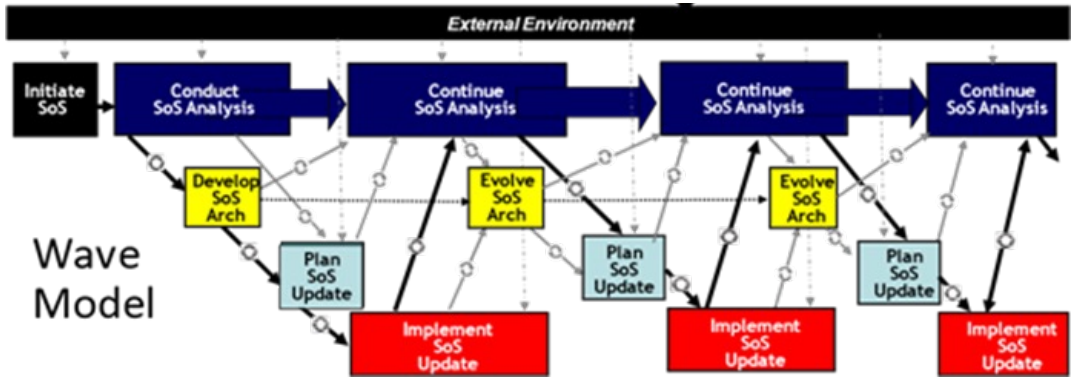


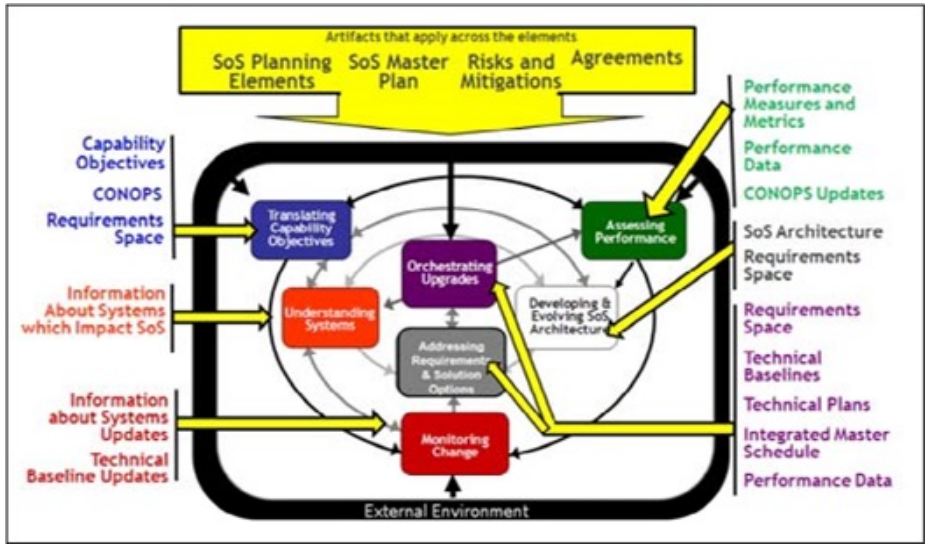




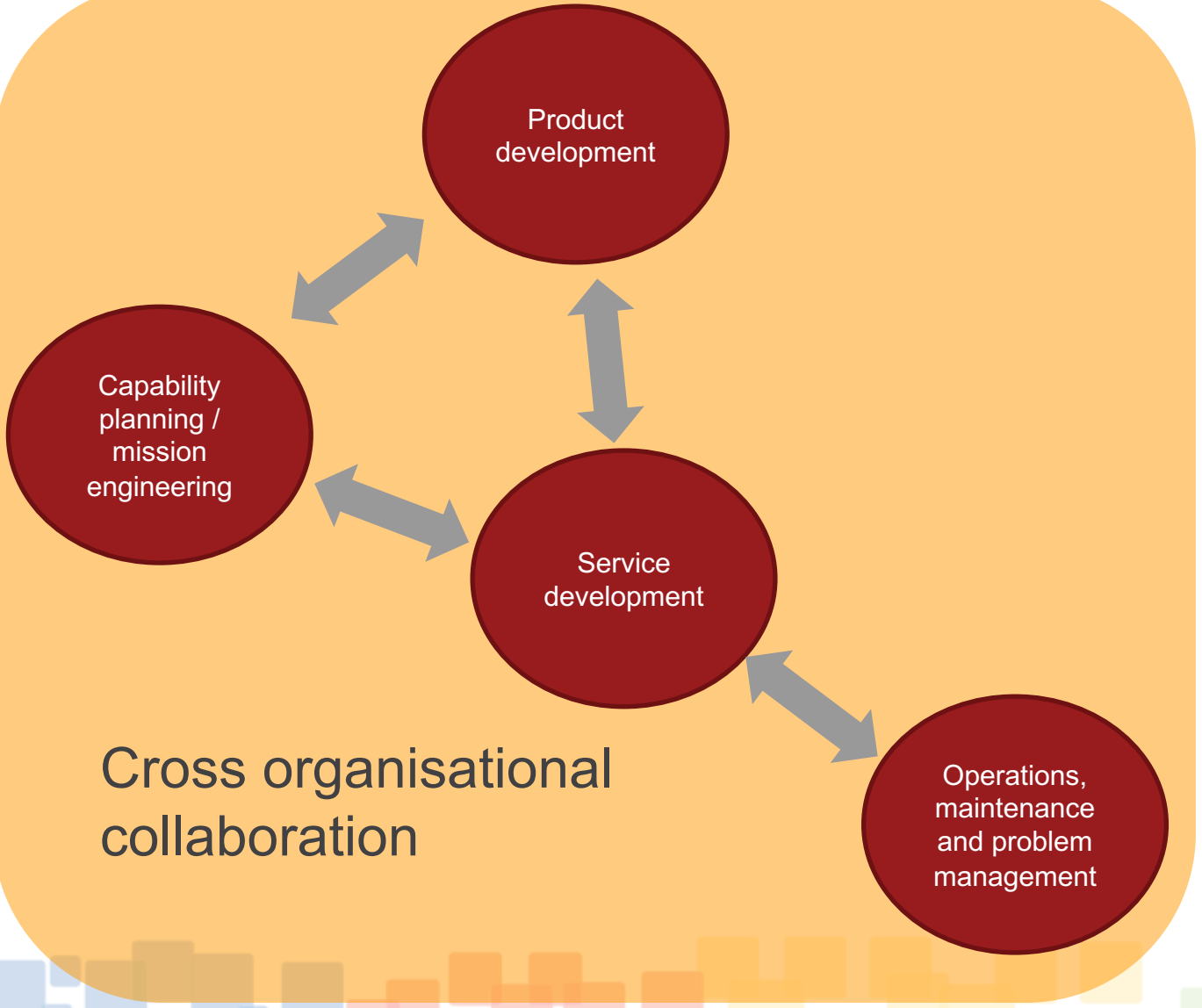
Wave model


Translating Capability Objectives
Assessing Performance
Orchestrating Upgrades
Understanding Systems
Developing & Evolving SoS Architecture
Addressing Requirements & Solution Options
Monitoring Change
External Environment


External Environment
Initiate SoS
Conduct SoS Analysis
Continue SoS Analysis
Continue SoS Analysis
Continue SoS Analysis
Develop SoS Arch
Evolve SoS Arch
Evolve SoS Arch
Plan SoS Update
Plan SoS Update
Plan SoS Update
Implement SoS Update
Implement SoS Update
Implement SoS Update
Wave Model


Artifacts that apply across the elements
SoS Planning Elements
SoS Master Plan
Risks and Mitigations
Agreements
Capability Objectives
CONOPS
Requirements Space
Information About Systems which Impact SoS
Information about Systems Updates
Technical Baseline Updates
Translating Capability Objectives
Assessing Performance
Orchestrating Upgrades
Understanding Systems
Developing & Evolving SoS Architecture
Addressing Requirements & Solution Options
Monitoring Change
External Environment
Performance Measures and Metrics
Performance Data
CONOPS Updates
SoS Architecture
Requirements Space
Requirements Space
Technical Baselines
Technical Plans
Integrated Master Schedule
Performance Data

The ~~four~~ *five* enterprises



- Different collaborating enterprises
- *Not* lifecycles stages
- Broadly linked to different ISO standards
  - ISO 15288 – product development
  - ISO 20000 – service development
  - ISO 55000 – Capability planning and Operations + Maintenance
  - ISO 44000 - Collaboration

