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System Re-tasking to Achieve Resilience in an SoS

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Outline

- Motivation
- Representation of an SoS
- Analytic framework
- Illustrative example
  - Notional 5-node SoS
  - Results and discussion
- Summary and Future work

Motivation

- What is resilience?
  - "Resilience is the ability of a system or organization to react to and recover from disturbances at an early stage with minimal effect on its dynamic stability"

    (Resilience Engineering: Concepts and Precepts (2010))

- Historical approach:
  - Improve resilience through over-design
  - Traditional systems engineering practices anticipate and resist disruptions
  - Resilience incorporated through classical reliability methods:
    - Redundancy
    - Preventive maintenance

Stand-in redundancy in SoSs

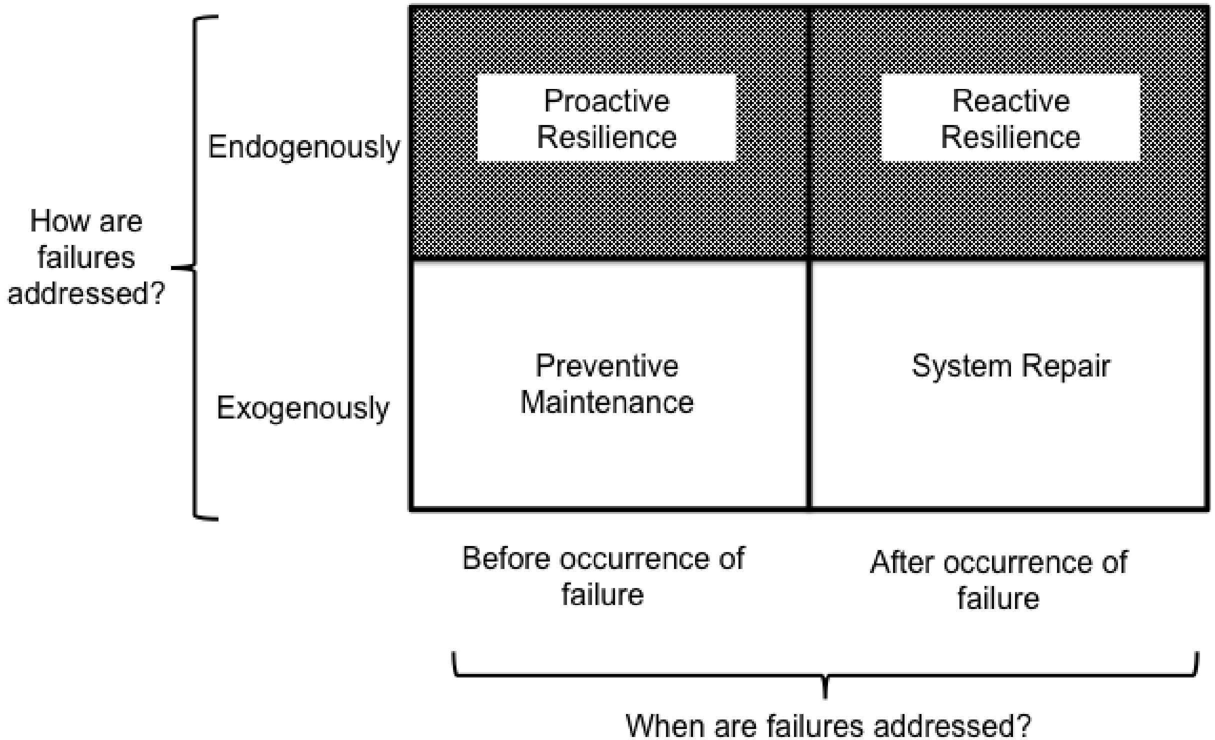
- Not suitable for SoSs:
  - —Heterogeneity, geographical distribution, interdependencies
  - —Backup systems are costly and impractical

- Stand-in redundancy:
  - —Compensate for loss of performance in one constituent system by re-tasking remaining systems
  - —As one node experiences degradation, other nodes can alter their operations to compensate for this loss

