We need a new design perspective for socio-technical systems.  
*Can Complex Network Perspective Be a Viable Candidate?*
Babak Heydari, Stevens Institute of Technology
**June 1 | 1:00 pm ET**

- Today’s session will be recorded.
- An archive of today’s talk will be available at: sercuarc.org
- Use the chat box to queue questions and comments and they will be answered during the last 10 minutes of the session.
- Any issues? info@sercuarc.org
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We need a new design perspective for socio-technical systems.

*Can complex network perspective be a viable candidate?*

*Babak Heydari*
Assistant Professor
School of Systems and Enterprises
Complex Evolving Networked Systems Lab (CENS)
Stevens Institute of Technology

SERC TALKS, June 1, 2016
Introducing Complex Evolving Networked Systems (CENS) members and sponsors

Current PhD Students: Mohsen Mosleh, Abbas Ehsanfar, Peter Ludlow, Patrick O’Brien, Vanessa Chioffi

Kia Dalili: Former PostDoc, now technical lead of data science group at Facebook NYC
Dave Gianetto: Former PhD Student, Engineering Fellow at Raytheon

Current and Previous Sponsors

- DARPA
- Lockheed Martin
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- Accenture
- SSE School of Systemic Enterprises
Toward Complex Socio-Technical Systems

- **Centralized ➔ Decentralized**
  - Group intelligence
  - Easier information access
  - Increased Resilience

- **Controlled ➔ Autonomous**
  - Increased uncertainty
  - Paradigm shift in computing
  (closer to the way human deals with the world)

- **Homogenous ➔ Heterogeneous**
  - Result of increased connectivity
  - Risk management (hedging)
  - Response to different inputs
Getting the Desired Systemic Behavior

- Do what engineers have been doing for decades [hierarchical design, control]
  - What about autonomy?

- Do what economists would do [Incentives]
  - What about system’s architecture and design aspects?

- Interaction and communication structure [network architecture]
  - Useful design lens for socio-technical systems
Complex Network Theory

- Node Complexity
- Link Complexity
- Peer-to-Peer (social) learning
- Strategic Interaction
- Weighted links
- Binary links

Graph Theory + (Evolutionary) Game Theory + Theories of Learning

Just a Junction!  Decision-making Agent  Decision-making & Adaptive Agent
Protein interaction network. [Image credit](#)

Power Grid Network in Northern Italy. [Image credit](#)

left-wing and right-wing blog interaction network. [Image credit](#)

Inter-bank trading network in Austria [Image credit](#)
Three Takeaways from Network Science

- **Similar structural attributes** in different systems
  - Small-world phenomenon
    - My average degree of separation on Facebook is 3.28! Check yours here: https://research.facebook.com/blog/three-and-a-half-degrees-of-separation/
  - High Transitivity (Your friend’s friend is also a friend!)
  - (Almost) power-law degree distribution.

- Networks naturally enable linking **micro (local)** to **Macro**
  - From preferential attachment to **scale-free** networks
  - From triadic closure to **high transitivity**

- Networks naturally enable linking **structure and behavior**
  - When nodes are agents
In coming years, we will increasingly be dealing with complex multi-mode systems in which humans and autonomous technologies interact, make collective decisions, negotiate, compete and coordinate to allocate resources and switch roles depending on the context.

An important engineering lens for such systems is the design of interaction network structure with the goal of impacting overall behavior of the system.

In order to be useful, the gap between complex network science and socio-technical systems engineering needs to be closed!
Example: Interdependent Decisions

- How to deal with interdependent decisions?
  - Theory of modularity

- Can we think more explicitly about who makes these decisions?
  - People
  - But also increasingly autonomous agents!
    - Autonomous vehicles
    - Disaster response hybrid teams
    - Algorithmic trading
    - Autonomous home energy management technology
So, we can consider a network where nodes are either decisions or decision-makers, depending on the context!

- **Types of Decisions**
  - Design Decisions
  - Resource allocation decisions

- **We might not like these interdependencies**
  - Lots of Coordination is needed!
  - Iterative process, resulting in considerable cost.
  - Scalability issues.
  - Prone to Instability
But interdependencies can translate into value!

