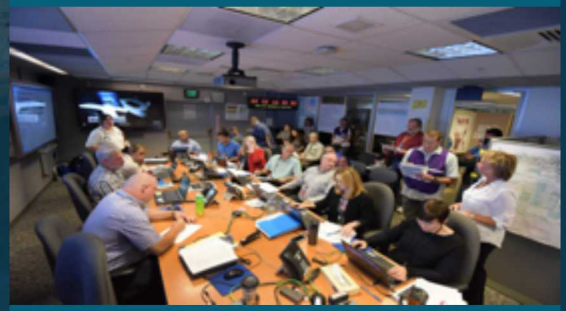
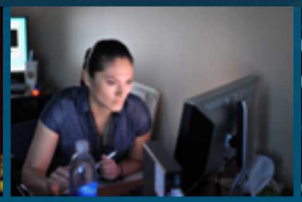
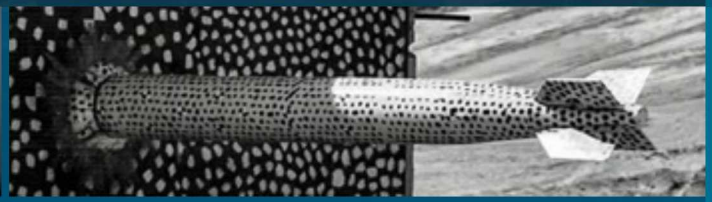
SAND2020-8240C

Sandia National Laboratories

Complexity of Wargames







Presented by: Kiran Lakkaraju

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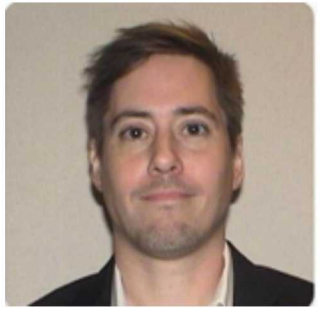
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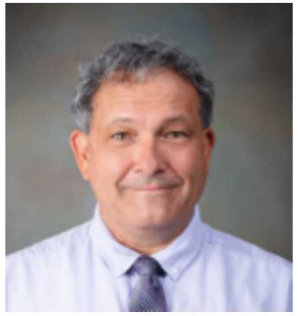
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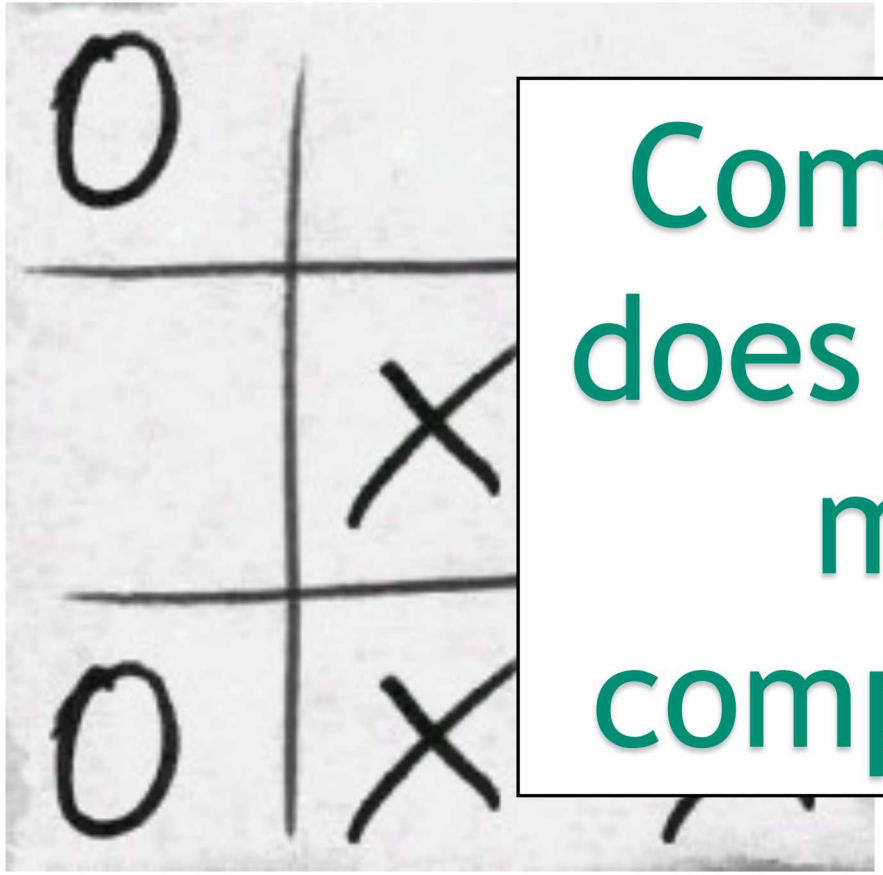
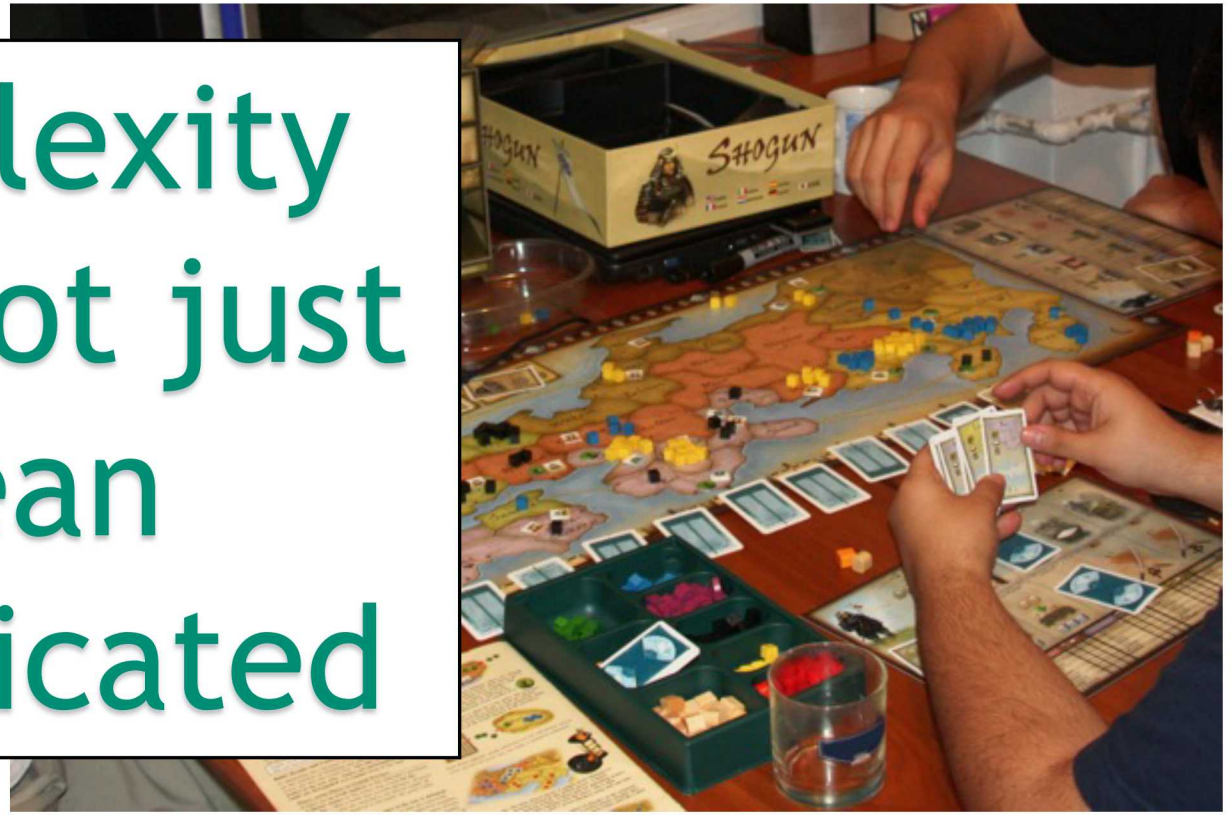
What does it mean for a wargame to be complex?



