Game-theoretic Risk Assessment for Distributed Systems (GRADS)

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By

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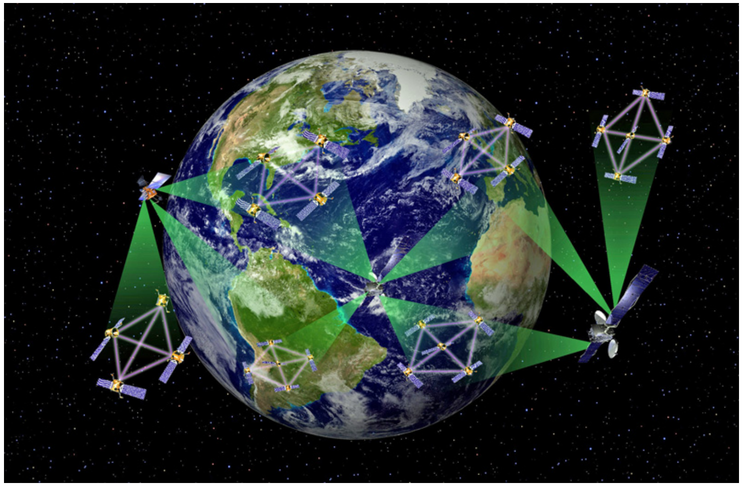
Distributed System Architectures

Upside Potential

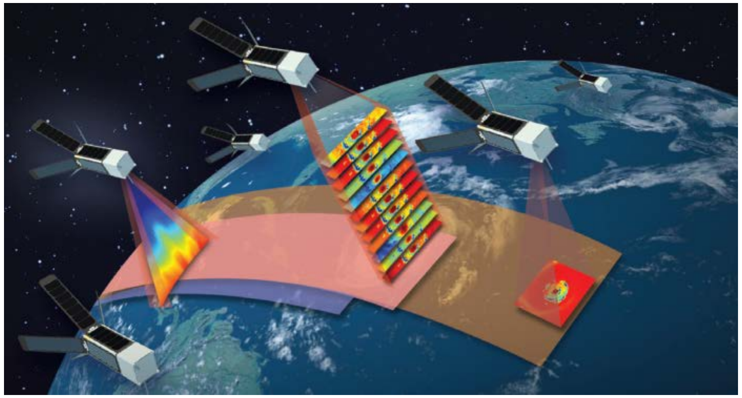
- Flexibility, robustness
- Resource efficiency – decentralization theorem

Downside Risk

- Interdependencies leading to cascading failures
- "Robust-yet-fragile" (Alderson and Doyle, 2010)



System F6 Concept (DARPA)



TROPICS Mission Concept (NASA, Lincoln Labs)

Research Questions

- **How to assess the strategic risk of distributed systems?**
  - Tradeoff between expected upside and possible downside
  - Strategic risk: decision stability (*NOT* uncertainty in value)
  - Evaluate an objective risk metric based on Selten's (1995) Weighted Average Log Measure (WALM) of risk dominance
- Use a stylized model of federated satellite systems:
  - Build on existing work with $n = 2$ symmetric players:

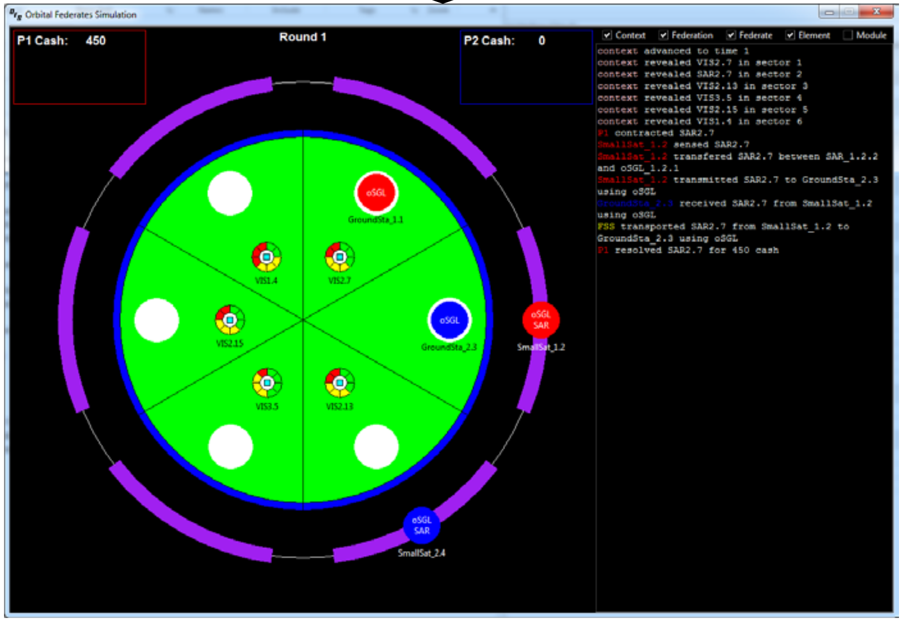
    P.T. Grogan, K. Ho, A. Golkar, and O.L. de Weck, "Multi-actor Value Modeling for Federated Systems," *IEEE Systems*, 2016. Early access.
  - Investigate asymmetric and $n > 2$ player strategic design games
  - Develop method in simplified *Orbital Federates* design context

