Network Complexity, Control, and Cooperation

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Outline

- Philosophy
- Complexity
- Control
- Cooperation
- Examples
New Philosophy for Applied Mathematics: Using Network Models to Embrace the Complexity

- Wicked Applications in Information and Social Sciences.
- Human-based Utility Functions/Metrics (non-linear)/Control Mechanisms
- New Structural Use of Geometry
- Higher Dimensional Data/Discrete Analytic Algorithms
- More Simulations/Games
- Measure real worth to the mission (of the organization or system) through cooperation
- Modeling that EMBRACES THE COMPLEXITY!!!
Observations


2) The framework embraces the complexity of networks through the measurement and use of diversity, specialization, energy, cooperation, and information to enhance performance.

3) Complexity as a global network metric includes network purpose, architecture, structure and process.

4) Information and energy resonance provide a way of viewing the exchange between networks to enable network control.

5) Effective influencing of networks is not done directly by control mechanisms using domination because they can be absorbed by the network’s dynamics or lost in friction. The influence should be delicate and indirect (cooperative) by matching the network in complexity. Network control often does not go to the most powerful but to the most subtle and flexible.
- Model, analyze, predict, & control the behavior of networks
- Understand linkages & interactions among network domains
- Enable humans to exploit information for timely, effective decision making
- Design robust networks that align with human cognitive capabilities

Layer Framework still valid
• **Network Nodes** represent an organization
  – Social and cognitive
  – Collaborative and distributed
  – Human & agent

• **Information**
  – Carried over the links
  – Required at the nodes

• **Sensitivity of Network’s Communication and Influence Links**
  – Formal & informal
  – Intact or broken
  – Bandwidth limited
Complexity
(as a metric or utility function)

Purpose (flow, grow, decide, perform, manage), Architecture (random, scaled), Entropy (information, energy), Structure, Process (dynamics, specialization, diversity), Attributes (data mining, underlying distribution), Dimensionality

**Structure:** Density, Spread (diameter/size), Balance (reciprocity, transitivity, clusters, silos), Variance (centralities), Centralizations, Black swans Normalized, non-linear, dynamic, local, global, subgroup
CONTROL ISSUES

B. West’s Universal Principle in Network Science

High-energy network

\( E_1, I_1 \) → \( E_2, I_2 \)

Low-energy network

Energy-dominated process

Low-information network

High-information network

\( E_1 > E_2; I_1 < I_2 \)

Information-dominated process
Control Results

• Information resonance enables the viewing of the information exchange or control between complex networks.

• Control of a complex network is not best done by direct force by authority, such action would be absorbed by the network’s dynamics. To be effective the influence should be delicate (cooperative) and indirect (through negotiation) and it must match the network in complexity.

• The interaction between complex clusters can be very weak and still the dynamics of the perturbed cluster can inherit the dynamics of perturbing cluster.
Successful Organizations consist of teams known for their trust and autonomy... the teams may involve people, computers, robots, sensors, vehicles.
Motivating Questions

Cooperation is complex and can provide control!

What makes one behavior more cooperative than another?

Can we determine why agents cooperate?

What behaviors indicate a player is trustworthy?

How and why should you decide who to trust?

Can a cooperative autonomous system be as effective as a centrally controlled system?
Existing Frameworks for Cooperation

von Neumann’s Cooperative Game Theory

- Agents work together for a common payoff

- Mathematical theory for dividing payoff among the participants ("Shapley value")

**Problem 1:** no concept of “team”
  - Agents participate only for selfish reasons
  - Not applicable to most cooperative systems

**Problem 2:** in practice, even selfish human behavior doesn’t follow the laws of economics
  - Prisoner’s Dilemma
Cooperative Game Theory

• A cooperative game is a set of players $T$ with an outcome for each subset $B \subseteq T$ and a payoff (utility) function for each outcome.

• Associates a value $v(B)$ to the outcome when $B$ participates.
Subset Team Games

*a new framework for studying cooperation*

**DEFINITION:** A subset team game is a set of players $T$ with an outcome for each subset $B \subset T$ and a utility function for each outcome and each subset $A \subset B$.

- Associates a value $v_A(B)$ to each subset $A$ of participating players $B$. 

\[ v_A(B) \]

- $A$ participates & assesses the outcome

\[ v(B) \]

- $B$ participates

\[ B^c \]

- $B^c$ does not participate

![Diagram of subset team game concept](image)
Measuring Player Contributions

**Cooperation Space**

- Perception of $T$
- Perception of $A^c$
- $v_T(T) > v_{A^c}(T)$

"ideal" cooperative behavior in quadrant

$v_{A^c}(T) > v_{A^c}(A^c)$

$m_A = 0$

$c_A = a_A + c_A$

"sensible" cooperative behavior
Using the Framework

**Practical aspects**

1. Decide on “value” or “utility” function $v_A(B)$
   - Should make sense for individuals and for subsets of players

2. Compute $v_T(T)$, $v_{A^c}(A^c)$, and $v_{A^c}(T)$
   - Must consider two outcomes: with all of $T$ participating, and with only $A^c$ participating

3. Use metrics to either
   - assess cooperative nature of the team
   - adjust behavior of players based on these metrics
Example: Pursuit-Evasion Games

*Using cooperation metrics to analyze and alter behavior*

- What is a **Pursuit-Evasion Game**?
  - Typically two teams with opposing goals
  - Endless variations: “cops and Robbers”, football, playground tag, etc.

