Game-theoretic Risk Assessment for Distributed Systems (GRADS)

Sponsor: DASD(SE)

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10th Annual SERC Sponsor Research Review
November 8, 2018
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Overview and Agenda

- Problem Statement
- Research Questions
- Foundations: Stag Hunt Game and Risk Dominance
- Research Plan: Application to NPOESS Scenario
- Conclusion and Future Work

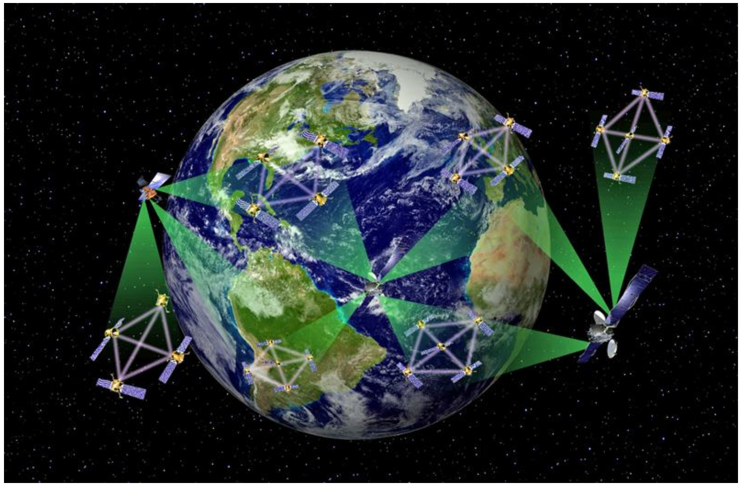
Distributed System Architectures

Upside Potential

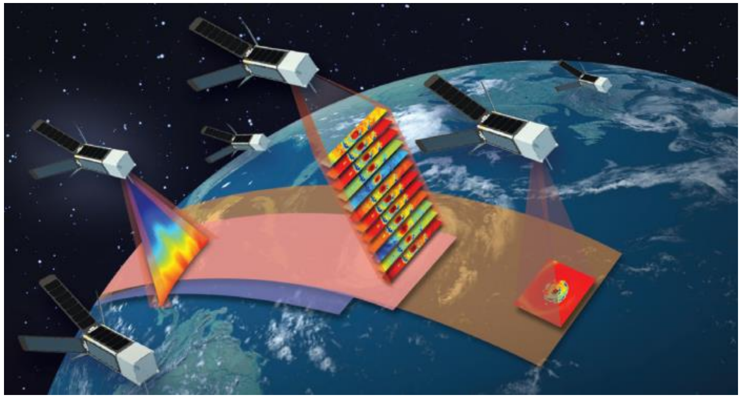
- Flexibility, robustness
- Mission effectiveness
- Resource efficiency

Downside Risk

- Interdependencies
- Complex behavior
- Cascading failures



System F6 Concept (DARPA)



TROPICS Mission Concept (NASA, Lincoln Labs)

Problem Statement

- Future complex engineered systems will have more **distributed architectures** with decentralized decision-making among multiple independent design actors
- Two types of risk in collaborative projects:
  - **Systemic risk**: cost, schedule, and technology uncertainty
  - **Collaborative risk**: conflict and coordination failures
- Need improved methods to assess collaborative risk
  - Identify and avoid poor strategic dynamics early
  - Improve strategic decision-making to balance efficiency (feasibility), effectiveness (desirability), and stability (viability)

Research Questions

- **How to assess collaborative risk in distributed systems?**
  - —Tradeoff between expected upside and possible downside
  - —Collaborative risk linked to decision stability, not uncertainty
  - —Evaluate an objective risk metric based on Selten's (1995) Weighted Average Log Measure (WALM) of risk dominance
- **How can a collaborative risk metric be operationalized to evaluate a realistic joint program proposal?**
  - —Develop scenario narrative following National Operational Polar-orbiting Environmental Satellite System (NPOESS) program
  - —Assess collaborative risk for a joint project between Department of Defense (DoD) and National Atmospheric and Oceanic Administration (NOAA)