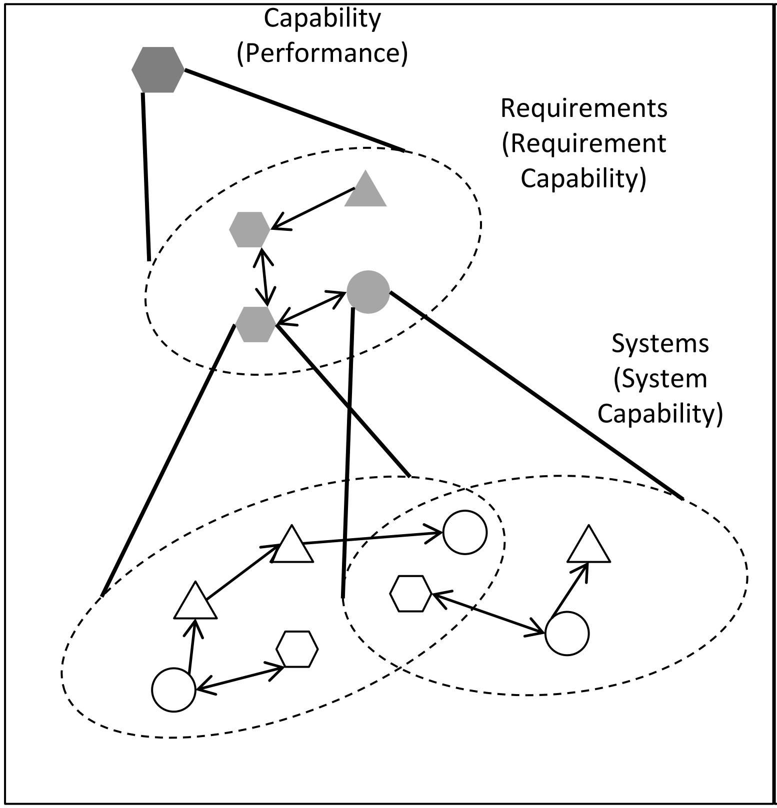
- Raises interesting questions:
  - —Given a system failure, what is the best configuration to compensate for the loss?
  - —What level of performance can be recovered with new configuration?
  - —What is upstream effect of stand-in redundancy on development costs and risks?

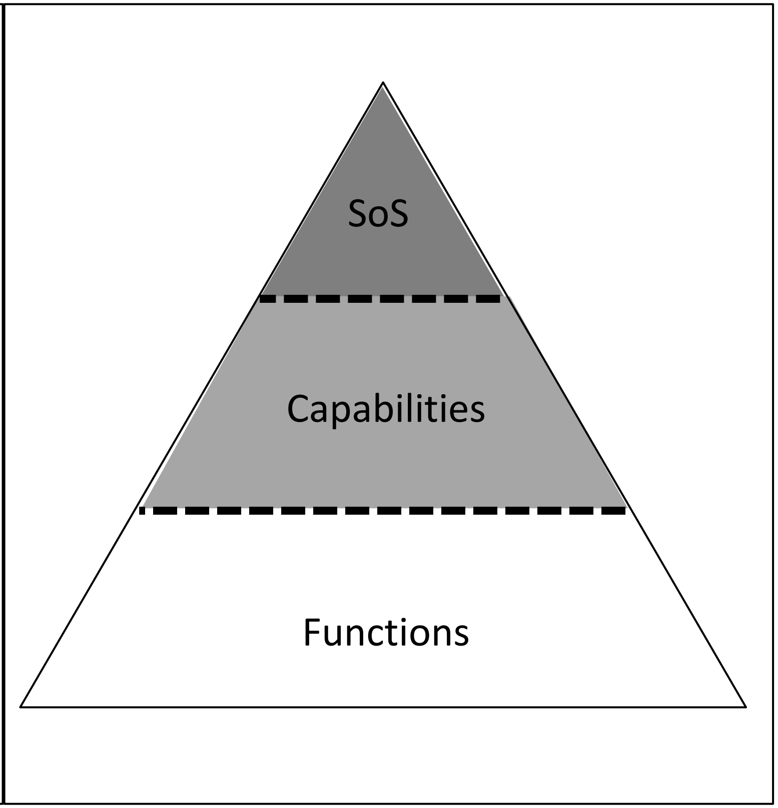
Stand-in redundancy in SoSs

- Impact of stand-in redundancy on resilience of SoS:
  - Reactive Resilience
  - Proactive Resilience



