Game-theoretic Risk Assessment for Distributed Systems (GRADS)

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By
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FHI 360 CONFERENCE CENTER
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www.sercuarc.org
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
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*.

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*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
• 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

<table>
<thead>
<tr>
<th>You</th>
<th>Partner</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stag</td>
<td>Stag</td>
<td>+4</td>
</tr>
<tr>
<td>Stag</td>
<td>Hare</td>
<td>+0</td>
</tr>
<tr>
<td>Hare</td>
<td>Hare</td>
<td>+2</td>
</tr>
<tr>
<td>Hare</td>
<td>Stag</td>
<td>+3</td>
</tr>
</tbody>
</table>
Round 2

- 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

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<tbody>
<tr>
<td>Stag</td>
<td>Stag</td>
<td>+4</td>
</tr>
<tr>
<td>Stag</td>
<td>Hare</td>
<td>+0</td>
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<tr>
<td>Hare</td>
<td>Hare</td>
<td>+2</td>
</tr>
<tr>
<td>Hare</td>
<td>Stag</td>
<td>+3</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
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<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stag</td>
<td>Stag</td>
<td>+4</td>
</tr>
<tr>
<td>Stag</td>
<td>Hare</td>
<td>+0</td>
</tr>
<tr>
<td>Hare</td>
<td>Hare</td>
<td>+2</td>
</tr>
<tr>
<td>Hare</td>
<td>Stag</td>
<td>+3</td>
</tr>
</tbody>
</table>
Analysis: Stag Hunt Game

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

<table>
<thead>
<tr>
<th></th>
<th>Hare</th>
<th>Stag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hare</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td>Stag</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td></td>
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<td>4</td>
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</table>
Stag Hunt with Uncertainty

- $p > u$: 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

\[ R = 0.7 \]

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<tr>
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<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Stag</td>
<td>0</td>
<td>4</td>
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\[ R = -2.3 \]

<table>
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<tr>
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<tbody>
<tr>
<td>Hare</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Stag</td>
<td>0</td>
<td>23</td>
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</table>

\[ R = 2.3 \]

<table>
<thead>
<tr>
<th></th>
<th>Hare</th>
<th>Stag</th>
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</thead>
<tbody>
<tr>
<td>Hare</td>
<td>2</td>
<td>-8</td>
</tr>
<tr>
<td>Stag</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
• 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:
    o Play stag hunt with neighbors
    o Imitate the “best” neighbor
Validation Results

1. von Neumann

2. Moore

3. Random graph

4. Rich-get-richer

5. Complete graph

**Validation Results**

### 1. von Neumann

- **Average % of stag-hunters**
- **Standard deviation % of stag-hunters**
- **Average # of rounds**

- **Graph Representation**

### 2. Moore

- **Average % of stag-hunters**
- **Standard deviation % of stag-hunters**
- **Average # of rounds**

- **Graph Representation**

### 3. Random graph

- **Average % of stag-hunters**
- **Standard deviation % of stag-hunters**
- **Average # of rounds**

- **Graph Representation**

### 4. Rich-get-richer

- **Average % of stag-hunters**
- **Standard deviation % of stag-hunters**
- **Average # of rounds**

- **Graph Representation**

### 5. Complete graph

- **Average % of stag-hunters**
- **Standard deviation % of stag-hunters**
- **Average # of rounds**

- **Graph Representation**
### Application Case: NPOESS

#### Independent
- DMSP
- POES

#### Joint
- DMSP
- JPSS
- NPOESS
- NPOESS

<table>
<thead>
<tr>
<th>Independent</th>
<th>Joint</th>
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<tr>
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<tr>
<td></td>
<td>Joint</td>
</tr>
<tr>
<td></td>
<td>NPOESS</td>
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<tr>
<td></td>
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**Diagram:**
- NOAA
- NASA
- Department of Defense

**Logos:**
- Systems Engineering Research Center
- Stevens Institute of Technology
- U.S. Department of Commerce
• 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**

<table>
<thead>
<tr>
<th>Arch.</th>
<th>Cost (0.25)</th>
<th>Obs. (0.05)</th>
<th>Coverage (0.30)</th>
<th>Downlink (0.10)</th>
<th>Latency (0.30)</th>
<th>Total Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMSP</td>
<td>0.92</td>
<td>0.50</td>
<td>1.00</td>
<td>0.90</td>
<td>0.13</td>
<td>0.68</td>
</tr>
<tr>
<td>NPOESS</td>
<td>0.65</td>
<td>0.98</td>
<td>0.30</td>
<td>0.98</td>
<td>1.00</td>
<td>0.72</td>
</tr>
<tr>
<td>DMSP*</td>
<td>0.10</td>
<td>0.50</td>
<td>1.00</td>
<td>0.90</td>
<td>0.13</td>
<td>0.43</td>
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**NOAA/NASA**

<table>
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<tr>
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<th>Latency (0.30)</th>
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<tbody>
<tr>
<td>POES</td>
<td>0.92</td>
<td>0.12</td>
<td>0.92</td>
<td>0.33</td>
<td>0.70</td>
<td>0.49</td>
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<tr>
<td>NPOESS</td>
<td>0.60</td>
<td>0.98</td>
<td>0.92</td>
<td>0.98</td>
<td>1.00</td>
<td>0.72</td>
</tr>
<tr>
<td>JPSS</td>
<td>0.00</td>
<td>0.28</td>
<td>0.92</td>
<td>0.98</td>
<td>1.00</td>
<td>0.46</td>
</tr>
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### Analysis Results

<table>
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<td>DMSP: 0.68</td>
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<td>POES: 0.49</td>
<td>NPOESS: 0.72</td>
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\[
R = \frac{1}{2} \ln \left( \frac{u_{\text{DoD}}}{1-u_{\text{DoD}}} \right) + \frac{1}{2} \ln \left( \frac{u_{\text{NOAA}}}{1-u_{\text{NOAA}}} \right) \\
= \frac{1}{2} \ln \left( \frac{0.86}{0.24} \right) + \frac{1}{2} \ln \left( \frac{0.12}{0.88} \right) \\
= -0.07
\]

- **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

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  — Henry Lee, M.E. Space Systems Engineering (Dec ‘18)

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