Orbital Federates Model

Board game to study collective decisions in federated satellite systems (Grogan and de Weck, 2015)

Python simulation (OFS-PY)
github.com/ptgrogan/ofspy

Design and strategy decisions, RNG seed



Initial cost and final value outcomes

Orbital Federates Design Scenario A

Monolithic (ϕ) Strategy: no interaction between players

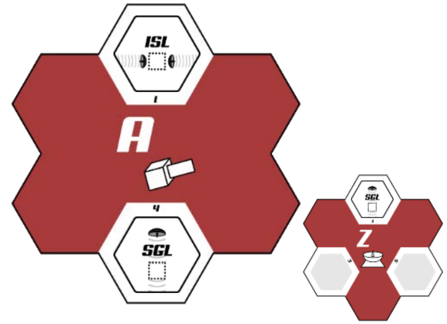
Distributed (ψ) Strategy: opportunistic data exchange: 100 for space-to-ground link (SGL), 100 for inter-satellite link (ISL)

d_1^{ϕ}

$$v_1^{\phi} = 0$$

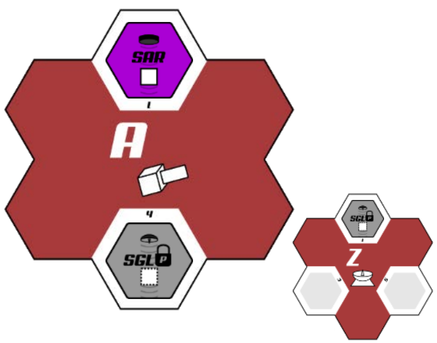
NPV with 1000 samples, 2% discount rate

d_1



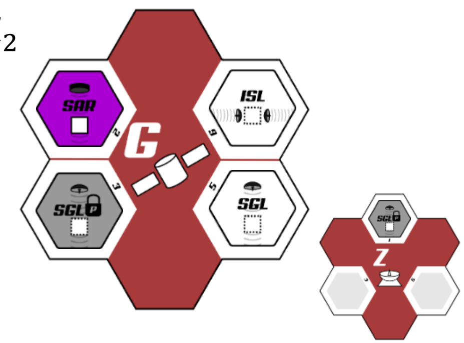
$$V_1^{\psi}(d_1, d_2, d_3) = 100$$

d_2^{ϕ}



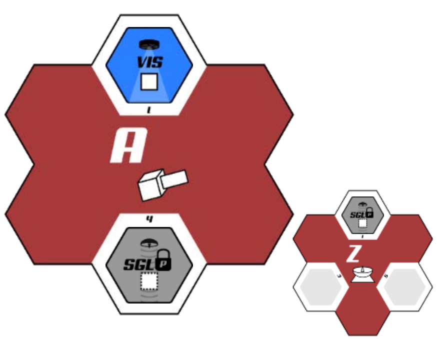
$$v_2^{\phi} = -39$$

d_2



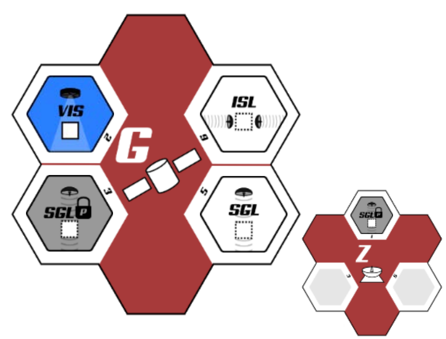
$$V_2^{\psi}(d_1, d_2, d_3) = 536$$

d_3^{ϕ}



$$v_3^{\phi} = 30$$

d_3



$$V_3^{\psi}(d_1, d_2, d_3) = 639$$

Foundation: Stag Hunt Game

	Hare (ϕ)	Stag (ψ)
Hare (ϕ)	2, 2	4, 0
Stag (ψ)	0, 4	5, 5

- Symmetric coordination game
- Two pure Nash equilibria:
  - —Risk-minimizing (Hare)
  - —Payoff-maximizing (Stag)
- How to select strategy?

Stag hunt by Gaston Phoebus
(Bibliotheque Nationale de France)

Equilibrium Selection Theory

- Harsanyi and Selten (1972): *Generalized Nash Solution for Two-person Bargaining Games*
  - —Efficient solutions maximize *product* of cooperative gains
  - —Generalized solution extends to incomplete information
- Harsanyi and Selten (1988): *A General Theory of Equilibrium Selection in Games*
  - —"Tracing" procedure to select risk dominant equilibrium
- Selten (1995): *Axiomatic Theory of Risk Dominance for Bipolar Games with Linear Incentives*
  - —Scalar measure to assess risk dominance

Deviation Losses

- Risk dominance based on concept of "deviation loss"