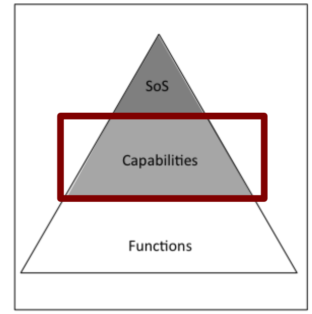
SoS Representation



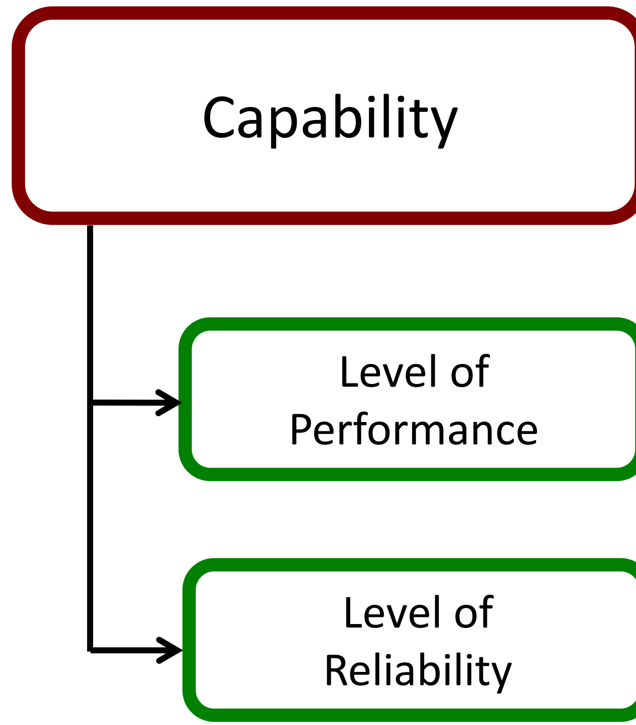


SoS Representation

- Consider metrics at capability level:
  - —Level of Performance (LoP)
  - —Level of Reliability (LoR)

