Game-theoretic Risk Assessment for Distributed Systems (GRADS)

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By
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11th Annual SERC Sponsor Research Review
November 19, 2019
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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

- **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 economic theory of Selten's (1995) Weighted Average Log Measure (WALM) of risk dominance

Framing Problem: Stag Hunt

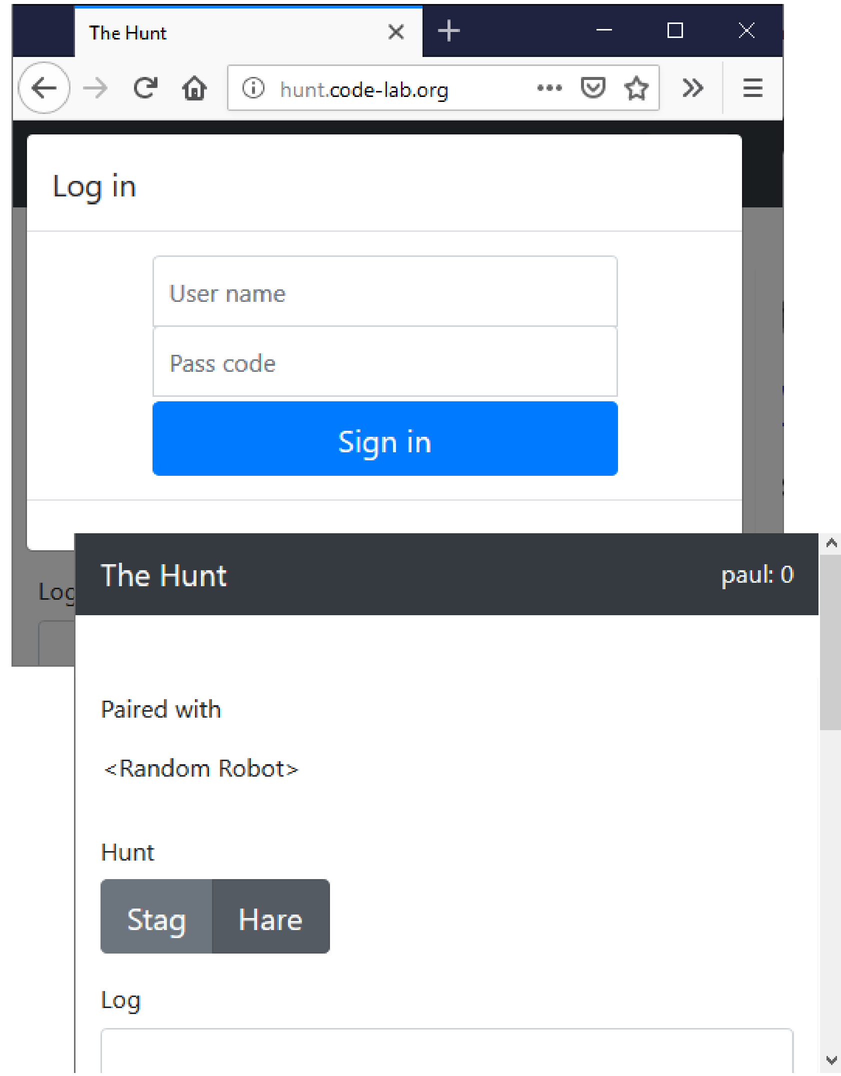
- Two hunters face a decision to either hunt **stag** or **hare**:
- Successful stag hunt yields *high reward* but requires *collaboration*
- Unsuccessful stag hunt yields *low or no reward* (!)
- Hare hunt yields *moderate reward* and can be pursued *independently*

Stag hunt by Gaston Phoebus
(Bibliotheque Nationale de France)

The Hunt Activity

- Connect to web application:
  - —http://hunt.code-lab.org
  - —Choose unique username (best if your real name!)
  - —Pass code is: **`atilla`**
- Three rounds of ~10 hunts:
  - —Choose either Stag or Hare
  - —High score demonstrates your Darwinian fitness!