First CMOS Front-end Circuits above 100GHz (Heydari, et al)

- They allow more efficient, customized design
- But also they allow for dynamic resource allocation, information access, etc!
Indirect Benefits

**Design:** Co-design, co-optimization

**Resource Allocation:**
- Energy
- Information
- Bandwidth

**Social and Organizational**
- Job opportunities
- Innovation
- Best Practices
- Marriage and dating
The connection model

\[
\begin{align*}
\text{Higher order indirect benefits} & \\
& \quad b(1) \geq b(2) \geq \ldots \geq b(d_{max})
\end{align*}
\]

\[
\begin{align*}
u_i(g) = & \sum_{j \neq i: j \in N^{n-1}(g)} b(d_{ij}(g)) - \sum_{j \neq i: j \in N(g)} c_{ij}
\end{align*}
\]

Total utility of the network is as follows:

\[
U(g) = \sum_{i=1}^{n} u_i(g)
\]

Who links to whom: Relevant questions

Science Question:
- If agents are autonomous, what kind of network will emerge? (pairwise stability)
  - For all $i/j$ in $g$, $u_i(g) > u_i(g-ij)$ and $u_j(g) > u_j(g-ij)$ AND
  - For all $i/j$ not in $g$, if $u_i(g+ij) > u_i(g)$, then $u_j(g+ij) < u_j(g)$

Engineering Questions:
- Structure to maximize total utility? (strong efficiency)
  \[ \tilde{g} = \arg \max_g \sum_{i=1}^n u_i(g) \]

Governance Question:
- Simultaneous stability and efficiency (as much as possible)
  - Price of Anarchy
  - Price of Stability
- How to alter cost and benefit parameters to minimize these costs for a given performance
The structure of the efficient network depends on the value of link costs and benefit functions.

\[ C < b(1) - b(2) \]

\[ b(1) - b(2) < C < b(1) + 0.5(n-2)b(2) \]

\[ C > b(1) + 0.5(n-2)b(2) \]

Complete graph

Star

Empty Network

However, homogenous assumption of costs and benefits does not hold in many real world settings!

Motivation:
Networks in which heterogeneous agents are each endowed with some resources (time, energy, bandwidth, etc.) and the total resource needed to establish and maintain connections for each node can be approximated to be proportional to its degree. E.g. airline routing strategy

Each agent pays its own fixed cost for every connection: $c_{ij} = c_i$ and $c_{ji} = c_j$

This model also captures heterogeneity of direct benefit (b1)
Without loss of generality: $c_1 < c_2 < \ldots < c_n$

1. Find the largest $m$ that satisfies $b(1) + (m-2)b(2) > (c_m + c_1)$. Connect $c_i$ to $c_1$ if $c_i \leq c_m$.

2. Connect $c_i$ to $c_j$ if $b(1)-b(2) > 0.5(c_i + c_j)$

Having two types of nodes with $C_L$ and $C_H$:

- If $C_L < b(1) - b(2) < C_H$, and
- $0.5(C_L+C_H) < b(1) + (N_L+N_H-1)b(2)$

the efficient structure is a core-periphery network

Possibility of a phase-transition.

Empirical Evidence?
- Baldwin, MacCormack and Rusnak (2014):
  - 1286 software, ~92% Core-periphery.
- Frickle and Lux (2015):
  - Interbank market, ~25% of banks in the core
- Verma et al. (2016):
  - World Airline Network

Once we have the cost and benefit models, we can determine:
- How many nodes in the core
- How to peripheries to the core.
Network Efficiency in Island-connection model

Another Simplifying Assumption:
- Island Model
- Multi-team settings
- Multi-cluster autonomous systems

Low intra-island connection cost $b(1) - b(2) > c^*$

Increasing Inter-Island connection cost ($C = c + \delta$)

- Truncated benefit $b(k) = 0 \ k > 3$
- The internal structure of islands is always complete graph

The efficient network has one of the following structures depending on \( b(1), b(2), b(3), c, \delta \): 

- Diameter of the efficient network \( \leq 3 \) and does not depend on \( b(k) \), \( k > 3 \)
- The internal structure of islands not only depends on \( b(1), b(2) \) and \( c \) but also on \( \delta \) and \( b(3) \)

Mohsen Mosleh, Pedram Heydari, Babak Heydari; manuscript to be submitted to Journal of Economic Theory
Higher levels of Heterogeneity

We assume:

- Heterogeneous Node states
- Connection Cost matrix
- Limited Capacity per Node, nonlinear cost model.