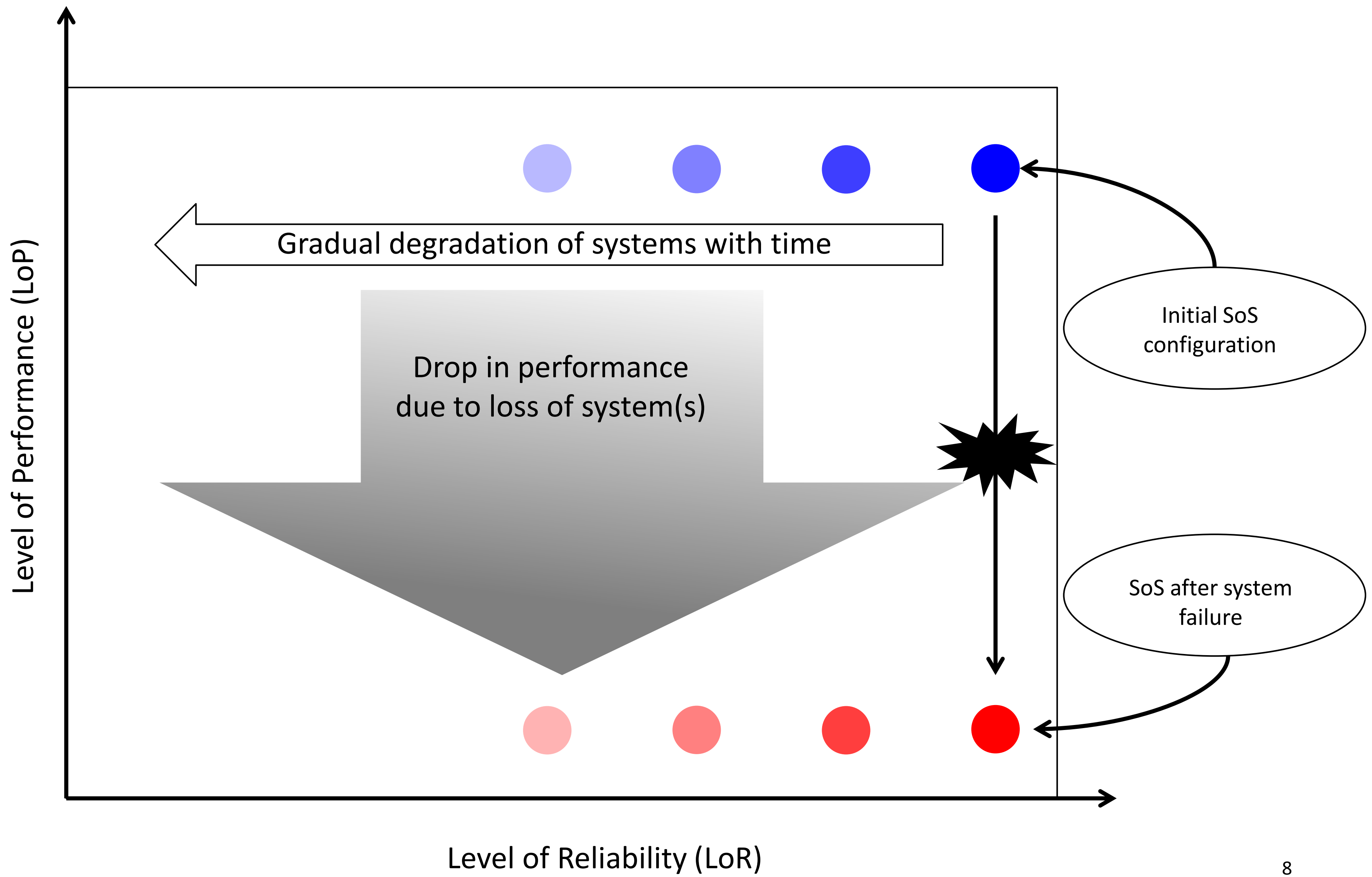


- LoP depends on systems, functions, performance metrics, interdependencies

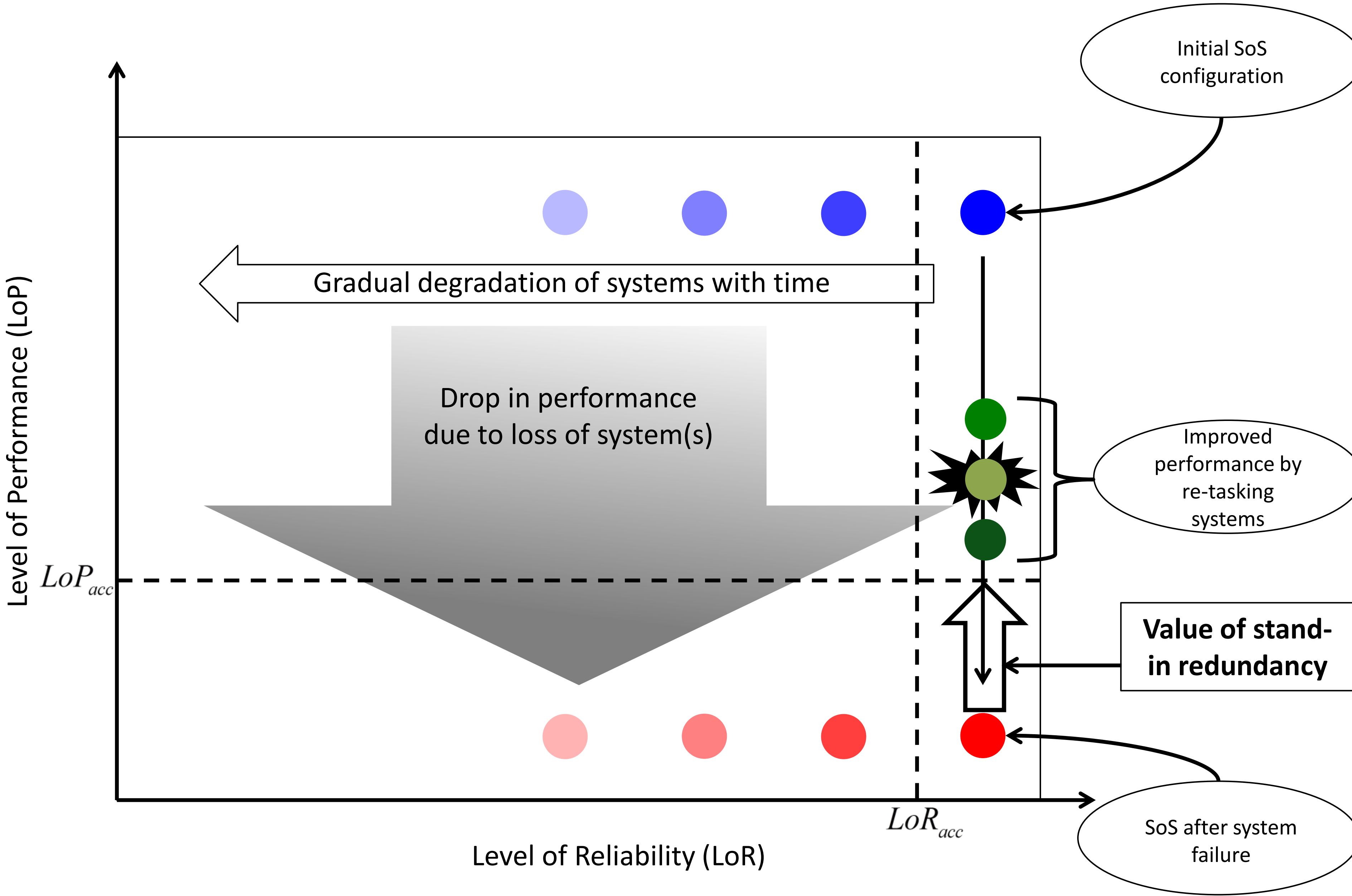


- LoR depends on reliability of individual systems

Analytic framework



Analytic framework



Analytic framework

Minimize $SoS\ operations\ cost$

Subject to :

$$LoP_i \geq LoP_i^T$$
$$LoR_i \geq LoR_i^T$$

SoS Operations Cost

Fully functional state: Number of systems, operating cost of each system

Failed system state:
Operating costs of remaining systems, cost to repair/replace system, downtime costs

Re-tasked state:
Operating cost of remaining systems, acquisition costs of additional features