FYI: source code available at: https://github.com/ptgrogan/hunt



Round 1

- Paired with a *Random Number Generator (Robot):*
  - —50% chance of selecting Stag
  - —50% chance of selecting Hare
- Play for about 10 rounds, cumulative score
- Update strategy anytime

You	Partner	Outcome
Stag	Stag	+4
Stag	Hare	+0
Hare	Hare	+2
Hare	Stag	+3

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Round 2

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- Paired with a *Hidden* partner:
  - —Paired with actual person in room *but do not know who*
  - —If odd number of participants, one is paired with robot
- Play for about 10 rounds, cumulative score
- Update strategy anytime

You	Partner	Outcome
Stag	Stag	+4
Stag	Hare	+0
Hare	Hare	+2
Hare	Stag	+3

Round 3

- Paired with a *Named* partner:
  - —Paired with actual person in room *and know their name*
  - —If odd number of participants, one is paired with robot
- Play for about 10 rounds, cumulative score
- Update strategy anytime

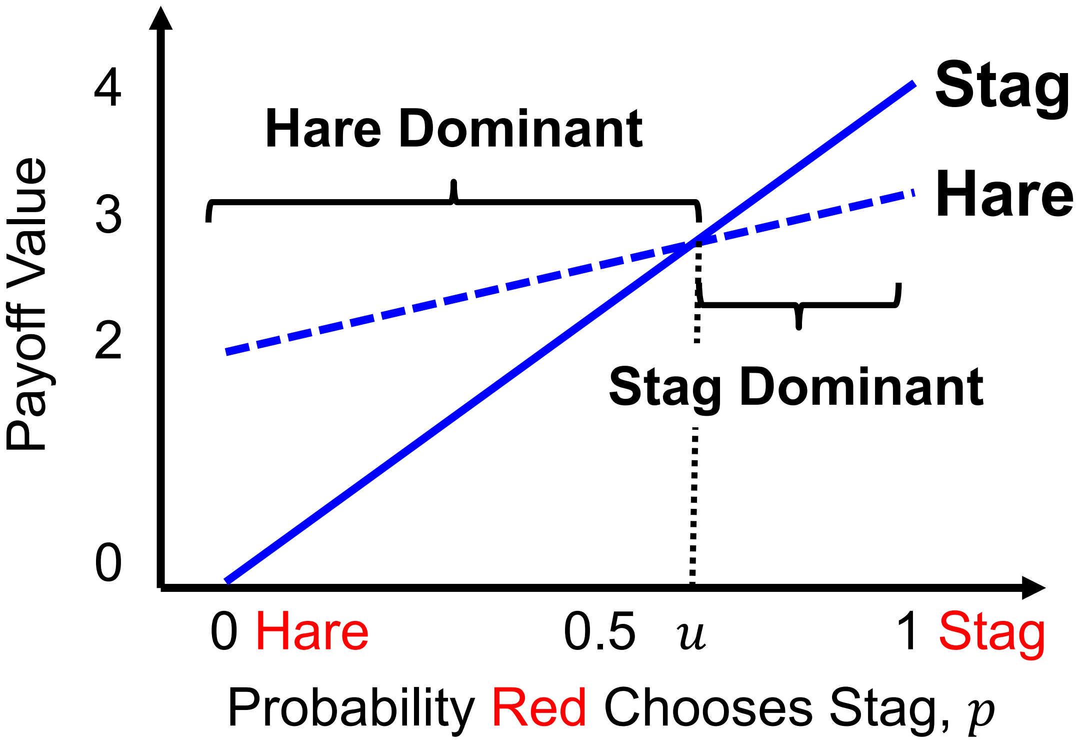
You	Partner	Outcome
Stag	Stag	+4
Stag	Hare	+0
Hare	Hare	+2
Hare	Stag	+3

Analysis: Stag Hunt Game

- Two pure Nash equilibria
  - Hare, Hare: risk-dominant equilibrium (minimize risk)
  - Stag, Stag: payoff-dominant equilibrium (maximize reward)