- Why use PEGs to study cooperation?
  - **Good metrics** are easy to find
  - **Simple** to state, simulate, and study, yet **complex** behaviors emerge
  - **Applications** to unmanned vehicles, human-robot teaming, and network science
Pursuit-Evasion Games

Preliminary results and observations

• Many metrics to work with
  – Number of opponents captured
  – Sum of distances to nearest opponents
  – Distance from goal
  – Time to first capture

• Observations
  – Altruistic players: slow-moving, but see and communicate over long distances
  – Selfish players: quick, relying on communications from other players
Pursuit-Evasion Games

Altruism & Selfish Cooperation (back to West’ Control issue)

Altruistic Case:
- slow
- large sensor & comm networks
- High Information

Selfish Case
- fast
- may not have information
- High Energy
Quest for the Elixir of Life (Initial State)

3 Lions (Speed 6.5, Sensor Range 20, Comm Range 50, Quadrant Search Mode) and 5 Wildebeests (Speed 5, Sensor Range 20, Comm Range 50 in Straight to water mode)
Stage 1: Time = 24

Lions 1 and 3 attempt to capture Wildebeest 1. Lion 2 changes course to move toward Wildebeest 3. Lion 2 and 3 are in comms range, therefore Lion 2 knows where to move to capture Wildebeest 3 although Lion 2 can not sense Wildebeest 3.
Stage 2: Time = 51

Lion 3 will capture Wildebeest 1. Lion 1 continues on path towards Wildebeest 1. Lion 2 can now sense Wildebeest 3 and attempts to capture. Wildebeest 5 will reach the watering hole safely.
Stage 3: Time = 83

Lion 1 attempts to assist Lion 2 in capturing Wildebeast 3. Currently both lions can only sense that one wildebeast so Wildebest 2 is undetected.
Stage 4: Time = 113

Wildebeast 3 will reach the watering hole safely after being pursued by both Lion 2 and Lion 1. Wildebeast 2 is still undetected.
Stage 5: Time = 130

Lion 2, after unsuccessfully chasing Wildebeast 3, waits by the watering hole, then senses Wildebeast 4 and captures it. Lion 1 now has no one to communicate with and nothing that it senses and will wait by the watering hole. Wildebeast 2 still undetected.
Stage 6: Time = 189

Once Wildebeast 2 comes into sensor range for Lion 1, Lion 1 easily pursues and captures.
Summary of Quest for the Elixir of Life

W5 reached at 56 seconds.
W1 captured at 59 seconds by Lion 3.
W3 reached at 115 seconds.
W4 captured at 129 seconds by Lion 2.
W2 captured at 196 seconds by Lion 1.

Cooperation: L2 and L3 share wildebeest location information to enable cooperation.
L1 and L3 and then L1 and L2 unnecessarily chase the same wildebeest
Searching: L2 is search mode when has no information.
3-species pursuer-evader

Seals
Penguins
Fish
Interdisciplinary Contest in Modeling

• 1337 three-undergraduate teams worked for 4 days in Feb 2012 to solve a criminal conspiracy network problem
• 83 people in the company (8 known conspirators, 7 known non-conspirators
• 400-600 messages
• 15 topics (3 conspiratorial topics)
Requirements

Requirement 1: Build a model to prioritize the 83 nodes by likelihood of being part of the conspiracy and explain your model and metrics. Are any senior managers of the company involved in the conspiracy.

Requirement 2: New information comes to light that Topic 1 is also connected to the conspiracy and that Chris is one of the conspirators --- redo!

Requirement 3: Explain how semantic and text analyses of the message traffic, if you could obtain the original messages, could help develop even better models.

Requirement 4: Explain the network modeling techniques you developed and how they can be used to identify, prioritize, and categorize nodes in a network database of any type, not just crime and message data.
Semantic Network Layer

Topics/Messages

- Semantic Network Analysis
  - Co-occurrence Matrix
  - MDS & Hierarchical Cluster

Text Analysis
- TF-IDF Statistics
  - Crime Weight & Crime Vector
  - Word-groups & Word-group Vector Space

Message Communication Network

- Social Network Vector Model
  - Personnel Vector
  - Vector Angle Calculation & Comparison

Social Network Layer

- Final Priority List & Identification of Conspirators
  - Bonacich Alpha Centralization
  - Organization Structure of Conspirators
**Information Network Layer**

- **Images & Chemical Data**
  - Descriptive Analysis
- **Descriptive Text**
  - Semantic Network Analysis
  - Co-occurrence Matrix
  - Text Analysis (TF-IDF Statistics)
  - MDS & Hierarchical Cluster
- **Cell Communication Network**
  - Word-groups & Word-group Vector Space
  - Social Network Vector Model
  - Infection Weight & Infection Vector
  - Cell Vector
  - Vector Angle Calculation & Comparison
- **Physical Link Network Layer**
  - Final Priority List & Identification of Infected Cells
  - Bonacich Alpha Centralization
  - Organization Structure of Infected Cells
Local structure
ICM (Feb 2013)

(next year’s problem will be another one involving network science)

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