Complexity does not just mean complicated



https://commons.wikimedia.org/wiki/File:Tic_Tac_Toe.jpg

https://commons.wikimedia.org/wiki/File:Playin_Shogun_board_game.jpg

Goal

Initial effort to define and implement methods for measuring the complexity of wargames across a diversity of metrics.

Complexity might provide a bridge between wargames and real-world systems

- Organize information
- Allow comparisons between wargames and behaviors within wargames.
- Increase reusability
- Potentially improve understanding

Process:

- Identify a set of appropriate complexity metrics
  - Leverage metrics from assessment of social simulations within the Ground Truth project.
- Apply complexity metrics to four different wargames
  - Compare results along multiple dimensions

Complexity Metrics

Measuring Complexity: Considerations

Many definitions of complexity – how do we capture what is important?

Want to capture complexity of the actors, environments, interactions, and outputs of a wargame

- And compare to the associated real world system, if possible

Existing metrics capture particular dimensions, but we want a broader span

- An organized combination of methods might capture a broader span of dimensions

Organizing Structure: Two Dimensions

Dimension 1: Tie to social sciences

- If metric is inspired by real-world social complexity metrics, there is an obvious tie to real-world systems
- If not, the metric might be more broadly applicable to a variety of topics

Dimension 2: Knowledge of system's causal structure

- Some dimensions of complexity may be tied to causal structure
- Metrics that don't rely on causal structure might be more broadly applicable
  - For example, to real-world systems

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	**Measures of System Intricacy** *How complicated is the causal structure?*	**Measures of Behavioral Capacity** *How do interactions and behaviors of actors affect complexity?*
Does not require knowledge of system structure	**Measures of State Space** *How many states or decisions are possible?*	**Measures of Social Organization** *How organized are social relationships in the wargame?*

Defining the Ground Truth for a Wargame

Fundamental concept is *causality*

Nodes include

- Player decisions/actions within the game
- Non-player consequences of actions
- Non-player/environmental occurrences that are exogenous from player decisions but affect players

Edges in decision graph represent causal implications of an action

Complexity Metric: Causal Complexity

Causal Complexity: measure of system intricacy of the ground truth

- $C=M*(1+D)$
  - C = causal complexity
    M = cyclomatic complexity
    D = feedback density

Cyclomatic Complexity: captures the interconnectedness of a graph

- $M=E-N+2P$
  - M= cyclomatic complexity
    N= nodes in the graph
    E= edges in the graph
    P= connected components

Feedback Density: fraction of ground truth edges and nodes that are involved in feedback loops (cycles)

- $D=(E\_loop+N\_loop)/(E\_total+N\_total)$
  - D = feedback density
    Eloop = edges that are included in at least one feedback loop
    Nloop = nodes that are involved in at least one feedback loop
    Etotal = total edges
    Ntotal = total nodes

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	**Measures of System Intricacy** *How complicated is the causal structure?*	**Measures of Behavioral Capacity** *How do interactions and behaviors of actors affect complexity?*
Does not require knowledge of system structure	**Measures of State Space** *How many states or decisions are possible?*	**Measures of Social Organization** *How organized are social relationships in the wargame?*

Complexity Metric: Number of Decisions

Number of distinct types of decisions that can be made by players

Relatively simple metric

- Further extensions might include extension to capturing the full space of potential decisions, or the full state space of the wargame

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	**Measures of System Intricacy** *How complicated is the causal structure?*	**Measures of Behavioral Capacity** *How do interactions and behaviors of actors affect complexity?*
Does not require knowledge of system structure	**Measures of State Space** *How many states or decisions are possible?*	**Measures of Social Organization** *How organized are social relationships in the wargame?*

Complexity Metric: Number of Differentiated Relationships

Number of distinct mechanisms that players in the wargame can use to interact with each other

Used in the social sciences to measure complexity of animal groups

Generalizable across wargames, since it allows for the definition of relationship to be tailored to the game

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	**Measures of System Intricacy** *How complicated is the causal structure?*	**Measures of Behavioral Capacity** *How do interactions and behaviors of actors affect complexity?*
Does not require knowledge of system structure	**Measures of State Space** *How many states or decisions are possible?*	**Measures of Social Organization** *How organized are social relationships in the wargame?*

Complexity Metric: Global Reaching Centrality

Measure of hierarchy in a social network

Quantifies hierarchy by considering the distribution of reach centralities within a network

$$GRC = \sum_{i \in V} \frac{[C_R^{\max} - C_R(i)]}{(N-1)}$$

	Not tied to social sciences	Inspired by the social sciences
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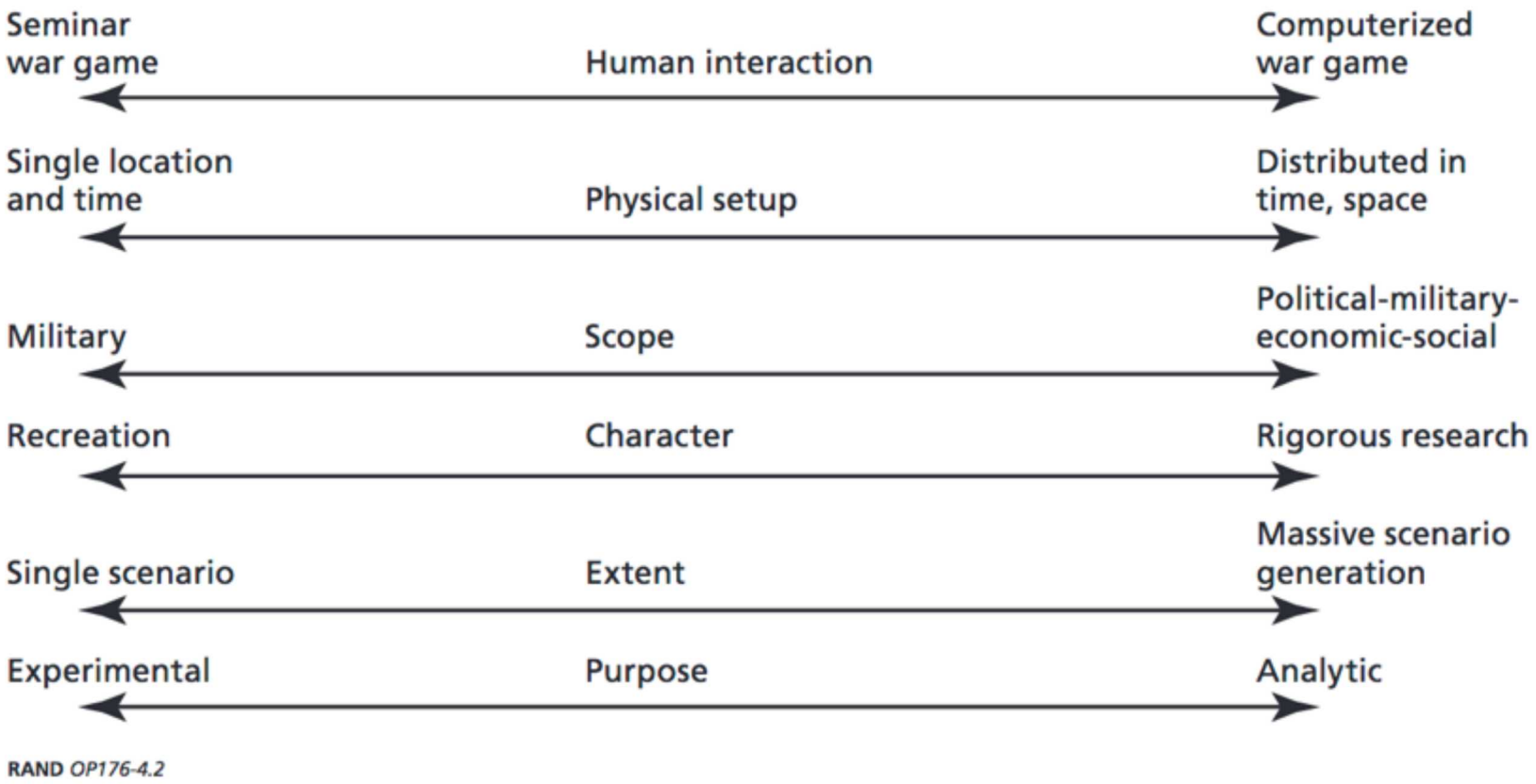
Mones, E., Vicsek, L., & Vicsek, T. (2012). Hierarchy measure for complex networks. PloS one, 7(3), e33799.