	Hare	Stag
Hare	2 / 2	3 / 0
Stag	0 / 3	4 / 4

Stag Hunt with Uncertainty



	Hare	Stag
Hare	2 2	0 3
Stag	3 0	4 4

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

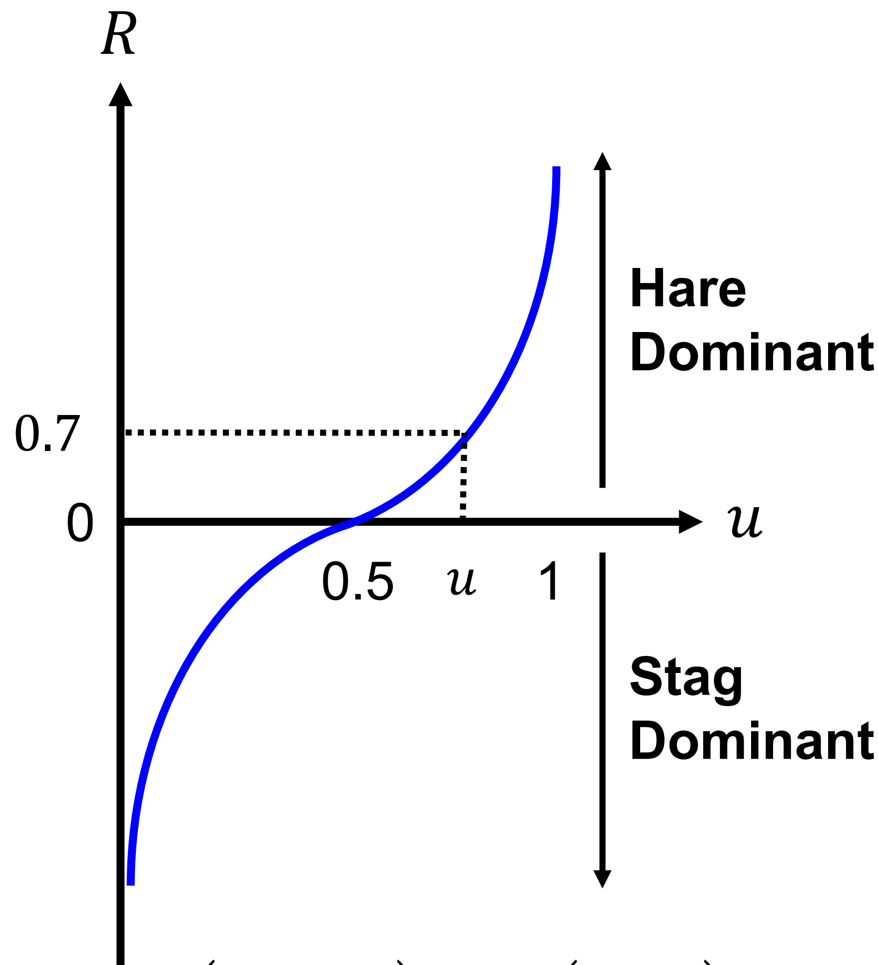
Risk Dominance Metric

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

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

- n-player general case:

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

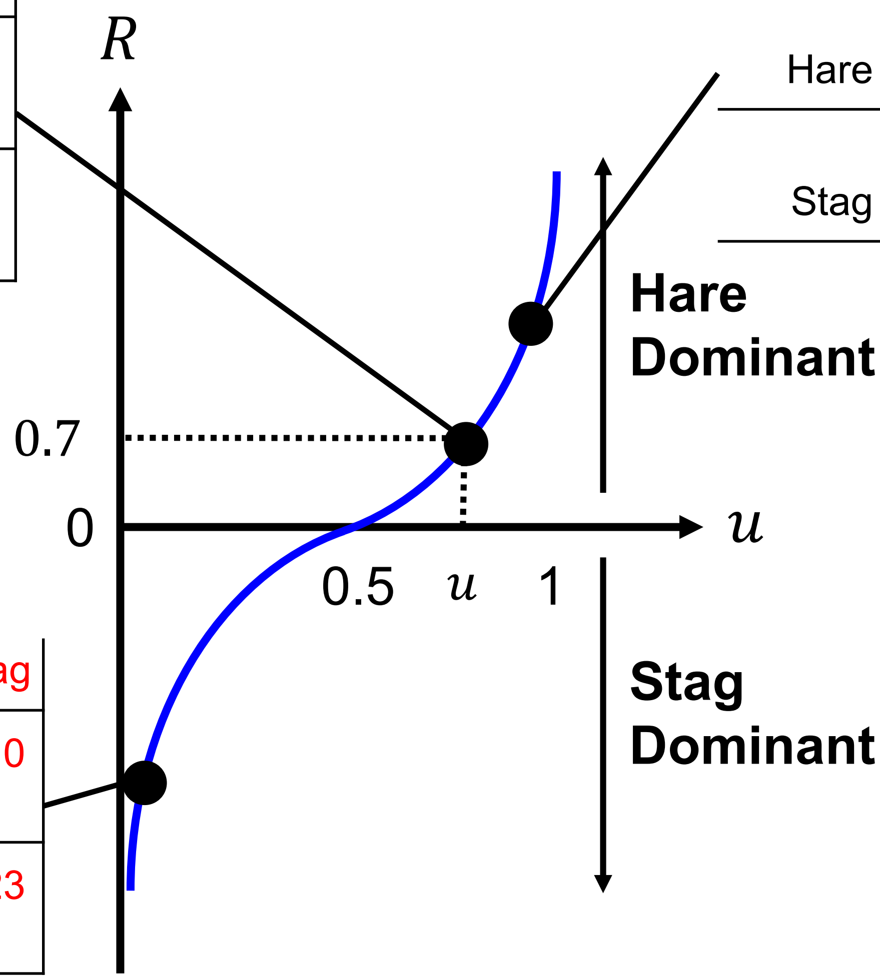


$$R = \ln\left(\frac{2/3}{1-2/3}\right) = \ln\left(\frac{2-0}{4-3}\right) \approx 0.7$$

Comparing Risk Dominance

$R = 0.7$	Hare	Stag
Hare	2 2	0 3
Stag	3 0	4 4

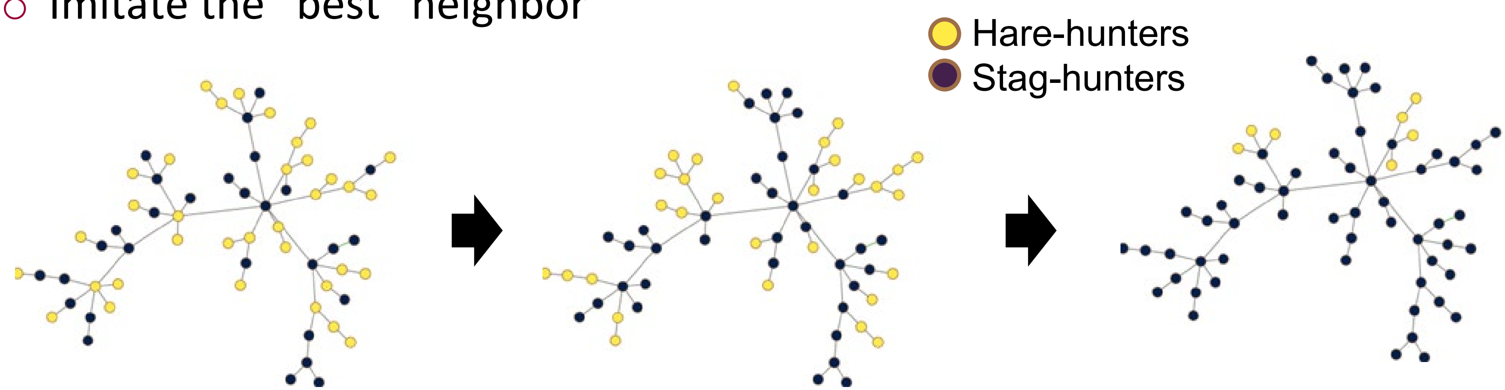
$R = 2.3$	Hare	Stag
Hare	2 2	-8 3
Stag	3 -8	4 4