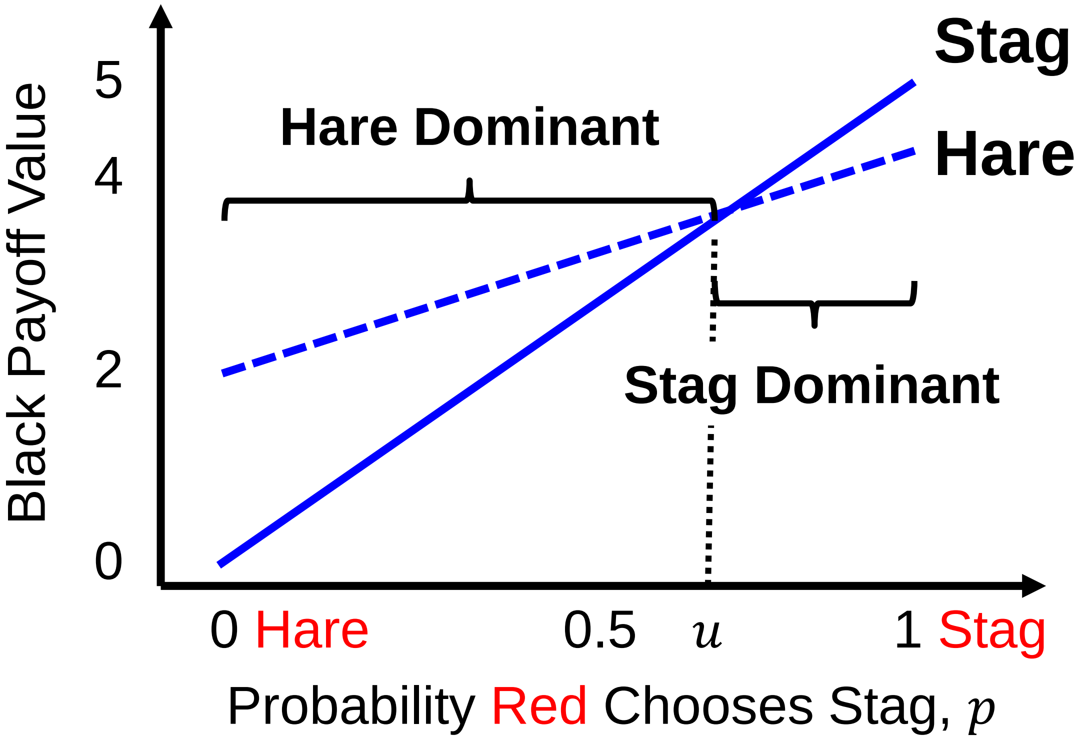
Foundation: Stag Hunt Game

	Hare	Stag
Hare	2 2	4 0
Stag	0 4	5 5

- Cell entries measure actor payoff/utility/value
- Two pure Nash equilibria
  - Hare, Hare: risk-dominant equilibrium (minimize risk)
  - Stag, Stag: payoff-dominant equilibrium (maximize reward)

Stag hunt by Gaston Phoebus (Bibliotheque Nationale de France)

Stag Hunt Under Uncertainty



	Hare	Stag
Hare	2 / 2	4 / 0
Stag	0 / 4	5 / 5

- $p > u$: choose stag option, $p < u$: choose hare option
- u: Normalized deviation loss, $u = \frac{(2-0)}{(2-0)+(5-4)} = \frac{2}{3}$

Risk Dominance Metric

- Proposed by Selten (1995) to meet a set of desirable axioms
  - Normative for rational actors
  - Purely objective (assumes $p = 0.5$)
- n-player general case:

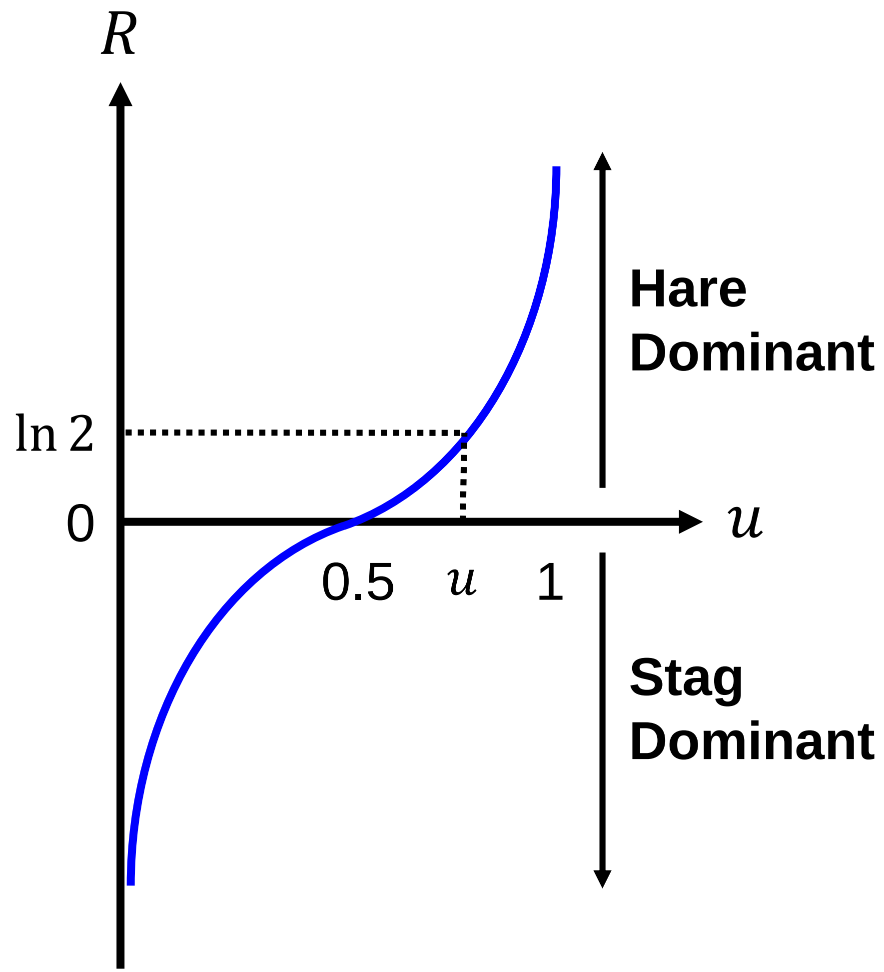
$$R = \sum_{i=1}^{n} w_i(A) \ln\left(\frac{u_i}{1 - u_i}\right)$$

- 2-player asymmetric case:

$$R = \frac{1}{2}\ln\left(\frac{u_1}{1 - u_1}\right) + \frac{1}{2}\ln\left(\frac{u_2}{1 - u_2}\right)$$

- 2-player symmetric case:

$$R = \ln\left(\frac{u}{1 - u}\right)$$



$$R = \ln\left(\frac{2/3}{1 - 2/3}\right) = \ln\left(\frac{2 - 0}{5 - 4}\right) = \ln 2$$

Strategic Design Games

- Engineering requires two levels of design decisions:
  - Strategy: long-term policy (collaboration or independence)
  - Design: architecture to maximize value in strategic context
- Strategy space:

$$\mathcal{S} = \{\underline{S}\text{tag}, \underline{H}\text{are}\}$$

- Design space:

$$\mathcal{D} = \{\underline{A}\text{xe}, \underline{B}\text{ow}, \underline{C}\text{lub}, \underline{D}\text{og}, \dots\}$$

- Multi-actor value function:

$$V^{s_1,s_2}(d_1, d_2): \mathcal{D}^2 \times \mathcal{S}^2 \rightarrow \mathbb{R}^2$$

	Hare	Stag
Hare	$V_1^{HH}(B,B) = 2$ $V_2^{HH}(B,B) = 2$	$V_1^{HS}(B,D) = 4$ $V_2^{HS}(B,D) = 0$
Stag	$V_1^{SH}(D,B) = 0$ $V_2^{SH}(D,B) = 4$	$V_1^{SS}(D,D) = 5$ $V_2^{SS}(D,D) = 5$

- Dog is selected "design" to execute Stag "strategy"
- Bow is selected "design" to execute Hare "strategy"
- Other designs could be tested

Ensuring Collaboration (1)

- Two general approaches to reduce collaborative risk:

1. **Increase upside potential**
   - —Increase benefit of collaboration
   - —Better design to hunt stag *together*
   - —Maximize denominator of R

	Hare	Stag
Hare	2, 2	4, 0
Stag	0, 4	5, 5

$$R = \ln\left(\frac{2-0}{5-4}\right) = \ln 2$$

- Fundamental problem: *robust-yet-fragile* behaviors
  - —Highly-optimized stag hunt design trades context-specific value for fragility
  - —Example: coordination overhead, mutual dependence

Ensuring Collaboration (2)

- Two general approaches to reduce collaborative risk:

2. Decrease downside risk

— Reduce penalty of coordination failure

— Better design to hunt stag *alone*

— Minimize denominator of R

	Hare	Stag
Hare	2, 2	4, 0
Stag	0, 4	5, 5

$$R = \ln\left(\frac{2-0}{5-4}\right) = \ln 2$$

- Reflects principle of *stable intermediate forms*

— Reduce coordination overhead

— Establish independent source of value regardless of coordination outcome

Application Case Scenario

- Study how concepts of collaborative risk dominance can be applied to a realistic systems design problem
- Retrospective study of National Polar-orbiting Operational Environmental Satellite System (NPOESS)
  - Proposed joint program between the U.S. Department of Defense (DoD) and U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)
  - Incorporate instruments developed under the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program
  - Motivated by resource efficiency (cost savings)

NPOESS Background

Polar-orbiting Operational Environmental Satellite (POES)

Defense Meteorological Satellite Program (DMSP)

Earth Observing System (EOS)

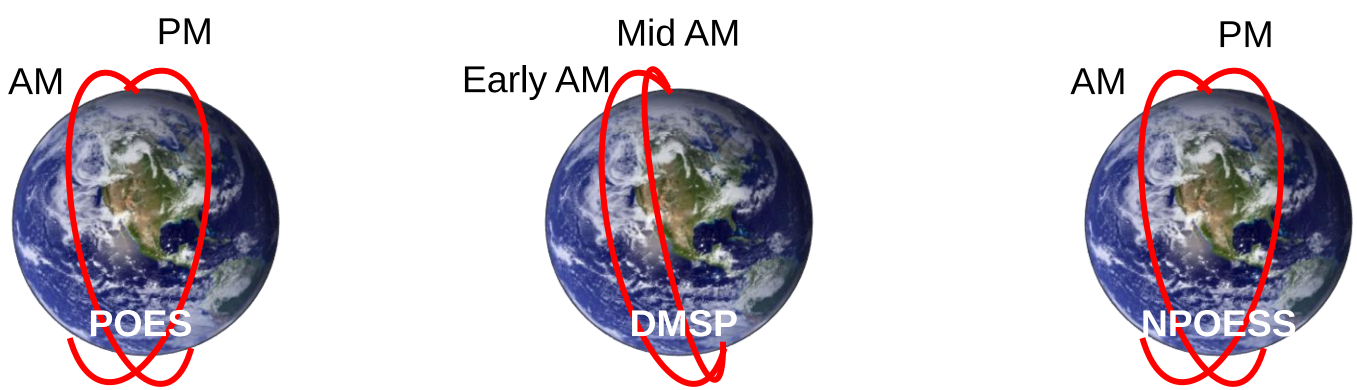
National Polar-orbiting Operational Environmental Satellite System (NPOESS)

Joint Polar Satellite System (JPSS)

Defense Weather Satellite System (DWSS)

Weather System Follow-on (WSF)