Wargames

Selected Wargames to Span Characteristics



Davis, P. K., & Henninger, A. E. (2007). *Analysis, analysis practices, and implications for modeling and simulation* (Vol. 176). Rand Corporation.

Selected Wargames to Span Characteristics

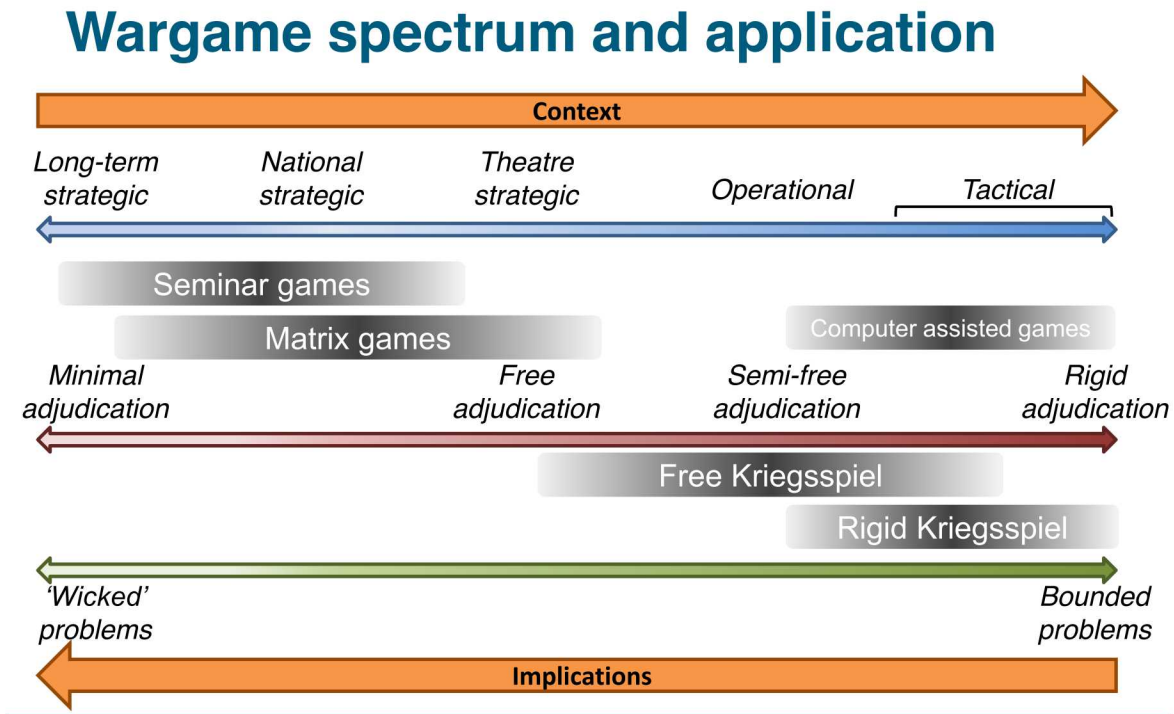


Diagram from: C. Marston. Wargaming in the uk. Presented at the 2016 Connections UK Conference, 2016.

Wargames Included In This Analysis

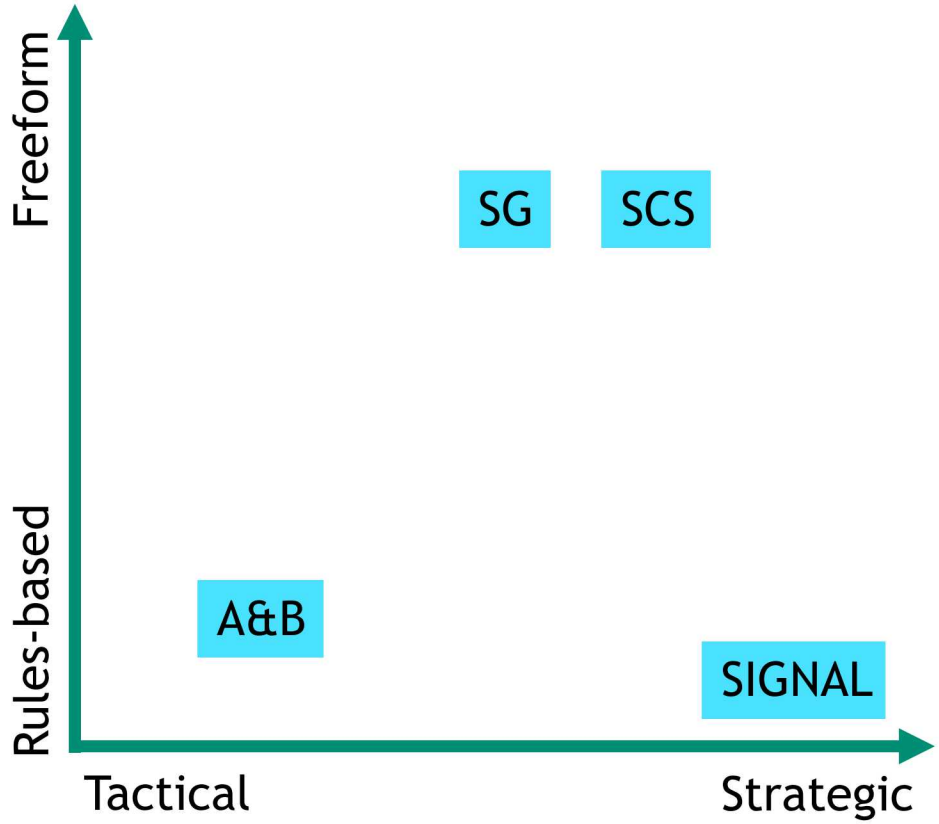
Angels & Bears (A&B)

MaGCK (SG)

- Stability Game (Israel vs. Hizbollah)

SIGNAL

South China Sea (SCS)