- Deviation loss measures utility loss if a player moves away from an equilibrium

$$L_i(\phi) \propto 2 - 0 = 2$$
$$L_i(\psi) \propto 5 - 4 = 1$$

- Deviation loss ratio measures relative losses between two equilibria

$$\lambda_i(\phi, \psi) = \frac{L_i(\phi)}{L_i(\psi)} = \frac{2}{1} = 2$$

	Hare (ϕ)	Stag (ψ)
Hare (ϕ)	2, 2	4, 0
Stag (ψ)	0, 4	5, 5

Risk Dominance

- Normalized deviation losses

$$u_i = \frac{L_i(\phi)}{L_i(\phi) + L_i(\psi)}$$

- Influence weights $w_i(A)$ measure the importance of one player on others' stability

	Hare (ϕ)	Stag (ψ)
Hare (ϕ)	2 2	4 0
Stag (ψ)	0 4	5 5

- Weighted average log measure (WALM) of risk:

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

  - $R_\psi > 0$: ϕ is "risk dominant"
  - $R_\psi < 0$: ψ is "risk dominant"

$$R(u, A) = 0.5 \ln\left(\frac{2}{1}\right) + 0.5 \ln\left(\frac{2}{1}\right)$$

$$= \ln\left(\frac{2-0}{5-4}\right) = 0.69$$

- Hare is risk dominant equilibrium in this game

$n = 2$ Asymmetric Design Games

- Can maximize value under independent strategy

$$\mathcal{V}_i^{\phi} = \max_{d \in \mathcal{D}_i} V_i(d_i)$$

- Collective value is a function of candidate designs $d_i, \ldots$

$$V_i(d_i), \qquad V_i^{\psi}(d_i, \ldots)$$

	Indep. (ϕ)	Collect. (ψ)
Indep. (ϕ)	$\mathcal{V}_1^{\phi}$ $\mathcal{V}_2^{\phi}$	$\mathcal{V}_1^{\phi}$ $V_2(d_2)$
Collect. (ψ)	$V_1(d_1)$ $\mathcal{V}_2^{\phi}$	$V_1^{\psi}(d_1, d_2)$ $V_2^{\psi}(d_1, d_2)$

$$R_{\psi}(d_1, d_2) = \sum_{i=1}^{2} \frac{1}{2} \ln\left(\frac{\mathcal{V}_i^{\phi} - V_i(d_i)}{V_i^{\psi}(d_1, d_2) - \mathcal{V}_i^{\phi}} \right)$$

$n = 3$ Asymmetric Design Games

	Indep. (ϕ)	Collect. (ψ)
Indep. (ϕ)	$\mathcal{V}_1^{\phi}$ $\mathcal{V}_2^{\phi}$ $\mathcal{V}_3^{\phi}$	$\mathcal{V}_1^{\phi}$ $V_2(d_2)$ $\mathcal{V}_3^{\phi}$
Collect. (ψ)	$V_1(d_1)$ $\mathcal{V}_2^{\phi}$ $\mathcal{V}_3^{\phi}$	$V_1^{\psi}(d_1, d_2)$ $V_2^{\psi}(d_1, d_2)$ $\mathcal{V}_3^{\phi}$