1960s 1970s 1980s 1990s 2000s 2010s



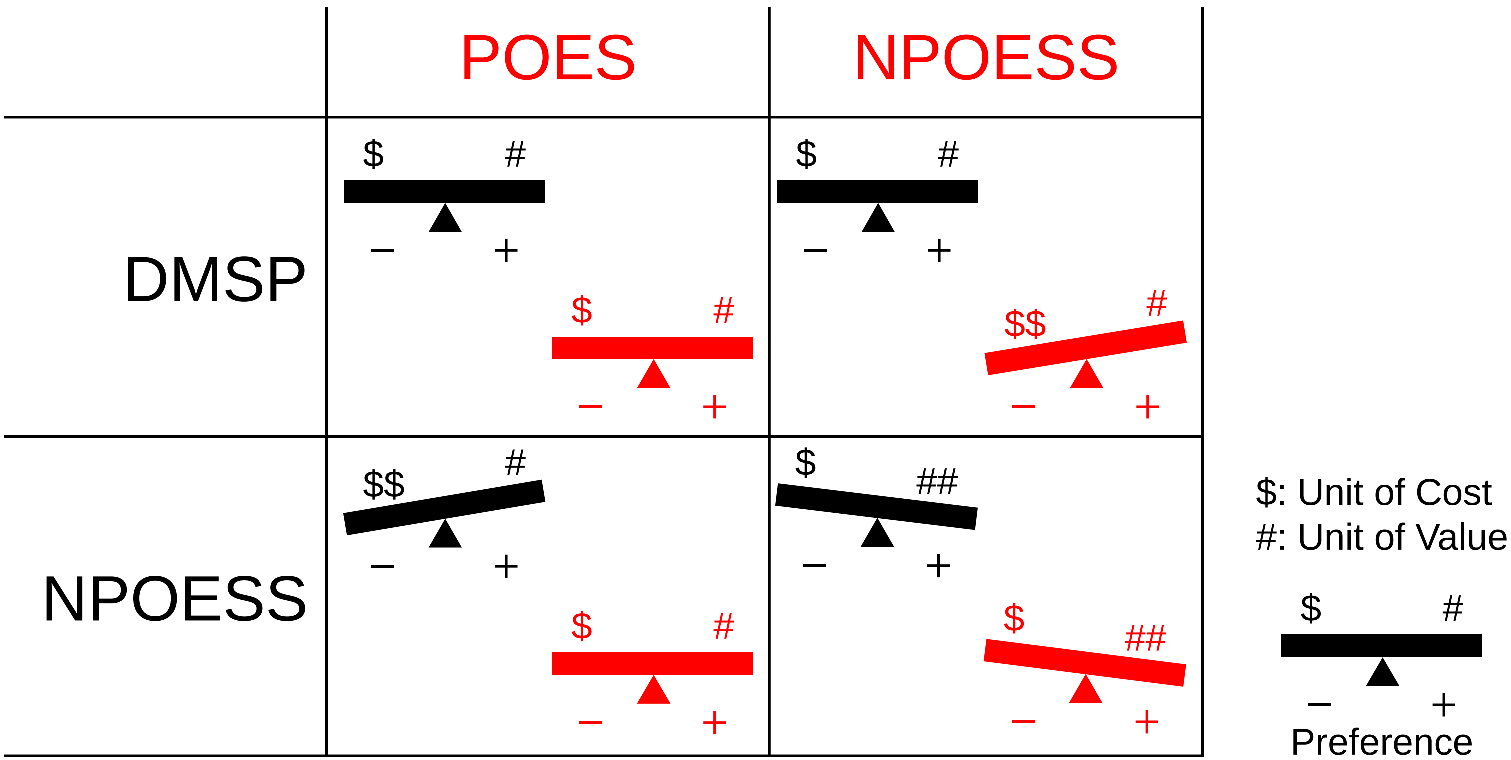
NPOESS Strategic Design Game

	POES	NPOESS
DMSP	DMSP POES	DMSP (JPSS)
NPOESS	(DWSS) POES	NPOESS NPOESS

Work in Progress

- Model alternative architectures/designs:
  - 2 baseline independent systems: DMSP, POES
  - 1 successful collaborative system: NPOESS
  - 2 “coordination failure” systems: *DWSS/WSF*, *JPSS*
- Simulate key performance attributes: measurements, revisit period, data latency, data volume, cost
- Model actor preferences (multi-actor value)
  - Subjective preferences and weights for each attribute
  - Aggregate preferences for each design alternative
  - Inherently subjective, many simplifying assumptions

Anticipated Results (Idealized)



Caveats and Limitations

- NPOESS program experienced substantial *systemic risk*, specifically cost growth studied by others
  - Goal is *not* to provide retrospective analysis or "hotwash"
  - Leverage large volume of information availability and academic/government reports
  - Purposefully simplify context and scenario for tractability
- This study focuses solely on *collaborative risk*
  - Use context of NPOESS to evaluate the usefulness of the proposed collaborative risk assessment methodology
  - Communicate and validate results of an analysis process

Conclusion and Future Work

- Two types of risk in collaborative projects:
  - —**Systemic risk**: cost, schedule, and technology uncertainty
  - —**Collaborative risk**: conflict and coordination failures
- Investigate Selten's risk dominance measure to assess collaborative risk from a game-theoretic perspective
- Demonstrate with application case based on NPOESS
  - —Define design space under collaborative/independent scenarios
  - —Model performance attributes for each design
  - —Model value preferences for each actor
  - —Assess risk dominance for strategic design game

Acknowledgements

- This material is based on work supported, in whole or in part, by the U.S. Department of Defense through the Systems Engineering Research Center (SERC) under Contract No. HQ0034-13-D-0004.
- Thanks to the graduate students working with me:
  - Ambrosio Valencia-Romero, Ph.D. Student Systems Engineering
  - Matthew Sabatini, M.E. Student in Space Systems Engineering
  - Henry Lee, M.E. Student in Space Systems Engineering

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