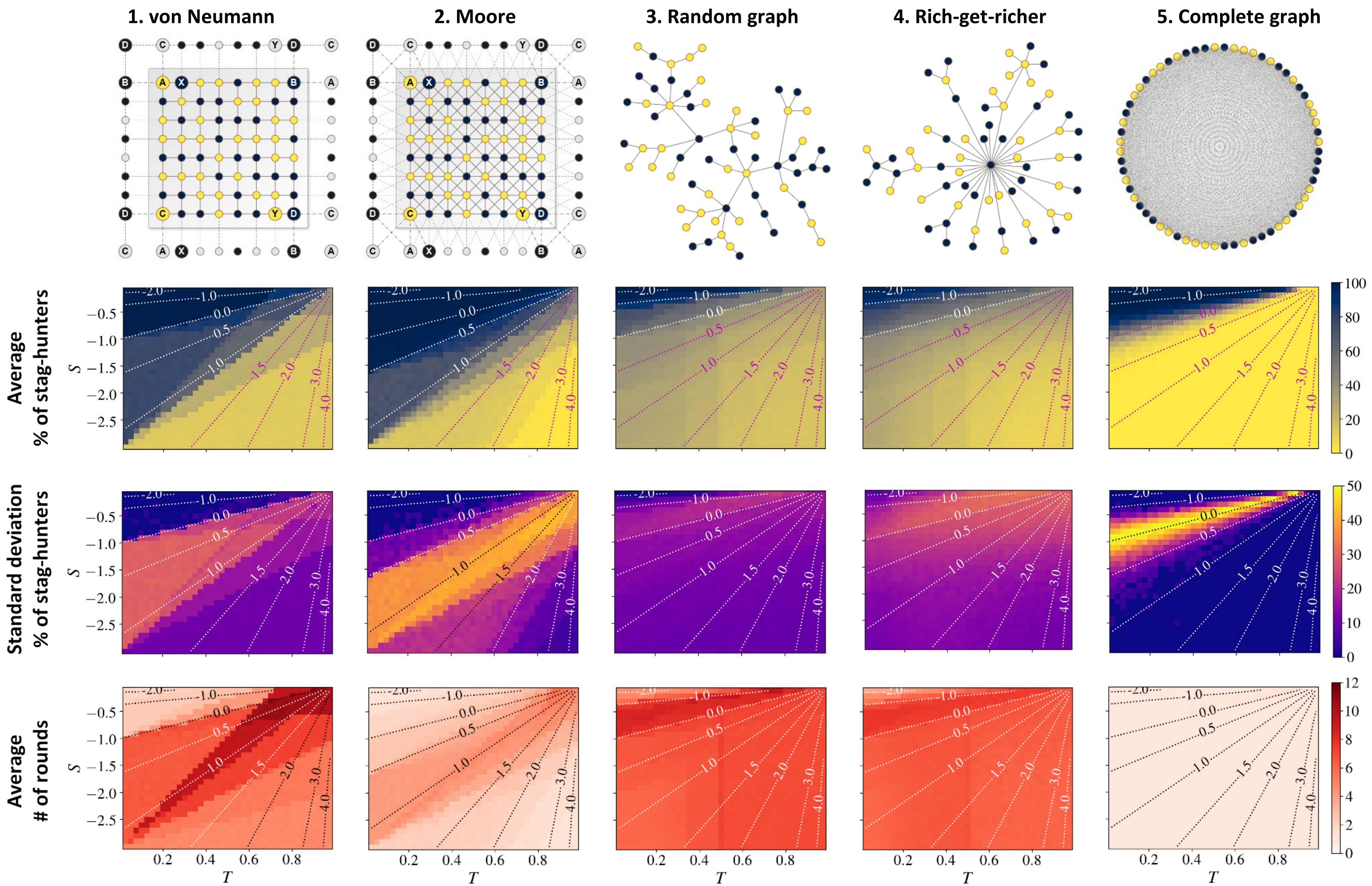
$R = -2.3$	Hare	Stag
Hare	2 2	0 3
Stag	3 0	23 23