Angels & Bears

Maritime conflict

Tactical level

- Units are aircrafts, naval vessels, and submarines

Players play on a map with a continuous coordinate system

Units can move certain amounts based on type of vehicle

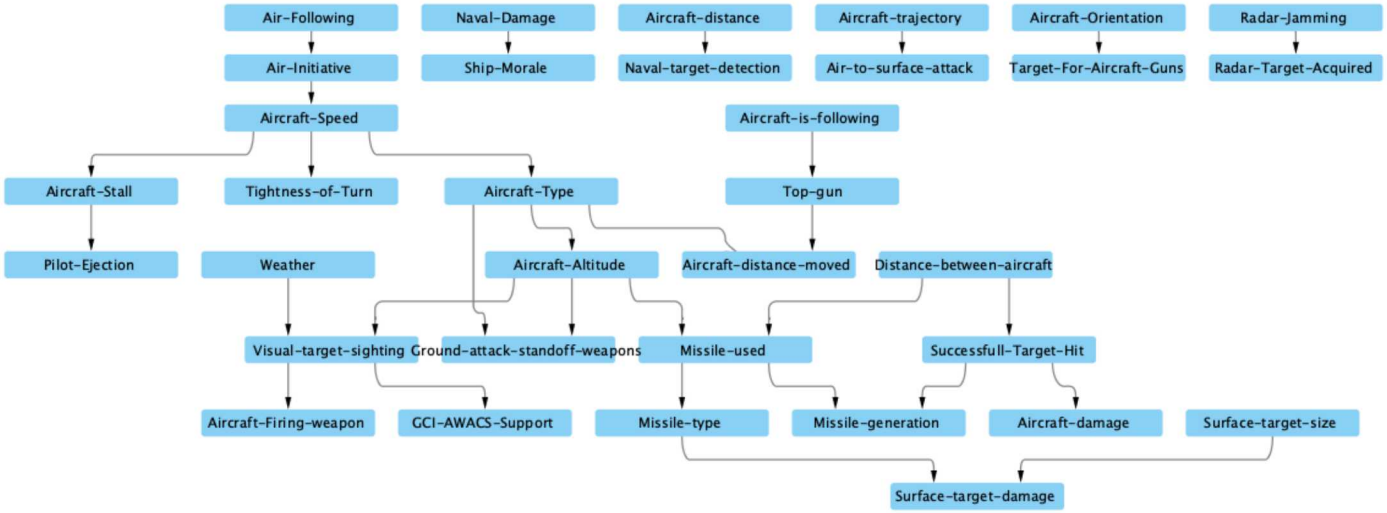
Rules intended to simulate combat

https://freewargamesrules.fandom.com/wiki/Angels_and_Bears

Actors:

- Aircraft
- Naval vessels
- Submarines

Angels & Bears: Ground Truth and Causal Complexity Calculations



Nodes	38
Edges	32
Cyclomatic Complexity	10
Feedback Complexity	0.8
Causal Complexity	18.0

Angels & Bears: Complexity Metrics

Potential decisions: see next slide

Number of differentiated relationships:

- Attack other player
  - This is a tactical warfighting game, so it is very limited in the interaction between players.

Social Organization:

- Social network definition: Nodes are players, edges indicate interaction.

Causal Complexity	18
Number of Decisions	27
Differentiated Relationships	1
Global Reaching Centrality	0.0

Social Network:

Angel's & Bears Potential Decisions

- Radar Missile Fire
- Target acquisition
- Naval ship placement
- Anti-aircraft fire
- Aircraft attacking ground targets
- Leave battle area
- Aircraft change altitude
- Aircraft change speed
- Aircraft change direction
- Air-to-air gun fire
- Air-to-air missile fire
- Air-to-air IR missles
- Air-to-air radar missiles
- Air target evasive maneuvers
- Decide on Top-Gun move
- Electronic Warfare
- Area bombing
- Cruise Missile Attack
- Within the horizon attack
- Over the horizon attack
- Beyond visual range attack
- Bearing only launch attack
- Ship maneuvering
- Submarine attack
- Submarine in Anti-Submarine Warfare role
- ASW aircraft
- Submarine firing cruise missiles

MaGCK Israel v. Hizbullah Matrix Game

Matrix Game to hypothesize about future conflict in Lebanon between Israel and Hizbullah

- Matrix game: type of wargame revolving around successful argumentation of the consequences of a proposed action
  - Players must reach consensus to adjudicate a situation, often operating within frameworks such as "pros & cons" or "three reasons"
  - Highly customizable to different scenarios
  - Limited game mechanics for combat
  - Victory scenarios are custom, often goal is stabilization

Three actors: Hizbullah, Israel, Lebanon

Game has a pre-war and wartime phase

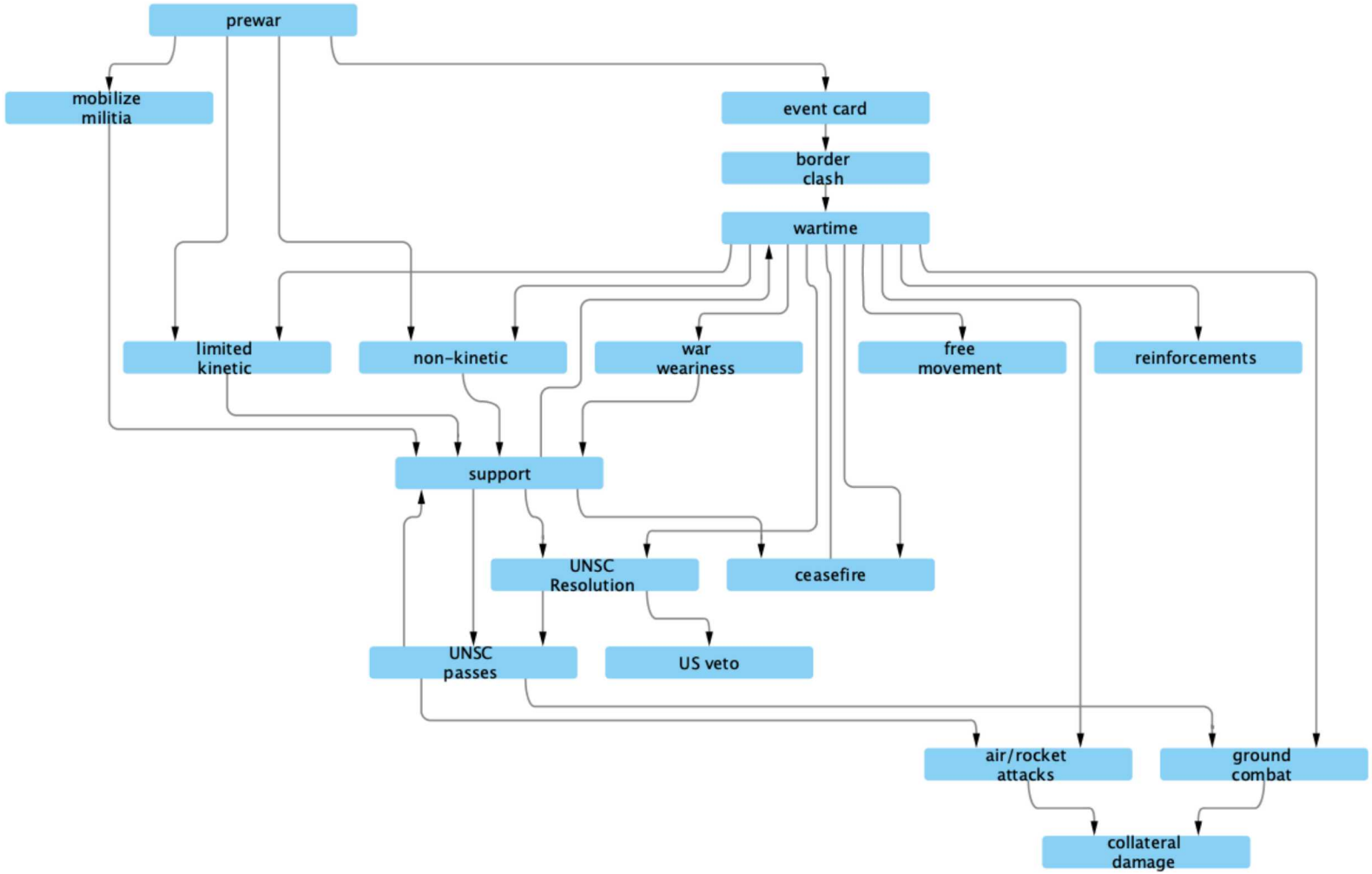
Victory earned through argumentation at the time of ceasefire, focuses on gaining political support

https://paxsims.wordpress.com/2018/05/03/israel-hizbullah-matrix-game-beta/

Actors:

- Israel
- Hizbullah
- Lebanon
- Civilians (UN observers, Refugee camps, Media)

MaGCK Israel v. Hizbullah Matrix Game: Ground Truth and Causal Complexity Calculations



Nodes	18
Edges	31
Cyclomatic Complexity	15
Feedback Complexity	0.55
Causal Complexity	23.26

MaGCK Israel v. Hizbullah Matrix Game: Complexity Metrics

Potential decisions
- Military
- Intelligence
- Political
- Diplomatic
- Economic

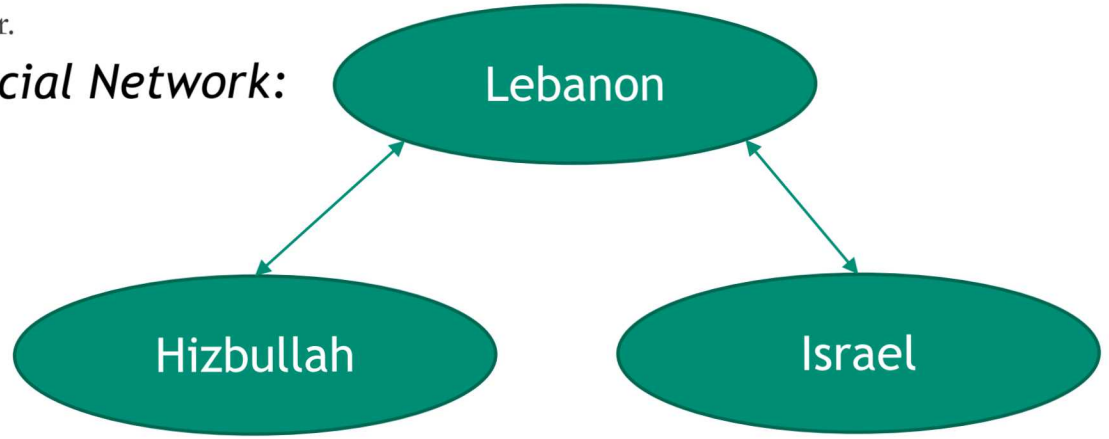
Differentiated relationships:
- Protect
- Promote
- Attack
- Undermine
- Compete

- Reinforcements
- Movement
- Ground combat
- Air attacks
- Rocket-hunting

Causal Complexity	23.26
Number of Decisions	10
Differentiated Relationships	5
Global Reaching Centrality	0.25

Social Organization:
- Nodes represent players. Edges represent the ability to cooperate with each other.

Social Network:



SIGNAL: Brief Description

Conflict, including deterrence and escalation, in a three-nation world with nuclear and non-nuclear capabilities

- Includes economic and diplomatic options

Player goals:

- Survive
- Accumulate resources
- Develop infrastructure

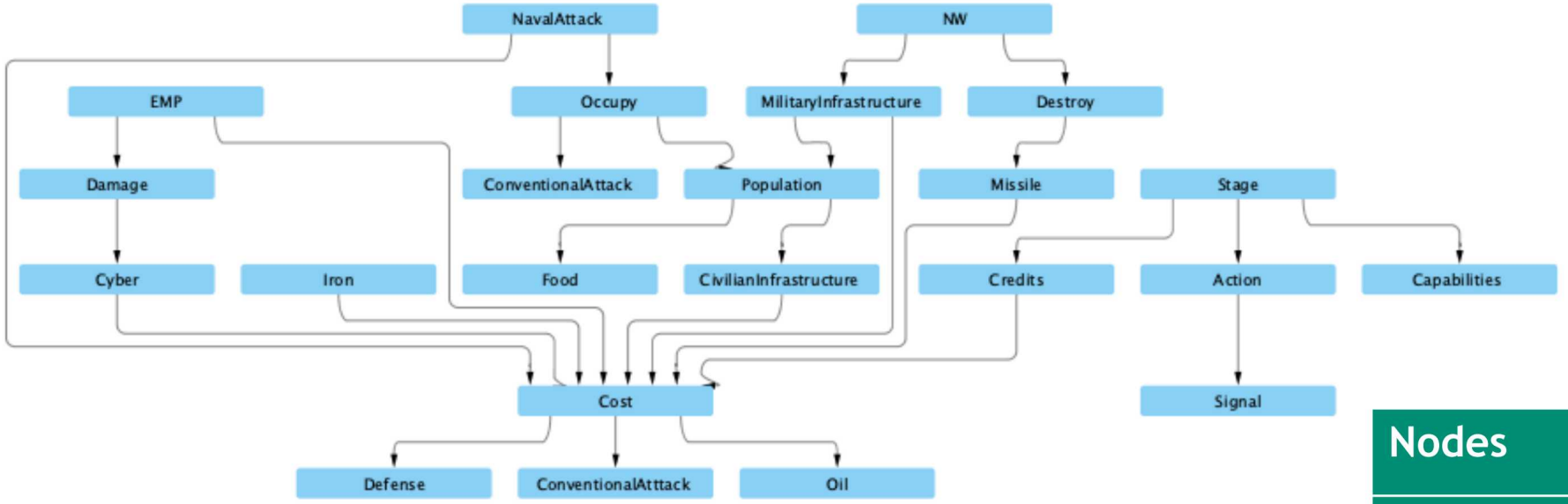
Hex-based map game board

https://thebulletin.org/2019/05/wargames-as-experiments-the-project-on-nuclear-gamings-signal-framework/

Actors:

- Green
- Purple
- Orange

SIGNAL: Ground Truth and Causal Complexity Calculations



Nodes	23
Edges	26
Cyclomatic Complexity	5
Feedback Complexity	1.0
Causal Complexity	10.0

SIGNAL: Complexity Metrics

Number of decisions: see next slide

Number of differentiated relationships:

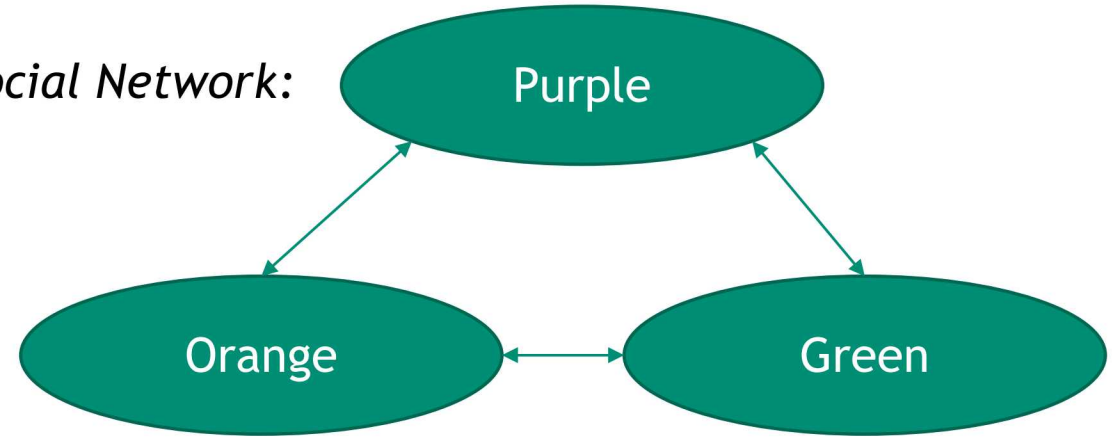
- Threaten another player
- Conduct attack on another player
- Support another player
- Trade with other player

Social Organization:

- Social network definition: Nodes are players, edges indicate interaction.