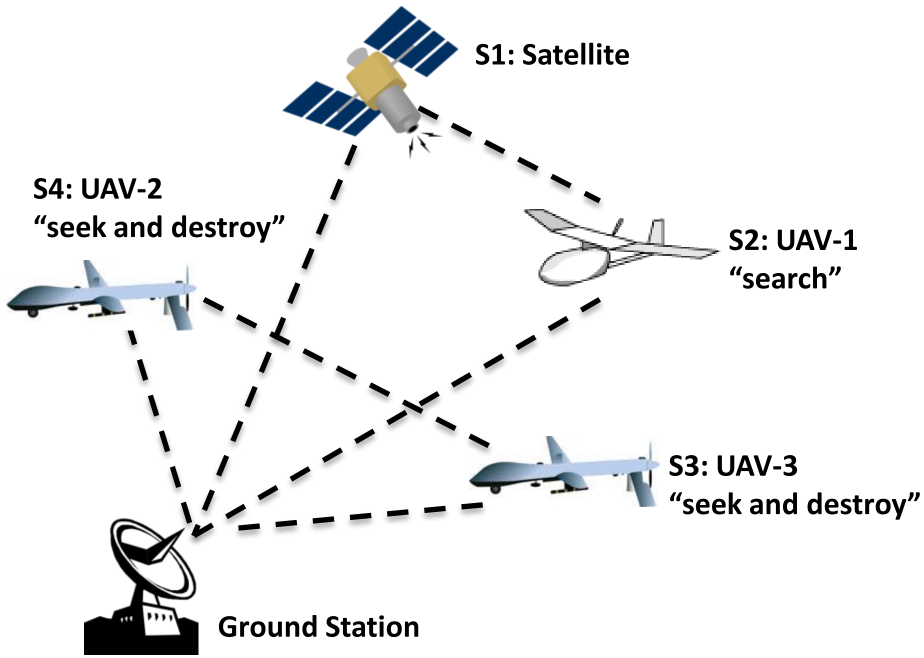
LoP:
systems, functions, performance metrics, interdependencies

LoR:
reliability of individual systems

Desired LoP, LoR:
Min. level of high performance and high reliability original SoS should satisfy

Acceptable LoP, LoR:
Min. acceptable level re-tasked systems must provide

Illustrative example



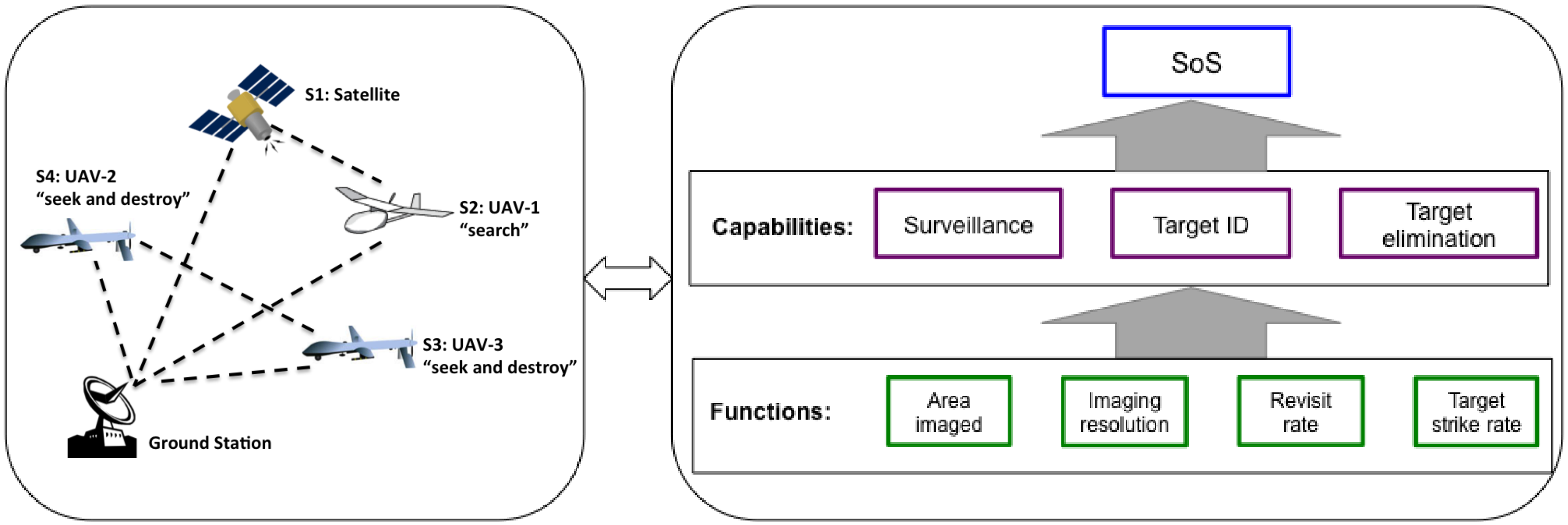
<u>Features available on each system:</u>

UAV1: High-definition camera
UAV2: Basic camera + weapons
UAV3: Basic camera + weapons

Capability	Description	Systems Needed
C1	Surveillance	S1
C2	Target identification	S1, S2
C3	Target elimination	S3, S4

Illustrative example

- Representation of SoS:

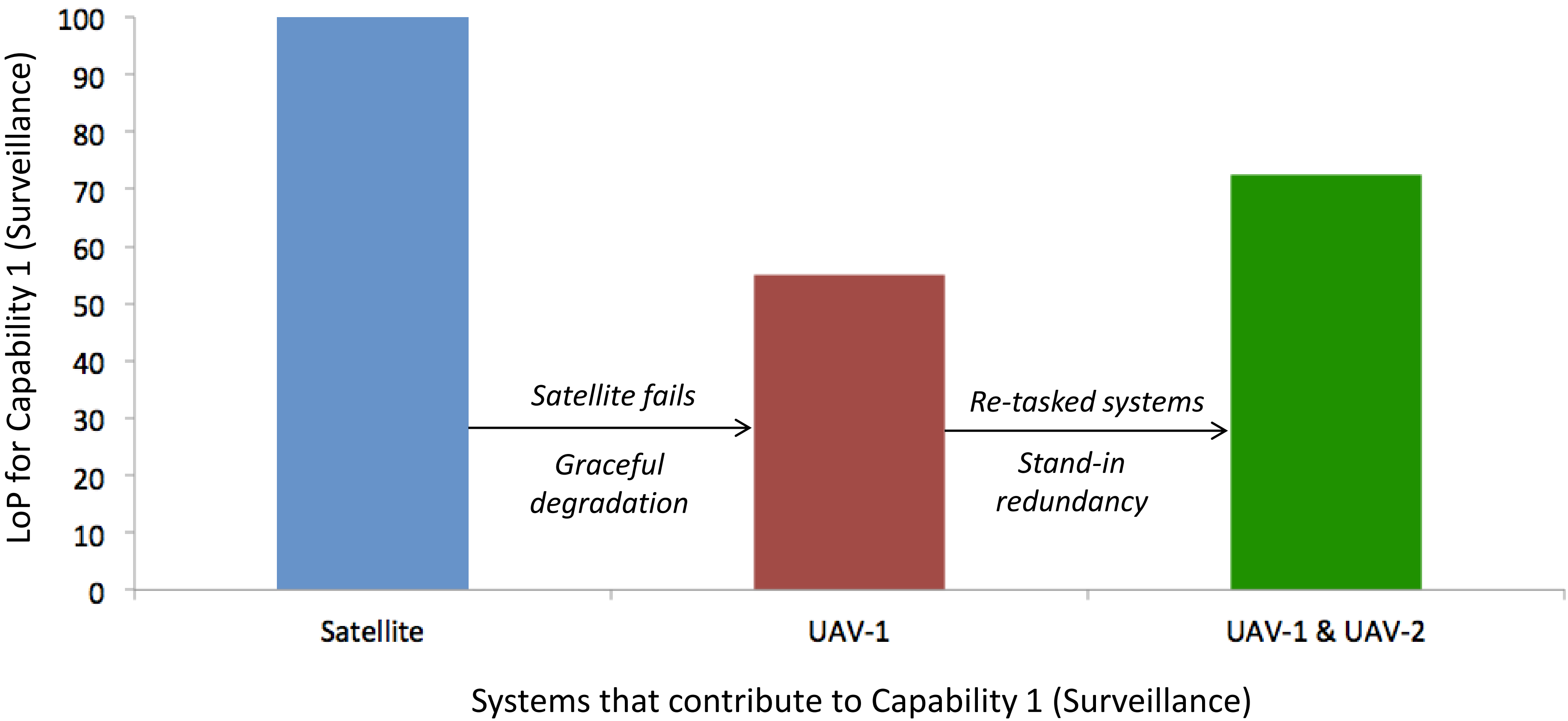


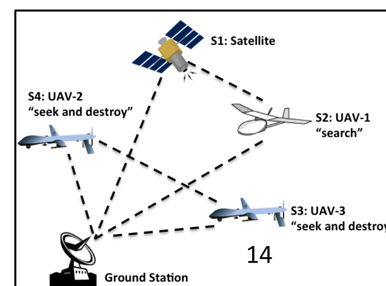
Systems and functions

Systems	Individual system functions/features			
	Area imaged	Imaging resolution	Revisit rate	Target strike-rate
Satellite	✔	✔	✔	-
UAV-1 "search"	✔ ↑	✔ ↑	✔	-
UAV-2 "seek and destroy"	✔ ↑	✔ ↑	✔	✔
UAV-3 "seek and destroy"	✔ ↑	✔ ↑	✔	✔