Indep. (ϕ)

	Indep. (ϕ)	Collect. (ψ)
Indep. (ϕ)	$\mathcal{V}_1^{\phi}$ $\mathcal{V}_2^{\phi}$ $V_3(d_3)$	$\mathcal{V}_1^{\phi}$ $V_2^{\psi}(d_2, d_3)$ $V_3^{\psi}(d_2, d_3)$
Collect. (ψ)	$V_1^{\psi}(d_1, d_3)$ $\mathcal{V}_2^{\phi}$ $V_3^{\psi}(d_1, d_3)$	$V_1^{\psi}(d_1, d_2, d_3)$ $V_2^{\psi}(d_1, d_2, d_3)$ $V_3^{\psi}(d_1, d_2, d_3)$

Collect. (ψ)

$$R_{\psi}(d_1, d_2, d_3) = \sum_{i=1}^{3} w_i(A) \ln \left(\frac{\mathcal{V}_i^{\phi} - V_i(d_i)}{V_i^{\psi}(d_1, d_2, d_3) - \mathcal{V}_i^{\phi}} \right)$$

Orbital Federates Design Scenario A

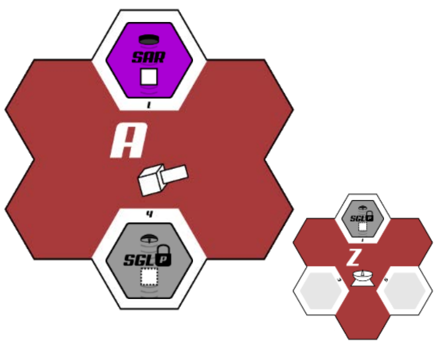
Monolithic (ϕ) Strategy: no interaction between players

d_1^{ϕ}

$$\boldsymbol{v_1^{\phi} = 0}$$

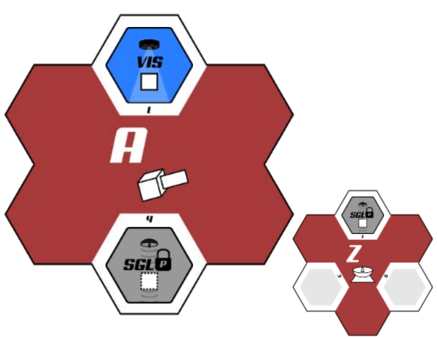
NPV with 1000 samples, 2% discount rate

d_2^{ϕ}



$$\boldsymbol{v_2^{\phi} = -39}$$

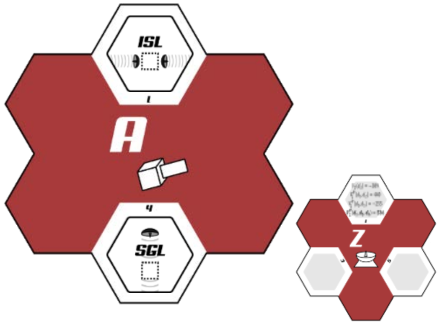
d_3^{ϕ}



$$\boldsymbol{v_3^{\phi} = 30}$$

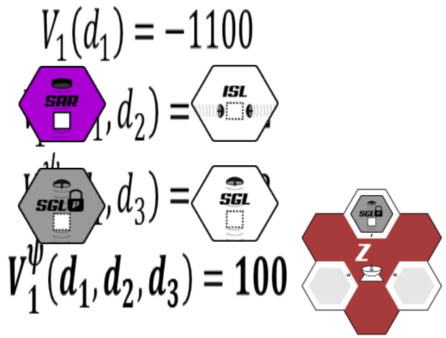
Distributed (ψ) Strategy: opportunistic data exchange: 100 for space-to-ground link (SGL), 100 for inter-satellite link (ISL)