Causal Complexity	10
Number of Decisions	25
Differentiated Relationships	4
Global Reaching Centrality	0.0

Social Network:



SIGNAL Potential Decision

- Place a signaling token
- Stage a Military Infrastructure Card
- Stage a Civilian Infrastructure Care
- Stage a Nuclear Weapon Card
- Stage a High Precision Low Yield NW card
- Stage an Electro-Magnetic Pulse NW card
- Stage a Conventional Infantry Assault Card
- Stage a Naval Assault Card
- Stage a Defense Card

- Stage a Cyber Attack Card
- Stage a Missile Strike Card
- Play a Military Infrastructure Card
- Play a Civilian Infrastructure Care
- Play a Nuclear Weapon Card
- Play a High Precision Low Yield NW card
- Play an Electro-Magnetic Pulse NW card
- Play a Conventional Infantry Assault Card
- Play a Naval Assault Card
- Play a Defense Card

- Play a Cyber Attack Card
- Play a Missile Strike Card
- Request a trade
- Accept a trade request
- Remove infrastructure
- Choose signaling token

South China Sea Matrix Game

Matrix game based on complex international relations in the South China Sea.

Focus on economic success

Wargame emphasizes process, not outcome (i.e., exploratory)

5 rounds
- US & China 10 minutes
- All others 5 minutes

Gameplay:
1. News report
2. Action
3. Argument

Bonus cards modify actions:
- Drawn at random before first round
- Possibly awarded after argument thereafter

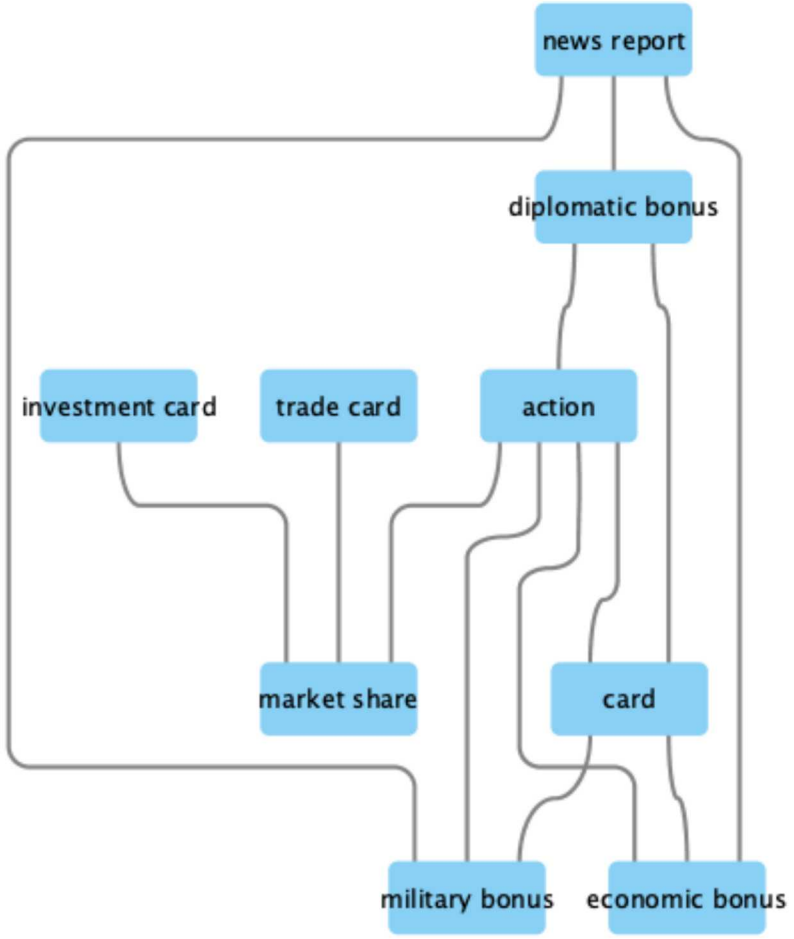
- 7 Nation-state actors
  - China
  - United States
  - Japan
  - Canada
  - Malaysia
  - Philippines
  - Vietnam

- 2 Economic actors
  - Global (Western) trade.
  - Chinese trade

All actors played by teams of 3 players.

Brynen, Rex and Tom Fisher (2017) "Diplomatic challenges in the South China Sea" *PAXsims https://paxsims.wordpress.com/2017/10/10/diplomatic-challenges-in-the-south-china-sea/*

South China Sea Matrix Game: Ground Truth and Causal Complexity Calculations



Nodes	9
Edges	13
Cyclomatic Complexity	6
Feedback Complexity	0.59
Causal Complexity	9.54

South China Sea: Complexity Metrics

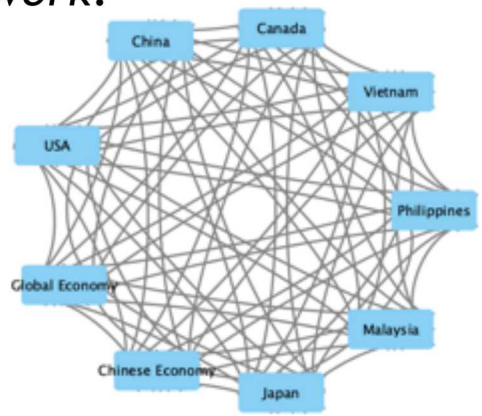
Number of decisions:
- Trade
- Diplomacy
- Internal Politics

Number of differentiated relationships:
- Trade
- Diplomacy
- Internal Politics

Social Organization:
- Social network definition: Nodes are players, edges indicate interact

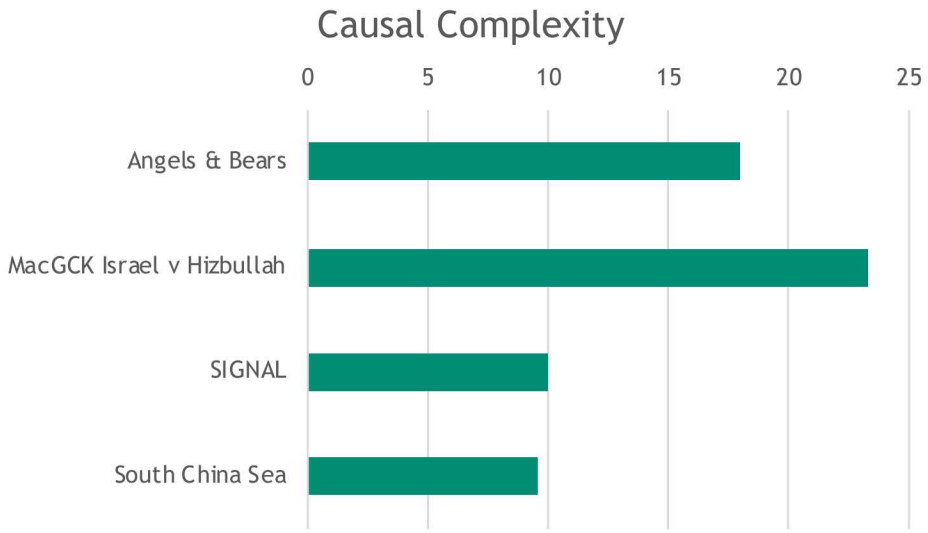
Causal Complexity	9.54
Number of Decisions	3
Differentiated Relationships	3
Global Reaching Centrality	0.0

Social Network:



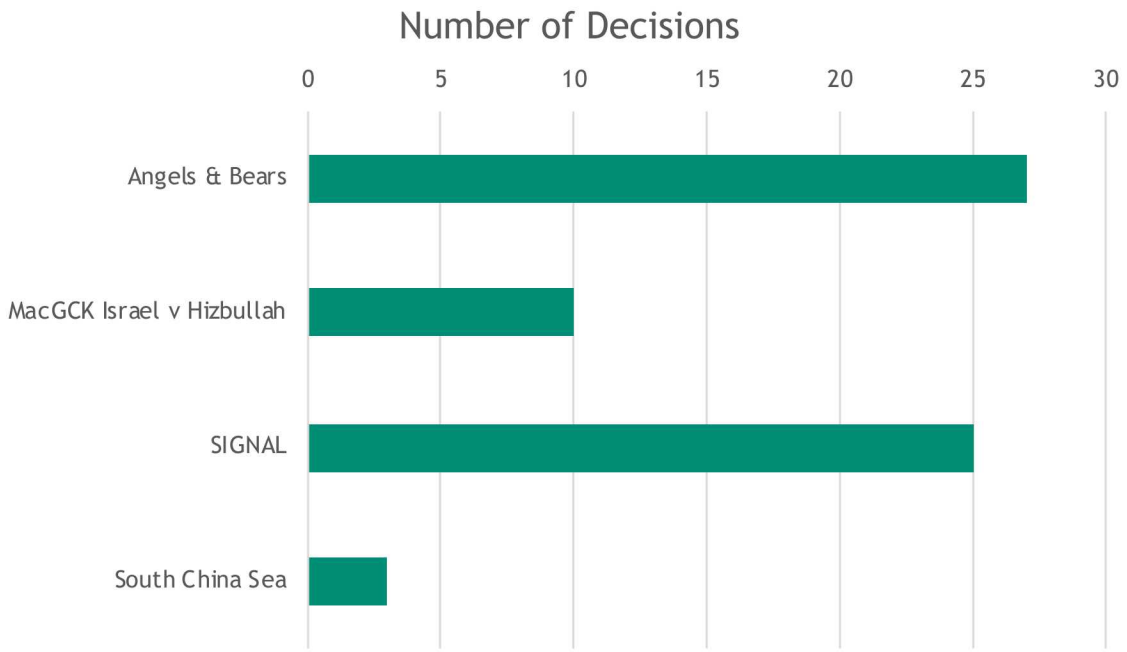
All interactions between two players, so # of decisions and # of differentiated relationships are the same in this ga

Comparison of Complexity Across Wargames: Causal Complexity



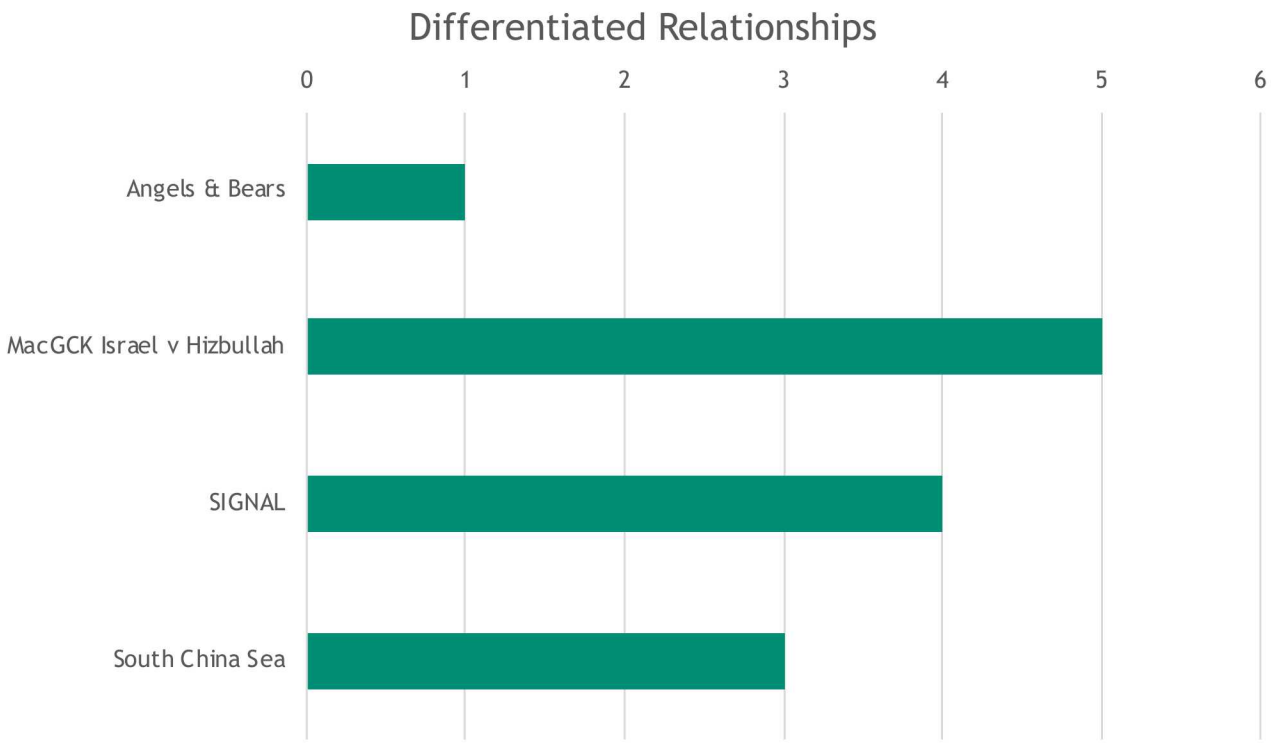
How complicated is the causal structure?

Comparison of Complexity Across Wargames: Number of Decisions



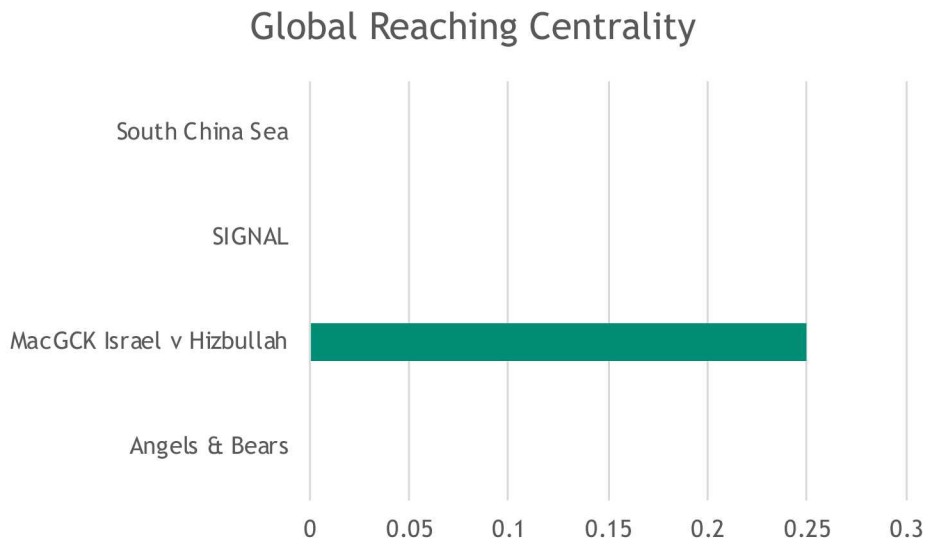
How many decisions are being made by actors in the wargame?

Comparison of Complexity Across Wargames: Number of Differentiated Relationships



How many ways do actors interact with each other?

Comparison of Complexity Across Wargames: Global Reaching Centrality



How much structure is there to the social network?

MaGCK Israel v Hizbullah: constrained structure defining how players are allowed to interact with each other

What have we learned?

There are many ways to define complexity.

We can leverage methods from other domains to help understand wargames.