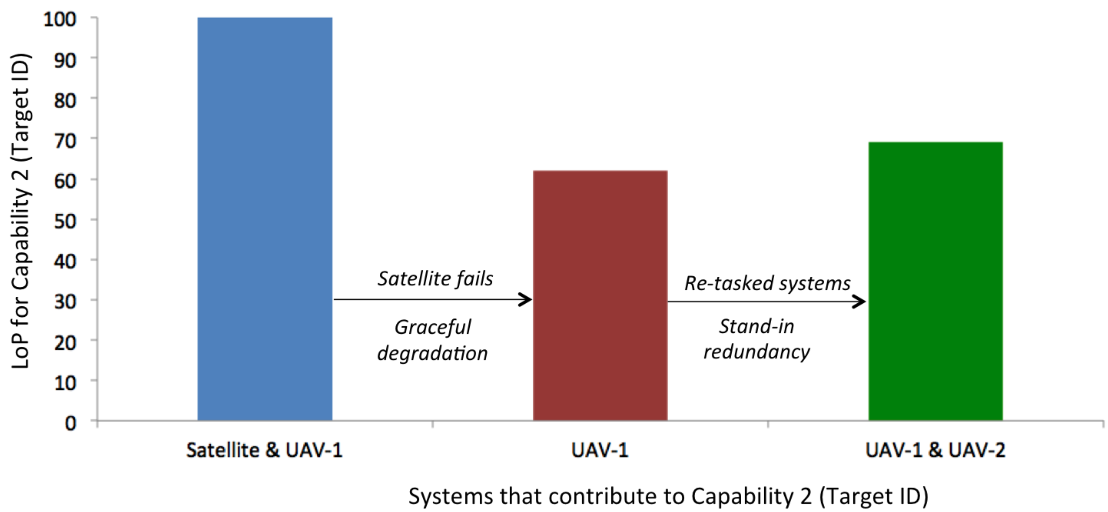
- Modifications/enhancements in SoS:
  - Features on satellite cannot be changed
  - Easier to retrofit UAVs with higher performance devices
  - (UAVs can also be reprogrammed for higher revisit rates)

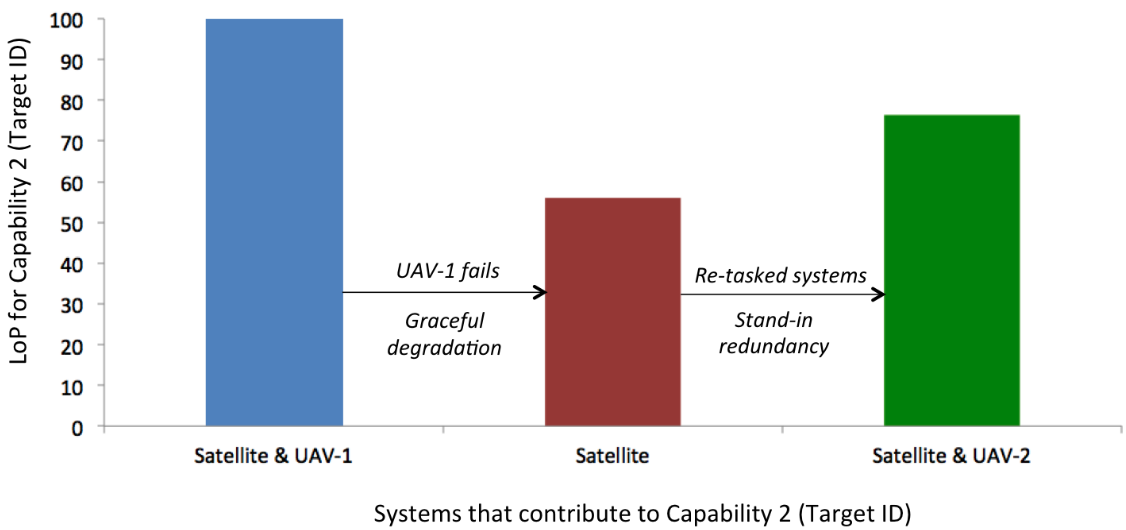
Results: Surveillance (C1)

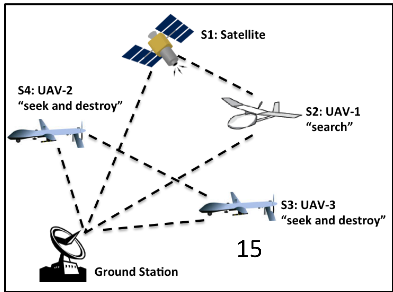




Results: Target identification (C2)







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Results: Target elimination (C3)