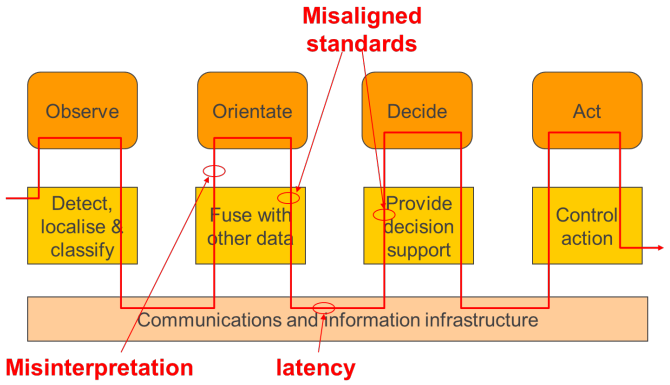
Progressively more difficult …

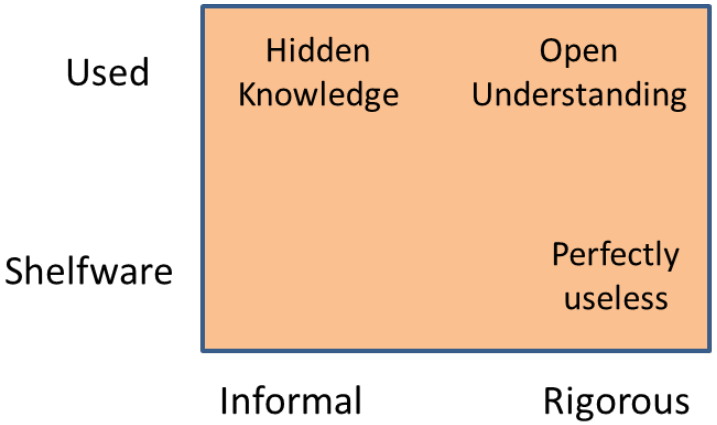
Type	Definition	ISO 15288	ISO 20000	ISO 55000	ISO 44001
System (added)	*A single product/service with single (albeit complex) lifecycle, comprising a mixture of new and off the shelf sub-systems. Its subsystems have minimal utility on their own – it is only used as a system. It has a single management organisation to manage upgrades, updates and maintenance through life.*	Yes			
Directed	Directed SoS are those in which the integrated system-of-systems is built 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 central managed purpose.	Yes	Yes		
Acknowledged	Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.	Yes	Yes	Yes	
Collaborative	In collaborative SoS the component systems interact more or less voluntarily to fulfill agreed upon central purposes.	Yes	Yes	Yes	Yes
Virtual	Virtual SoS lack 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 must rely upon relatively invisible mechanisms to maintain it.	*Yes*	*Yes*	*Yes*	*Yes*
		(If the pain is great enough to warrant moving the SoS from virtual to collaborative)			

Key principals for realising effective SoS

Understanding

- Principle 1 – Recognise that your SoS will comprise multiple systems, working to deliver multiple services as part of a wider mission / capability. There will be multiple lifecycles and disagreements over SoS purpose and boundary.
- Principle 2 – Do not attempt to oversimplify the situation, focus on getting *sufficiently consistent* understanding of the Systems and SoS.
- Principle 3 – Develop an integration architecture that describes the functionality, performance and commercial / organisational aspects of the SoS. The more open and modular the architecture, the easier it will be to evolve the SoS.