Validation Study

- **Risk dominance an indicator for strategy selection?**
  - —Single-shot non-cooperative game theory: yes
  - —What about cooperative games with communication or learning?
- Simulate the formation and dissolution of collaborative partnerships between *pairs* of simulated agents
  - —Fixed interaction network structure, payoffs, and initial strategy selection
  - —Repeat until convergence:
    - Play stag hunt with neighbors
    - Imitate the “best” neighbor



Validation Results



Application Case: NPOESS

	Independent	Joint
Independent	DMSP POES	DMSP JPSS
Joint	DMSP* POES	NPOESS NPOESS

Stakeholder Value Models

- Five key architecture attributes driving stakeholder preference:
  1. **Cost**: quantity of resources required to support architecture
  2. **Observations**: types of phenomena that can be observed
  3. **Coverage**: frequency of observations at points of interest
  4. **Downlink**: capability to retrieve remote observations to a ground network
  5. **Latency**: time delay between downlink opportunities
- Quantify attributes for architecture d in modeling environment:

$$X_i(d)$$

- Multi-attribute (e.g. additive) utility functions to aggregate stakeholder value preferences:

$$V(d) = \sum_{i=1}^{5} w_i X_i(d)$$

Example Stakeholder Values

- **DoD**

Arch.	Cost (0.25)	Obs. (0.05)	Coverage (0.30)	Downlink (0.10)	Latency (0.30)	**Total Value**
DMSP	0.92	0.50	1.00	0.90	0.13	**0.68**
NPOESS	0.65	0.98	0.30	0.98	1.00	**0.72**
DMSP*	0.10	0.50	1.00	0.90	0.13	**0.43**

- **NOAA/NASA**

Arch.	Cost (0.25)	Obs. (0.05)	Coverage (0.30)	Downlink (0.10)	Latency (0.30)	**Total Value**
POES	0.92	0.12	0.92	0.33	0.70	**0.49**
NPOESS	0.60	0.98	0.92	0.98	1.00	**0.72**
JPSS	0.00	0.28	0.92	0.98	1.00	**0.46**

Analysis Results

	Independent	Joint
Ind.	DMSP: 0.68 POES: 0.49	DMSP: 0.68 JPSS: 0.46
Joint	DMSP*: 0.43 POES: 0.49	NPOESS: 0.72 NPOESS: 0.72

$$R = \frac{1}{2}\ln\left(\frac{u_{DoD}}{1-u_{DoD}}\right) + \frac{1}{2}\ln\left(\frac{u_{NOAA}}{1-u_{NOAA}}\right)$$
$$= \frac{1}{2}\ln\left(\frac{0.86}{0.24}\right) + \frac{1}{2}\ln\left(\frac{0.12}{0.88}\right)$$
$$= -0.07$$

- Joint program *slightly* risk dominant … desirable under cooperative game theory
- More attractive to NASA/NOAA ($u = 12\%$) than DoD ($u = 86\%$)
- Risk dominance could be used to evaluate other joint program architectures in tradespace analysis

Conclusion

- Two types of risk in collaborative projects:
  - **Systemic risk**: cost, schedule, and technology uncertainty
  - **Collaborative risk**: conflict and coordination failures
- Selten's risk dominance measure can be used to assess collaborative risk from a game-theoretic perspective
- Validated in multi-agent simulations with evolutionary dynamics
- Demonstrated in an example application case based on NPOESS
  - Describe strategic design scenario
  - Quantify stakeholder value
  - Analyze risk dominance and strategic dynamics
  - (Future) Explore alternative joint program architectures

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 for their contributions:
  - —Ambrosio Valencia-Romero, Ph.D. Candidate in Systems Engineering
  - —Matthew Sabatini, M.E. Student in Space Systems Engineering
  - —Henry Lee, M.E. Space Systems Engineering (Dec '18)

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Grogan, P.T. and A. Valencia-Romero (2019). "Strategic Risk Dominance in Collective Systems Design," *Design Science*, In press.