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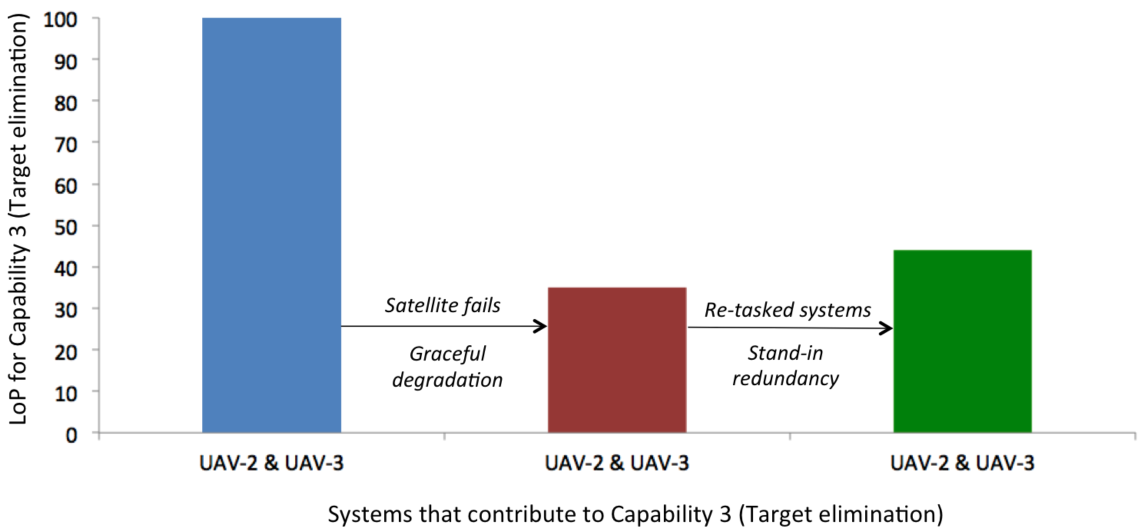
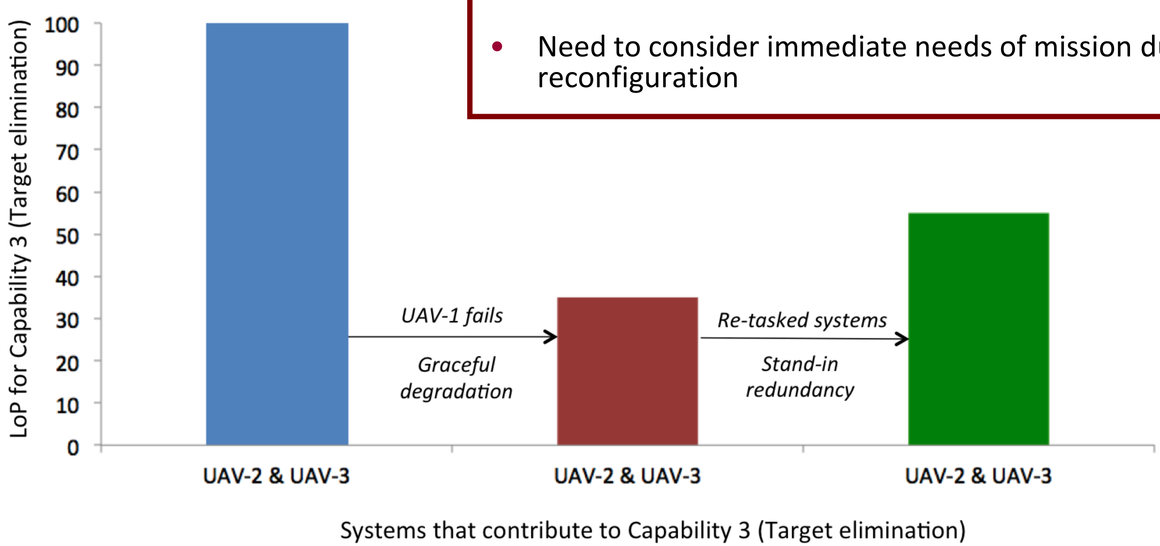
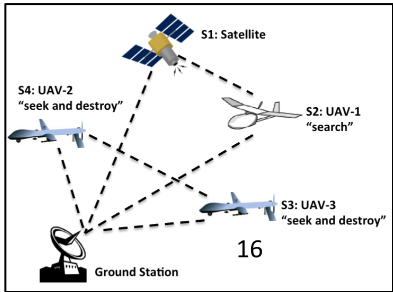


- Indirect impact of system failure on capabilities
- Need to consider immediate needs of mission during functional reconfiguration





Discussion

- Using stand-in redundancy, systems can:
  - Contribute to SoS-level capabilities in ideal case, and
  - "Stand-in" for failed functions during failures
- Limit to level of stand-in redundancy that can be incorporated
  - Appropriate resource allocation
- Need to consider balance between ***resilience***, ***costs***, and ***adaptability*** of the SoS
  - For example, multi-modal transportation networks are designed for long lifetimes with gradual modifications and/or upgrades

Summary and future work

- Large scale SoSs evolve with time along with changing environment
- This approach indicates incremental enhancements/modifications to existing systems can provide inherent resilience
- Approach can help decision-makers quantitatively assess resilience of different SoS architectures
- Future work:
  - Expand static model to dynamic model (resilience under uncertainty)
  - Track system degradation with time (proactive resilience)
  - Consider multi-system failures