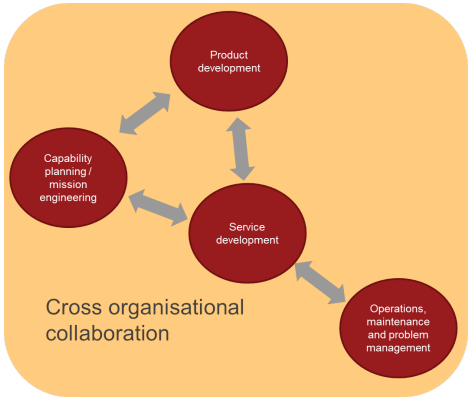


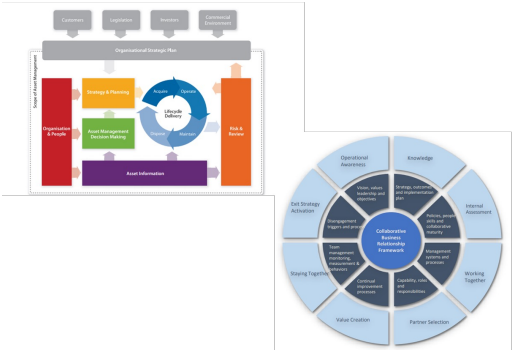


Key principals for realising effective SoS

Approach

- Principle 4 – Use 4 different approaches for the 4 different enterprises. Implement the appropriate practice for each enterprise. Good practice for one approach may not be good practice for another – one size does not fit all. The processes, tools, culture, management and leadership styles need to be different
- Principle 5 – Integrate the four different approaches. Remember that the are collaborating enterprises, not stages in a lifecycle.





Key principals for realising effective SoS

Collaboration

- Principle 6 – Balance the costs and benefits for everyone participating in the SoS. The more participants want to be in the SoS, the more committed they will be to fix problems and expand use.
- Principle 7 – Focus on the easiest and highest value services to improve. The epitome of skill is not to build an expensive new system to deliver a new service, it is to deliver the new service by reusing the existing systems.

Summary and conclusions

An SoS is a system, with
- Performance
- Effectiveness
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- Architecture
- Hierarchy
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- Lifecycle

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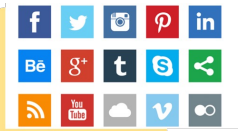

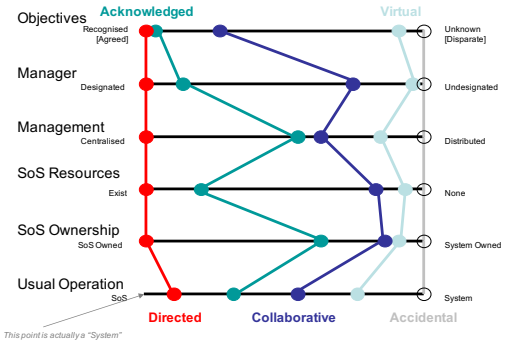

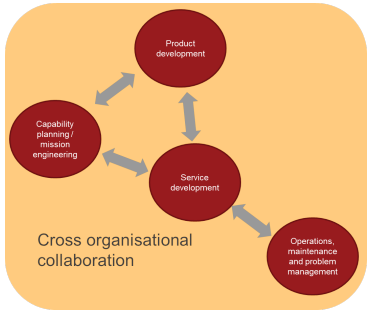

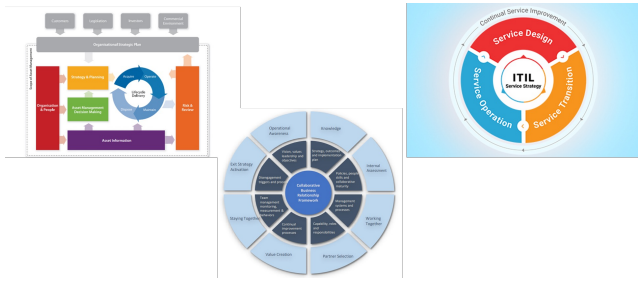

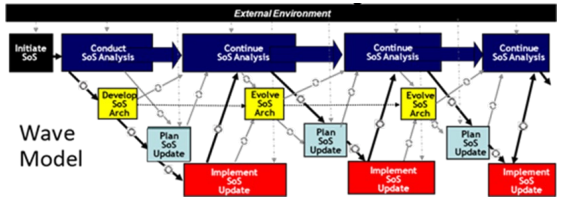

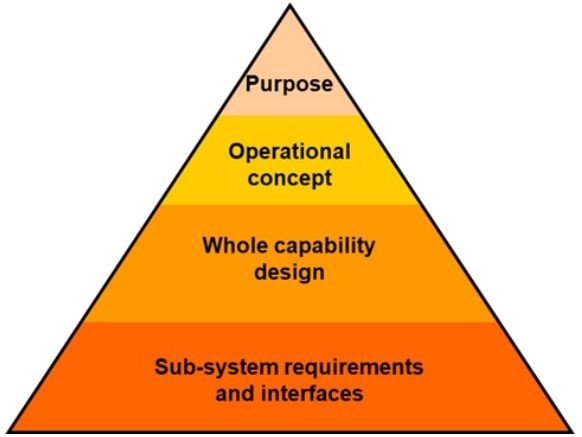

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