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Backup

Measuring Complexity

- ***Challenges***
  - Many definitions of complexity – how do we capture what is important?
  - How to avoid the temptation of focusing on easy measurements (e.g., number of actors represented)?
- ***Considerations***
  - Want to capture complexity of the actors, environments, interactions, and outputs of a simulation
    - And the real world, if possible
  - Want metrics that have the potential to compare simulations to the real world
  - Want metrics that consider different parts of the simulations – causal structure, outputs…
  - Existing metrics capture particular dimensions, but we want a broader span
    - An organized combination of methods might capture a broader span of dimensions

System/model characteristics that make simulation difficult

Lack of established theory
Lack of data
High signal-to-noise ratio
Adaptive behavior
High throughput
Heterogeneity of subcomponents
Multi-scale interaction
Bifurcations and phase change
Cascading behavior
Feedback loops
Non-linearity
Goal-driven and/or gaming behavior
Humans in the loop
Reliance on soft quantities

Intended uses that make simulation difficult

Qualitative questions
Need for real-time or quick turnaround
Feedback between model and system
Scenarios that have never occurred

Organizing Structure: Two Dimensions

Dimension 1: Tie to social sciences

- If metric is inspired by real-world social complexity metrics, there is an obvious tie to real-world systems
- If not, the metric might be more broadly applicable to a variety of topics

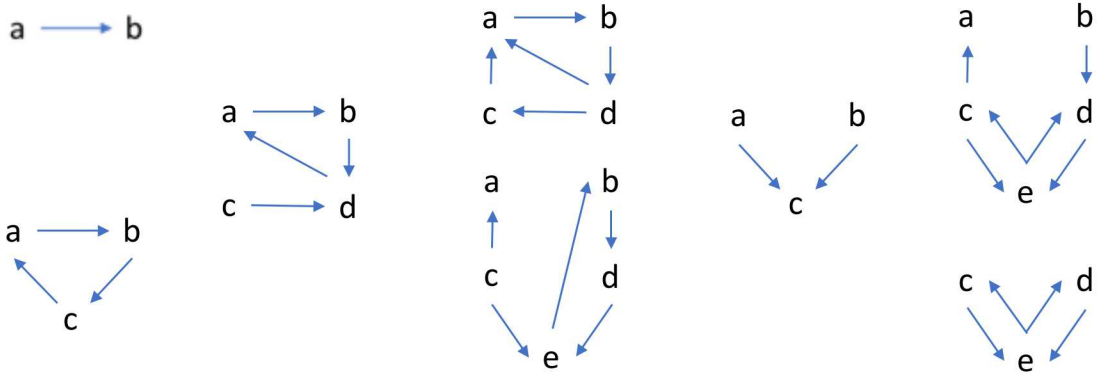
Dimension 2: Knowledge of system's causal structure

- Some dimensions of complexity may be tied to causal structure
- Metrics that don't rely on causal structure might be more broadly applicable
  - For example, to real-world systems

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure		
Does not require knowledge of system structure		

Organizing Structure: Measures of System Intricacy

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	**Measures of System Intricacy**	
Does not require knowledge of system structure		



Measures of System Intricacy

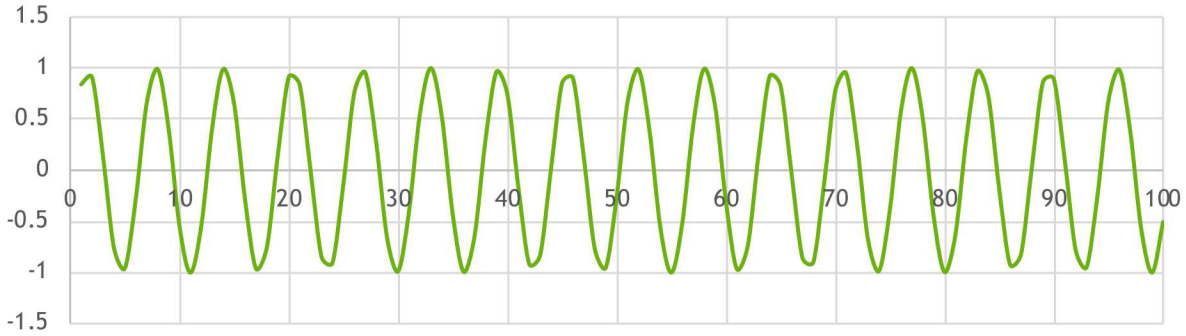
- *How complicated is the causal structure?*
- Intuition: the more components and causal relationships a system has, the more complex it is
- For Ground Truth simulations, this captures information about nodes (variables), edges (causal relationships), and their relationships

Examples:

- Number of causal influences (edges) between nodes in the ground truth diagram
- Number of spanning trees of the graph (a measure of the interconnectedness of nodes in the graph)
- Cyclomatic complexity, which incorporates the nodes, edges and the number of connected components
- Number of actors, behaviors, characteristics, etc.

Organizing Structure: Information-Theoretic Complexity

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure		
Does not require knowledge of system structure	**Information-Theoretic Complexity**	



Information-Theoretic Complexity

- *What is the information content and uncertainty in the system's behavior (output)?*
- Intuition: a more complex system will generate more information over time
  - How compactly could you store that information?
- Has been developed and used in several fields
- May not capture our intuition of complexity
  - For example, might consider randomness to be complexity, since uncertainty and information content are entangled
- For Ground Truth, calculated using simulation results

Examples:

- Entropy or information content
- Mutual information
- Forecast complexity
- Autoregression
- Hurst exponent
- Kullback-Leibler divergence
- Cross-entropy
- Compression ratio
- Normalized compression distance
- Hierarchical clustering
- Kolmogorov complexity

Organizing Structure: Behavioral Capacity

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure		**Behavioral Capacity**
Does not require knowledge of system structure		

Behavioral Capacity

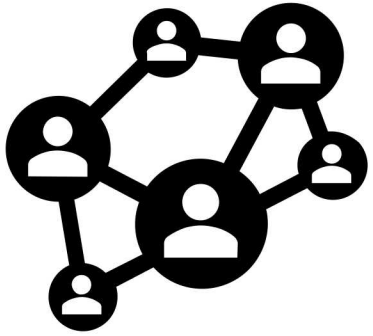
- *How do interactions and behaviors of actors in the system affect complexity?*
- Intuition: in complex social systems, entities can employ a diverse and impactful set of behaviors and relationships
- Correspond to intuition about social complexity
- Connect to social and behavioral theory on humans, animals
- For the Ground Truth Program, calculated using the causal structure (ground truth)

Examples:

- Number of differentiated relationships
- Interdependence between actors
- Group membership
- Interaction between actors and groups
- Interactions between groups
- Operant conditioning, learning, and adaptation of actors

Organizing Structure: Measures of Social Organization

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure		
Does not require knowledge of system structure		**Measures of Social Organization**



Measures of Social Organization

- *How organized are social relationships in the system?*
- Intuition: complex social systems demonstrate
  - Emergent hierarchical organization
  - Complicated interactions among individuals/groups
    - How individuals form groups
    - How groups combine to form larger groups
    - How individuals and groups interact
- For Ground Truth, calculated using simulation output

Examples:

- Number of causal influences (edges) between nodes in the ground truth diagram
- Number of spanning trees of the graph (a measure of the interconnectedness of nodes in the graph)
- Cyclomatic complexity, which incorporates the nodes, edges and the number of connected components

Organizing Structure: Measures of Social Organization

	Not tied to social sciences	Inspired by the social sciences
Requires knowledge of system structure	Measures of System Intricacy	Behavioral Capacity
Does not require knowledge of system structure	Information-Theoretic Complexity	Measures of Social Organization