d_1



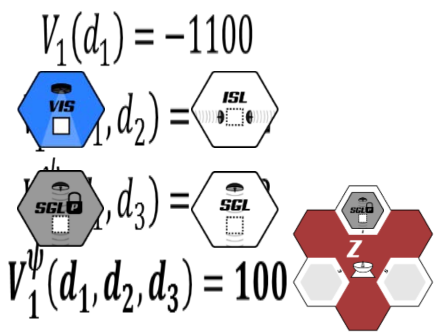
$$V_1(d_1) = -1100$$
$$V_1^{\psi}(d_1, d_2) = -572$$
$$V_1^{\psi}(d_1, d_3) = -653$$
$$\boldsymbol{V_1^{\psi}(d_1, d_2, d_3) = 100}$$

d_2



$$V_2(d_2) = -389$$
$$V_2^{\psi}(d_1, d_2) = 440$$
$$V_2^{\psi}(d_2, d_3) = -255$$
$$\boldsymbol{V_2^{\psi}(d_1, d_2, d_3) = 536}$$

d_3



$$V_3(d_3) = -320$$
$$V_3^{\psi}(d_1, d_3) = 386$$
$$V_3^{\psi}(d_2, d_3) = -158$$
$$\boldsymbol{V_3^{\psi}(d_1, d_2, d_3) = 639}$$

Strategic Design Game A

	Mono. (ϕ)	Distrib. (ψ)
Mono. (ϕ)	0 -39 30	0 -389 30
Distrib. (ψ)	-1100 -39 30	-572 440 30

Mono. (ϕ)

	Mono. (ϕ)	Distrib. (ψ)
Mono. (ϕ)	0 -39 -320	0 -255 -158
Distrib. (ψ)	-652 -39 386	100 536 639

Distrib. (ψ)

Player Weights and Risk Dominance

$$\ln\left(\frac{u}{1-u}\right) = \begin{bmatrix} 2.40 \\ -0.50 \\ -0.55 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 0.533 & 0.467 \\ 0.876 & 0 & 0.124 \\ 0.783 & 0.217 & 0 \end{bmatrix}, \qquad w(A) = \begin{bmatrix} 0.455 \\ 0.296 \\ 0.249 \end{bmatrix}$$

$$R_\psi = 0.455 \cdot 2.40 - 0.296 \cdot 0.50 - 0.249 \cdot 0.55 = 0.80$$

- Players do not have equal influences on stability
  - Player 1 is most influential on stability, sees ψ as very unstable
  - Players 2 and 3 have similar influence on stability, see ψ as more stable
- $R_\psi > 0$: Monolithic/independent strategy ϕ is “risk dominant”

Orbital Federates Design Scenario B

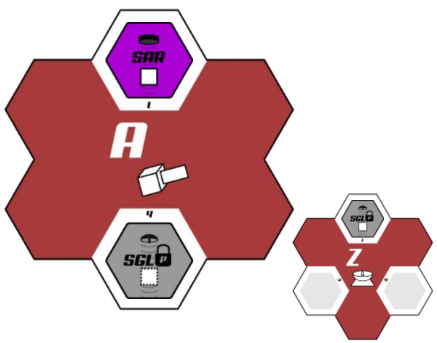
Monolithic (ϕ) Strategy: no interaction between players