This will introduce modularity!
We need agent-based simulation.

Uniform Environment
- Communication costs are low and links abundant.
  System remains non-modular.

Slightly non-uniform Environment
- As communication costs rise, the system moves to a more modular set up to compensate for higher costs

Highly non-uniform environment
- The system is completely modularized.

What if we want to look at the behavior of decision-making agents as a function of network structure more explicitly?

- Strategic behavior becomes crucial!
  - Cooperation
  - Trust
  - Fairness

- As Engineers, why do we care?
  - Translates into performance!
  - Prisoners’ Dilemma

- Also important in hybrid cases
  - Cooperative machines!
  - Fair Autonomous agents!

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### Player A x Player B

<table>
<thead>
<tr>
<th></th>
<th>Defection</th>
<th>Cooperation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defection</td>
<td>(P: 1, P: 1)</td>
<td>(T: 5, S: 0)</td>
</tr>
<tr>
<td>Cooperation</td>
<td>(S: 0, T: 5)</td>
<td>(R: 3, R: 3)</td>
</tr>
</tbody>
</table>

Graph Theory +
(Evolutionary)
Game Theory +
Theories of Learning

Graph Theory +
Game Theory

Peer-to-Peer
(social)
learning

Strategic Interaction

Weighted links

Binary links

Node Complexity

Link Complexity

Just a Junction!

Decision-making Agent

Decision-making & Adaptive Agent

Prisoners' Dilemma

Cooperation

Trust

Fairness
Structure and Group Norms

A Multi-layer Computational Framework Developed by Gianetto and Heydari

Convergence criteria

- no more than 1 node changes in 100 generations
- 21 structures have wide range of key structural characteristics:
  - degree
  - path length
  - modularity
  - girth
  - clustering

\[
W(s_n \rightarrow s_o) = \frac{\prod_n - \prod_o}{\Delta \cdot k_{max}}
\]


Stochastic evolutionary rule

Three-component stochastic strategy:
- \(y = \text{prob. to C on first move (trust)}\)
- \(p = \text{prob to C after C (reciprocity)}\)
- \(q = \text{prob to C after D (forgiveness)}\)

Harmony | Stag Hunt | Snowdrift | Prisoners Dilemma

Repeated cooperative dilemma

\[
\begin{pmatrix}
  c & d \\
  c & d \\
  R = 1 & S \\
  T & P = 0
\end{pmatrix}
\]

General Pairwise Stylized Games

Both cooperate

\[
\begin{pmatrix}
R = 1 \\
S \\
P = 0
\end{pmatrix}
\]

Both defect

Less to lose

More to lose

Sucker's Payoff (S)

Temptation To Defect (T)

Harmony

Snowdrift

Stag Hunt

Prisoner's Dilemma

\[
\begin{pmatrix}
c \\
d
\end{pmatrix}
\]
Modularity decreases cooperation dispersion across games

- Games that advantage defectors (PD) become more cooperative
- Games that advantage cooperators (HG) become less cooperative
- Behavior motivated by fear (S) and greed (T) moderates with modularity. Distinct communities allow strategies beyond expected global norms to form.