d_1^ϕ

$\boldsymbol{v_1^\phi = 0}$

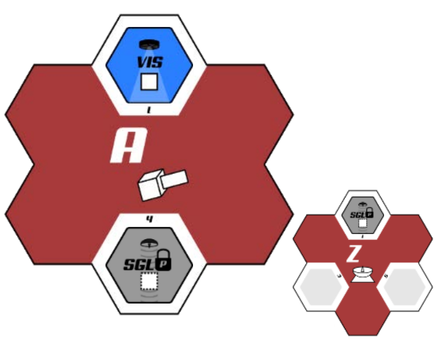
NPV with 1000 samples, 2% discount rate

d_2^ϕ



$\boldsymbol{v_2^\phi = -39}$

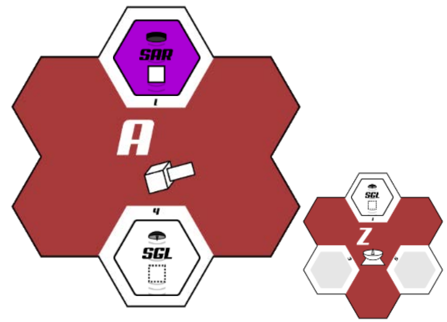
d_3^ϕ



$\boldsymbol{v_3^\phi = 30}$

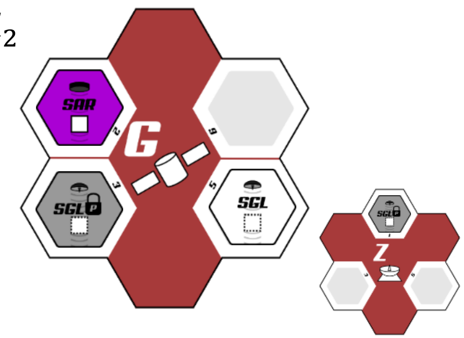
Distributed (ψ) Strategy: opportunistic data exchange: 100 for space-to-ground link (SGL), 100 for inter-satellite link (ISL)

d_1



$$V_1(d_1) = -104$$
$$V_1^\psi(d_1, d_2) = 83$$
$$V_1^\psi(d_1, d_3) = 33$$
$$\boldsymbol{V_1^\psi(d_1, d_2, d_3) = 271}$$

d_2



$$V_2(d_2) = -288$$
$$V_2^\psi(d_1, d_2) = 141$$
$$V_2^\psi(d_2, d_3) = -288$$
$$\boldsymbol{V_2^\psi(d_1, d_2, d_3) = 150}$$

d_3

$$V_3(d_3) = -220$$
$$V_3^\psi(d_1, d_3) = 391$$
$$V_3^\psi(d_2, d_3) = -161$$
$$\boldsymbol{V_3^\psi(d_1, d_2, d_3) = 378}$$

Strategic Design Game B

	Mono. (ϕ)	Distrib. (ψ)
Mono. (ϕ)	0 / -39 / 30	0 / -288 / 30
Distrib. (ψ)	-104 / -39 / 30	83 / 141 / 30

Mono. (ϕ)

	Mono. (ϕ)	Distrib. (ψ)
Mono. (ϕ)	0 / -39 / -220	0 / -288 / -161
Distrib. (ψ)	33 / -39 / 391	271 / 150 / 378

Distrib. (ψ)

Player Weights and Risk Dominance

$$\ln\left(\frac{u}{1-u}\right) = \begin{bmatrix} -0.96 \\ 0.28 \\ -0.33 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 0.566 & 0.434 \\ 0.989 & 0 & 0.011 \\ 0.961 & 0.039 & 0 \end{bmatrix}, \qquad w(A) = \begin{bmatrix} 0.494 \\ 0.288 \\ 0.218 \end{bmatrix}$$

$$R_\psi = -0.494 \cdot 0.96 + 0.288 \cdot 0.28 - 0.218 \cdot 0.33 = -0.46$$

- Players do not have equal influences on stability
  - Player 1 is most influential on stability, sees ψ as more stable
  - Players 2 and 3 have similar influence on stability
  - Player 2 sees ϕ as more stable, player 3 sees ψ as more stable
- $R_\psi > 0$: Distributed/collective strategy ψ is "risk dominant"

Strategic Risk Assessment

Design Scenario A

- High(er) payoffs for distributed system concepts
  - Player 1 (most influential) is at unstable local equilibrium: fears large losses of uncorroborated collective action
  - Players 2 and 3 are more stable, but not significant enough to change strategic risk
- Strategic risk assessment: monolithic system is more stable

Design Scenario B

- Low(er) payoffs for distributed system concepts
  - Player 1 (most influential) is at stable local equilibrium: benefits from independent value generation
  - Player 2 is at unstable local equilibrium, but not significant enough to change strategic risk
- Strategic risk assessment: distributed system is more stable

Extension and Future Work

Applications to Systems Engineering practice:

- Tradespace analysis
  - Assess WALM risk dominance for enumerated design space
  - Eliminate high-payoff but unstable design alternatives
- Strategy analysis
  - Assess WALM risk dominance for collective strategies (operational rules for player interactions)
  - Identify "good" strategies which stabilize high-payoff designs

Necessary steps to advance GRADS research:

- Theoretical extensions:
  - Currently violates "linear incentives" assumption
  - How to practically but rigorously quantify deviation losses?
- Practical extensions:
  - Develop multi-actor value function for real-world system (space or non-space domain)
  - Assess WALM risk of alternative architectures if a bipolar game

Questions?

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