<table>
<thead>
<tr>
<th>Modularity</th>
<th>Cooperation Versus Modularity by Game Type</th>
<th>Dispersion of Cooperation Across Games</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>Harmony (HG)</td>
<td>1 full</td>
</tr>
<tr>
<td>0.0</td>
<td>Prisoner's Dilemma (PD)</td>
<td>4 er</td>
</tr>
<tr>
<td>0.0</td>
<td>Snowdrift (SD)</td>
<td>10 lattice</td>
</tr>
<tr>
<td>0.0</td>
<td>Stag Hunt (SH)</td>
<td>14 ba</td>
</tr>
<tr>
<td>0.2</td>
<td>Harmony (HG)</td>
<td>1 full</td>
</tr>
<tr>
<td>0.2</td>
<td>Prisoner's Dilemma (PD)</td>
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<tr>
<td>0.6</td>
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</table>

Gianetto, D., Heydari, B., Modularity is essential for the evolution of cooperation Under uncertainty, Scientific Reports, Nature Publishing Group, April 2015
Recourse sharing and Fairness
The Ultimatum Game

- Two players decide how to split an amount of money.
- No haggling! Proposer suggests the split, if Responder accepts, money will be split, otherwise they both get nothing.

Human has a sense of fairness!
Experimental results of UG: offer: 30-50%, demand: 25-40%

Why natural selection favors the selection of the seemingly unfit fair behavior? (mechanisms behind emergence of fairness)

- Reputation
- Uncertainty
- Empathy
- Pure randomness and bounded rationality
- Heterogeneity
- Structure of social interaction
Relation of Structural Features and Fairness Parameters

- We created an ABM: Agents play the UG on networks
- Started with 300 networks, and selected 26 representative networks, each with 100 nodes, that sufficiently capture the effect of structure
- Strategies averaged over 1026 initializations (less than 0.01 variations) for each network structure
- Total simulation time: 40min on a 256-core Cray cluster

Why Skewness?
- A hub in the network has the luxury of being fair while keeping a high game score once it plays the UG with all of its neighbors.
- Having a higher payoff while being fair and being connected to a larger number of agents, the fairer strategy of the hubs have higher chance of percolation in the population

Why Modularity
- In a modular structure, each agent plays the UG with a certain number of neighbors as opposed to the whole population. Therefore, it is the score of the agent relative to the score of those neighbors that is important in the course of evolution of strategies.
- Hence, there is more pressure not to allow an opponent not to get away with a larger share of the pie.
Applications: Healthcare competition in ACA

Have the health care exchanges become more structurally viable since their launch in terms of participation and competition?

Timely application of this research is healthcare competition
Bipartite graph of insurers and counties

The figure is an insurer-to-county bipartite graph visualization (using [119]) of the local health care market nearest to the Optima insurer. Node color and symbols are shown on the figure, circle nodes are colored based the state in which the county resides and circle area is proportional to the income resources in the county (population * median income). Links between insurer and county are colored based on the median cost of plans provided to the connected county. Lightly weighted gray links are formed between adjacent counties. County selection by insurer can be seen where Kaiser, for example, offers plans in a select few counties (some with no other choice). However, Optima offers insurance plans to the majority of counties (at a higher cost) and Aetna’s plans compete more directly with Optima both spatially (similar county set) and in cost.
Insurer projection of network

Edges between insurers that compete in **same counties**

Thick edge = competition in many counties

2013-09-30

Most competitive insurers

Least competitive insurers
Assessing competition and participation

What role does the network structure play with participation & competition in the federal marketplace?

Figure 6.1: Stylized games payoffs structure. The figure, adapted from [187], presents a two-dimensional plane of payoffs where $S$ is received by a player for cooperating while an opponent defects and $T$ is received by a player who defects while an opponent cooperates. Hence, $S$ is representative of fear motivation (the more negative the more fear) and $T$ is representative of greedy motivation (the more positive the more greed) [47].

An artificial way to model collective behavior by using game theoretic social dilemmas. Here, one agent, or player, plays against another in a simple symmetric two-person game where the payoff to each player is dependent both on their move and their opponent's move, both players have two moves to choose from, cooperate or defect. Cooperation moves give a larger payoff to both players in sum but each player individually gets less than if they were to defect. Mutual defection is punished by both players getting a smaller payoff (see § 6.1.1). The relative payoffs for each combination of player moves can be changed to result in four stylized games, each with a different dilemma character, represented by a fear $S$ versus greed $T$ plane of payoffs, figure 6.1.

With the game defined, the interactions between players can be modeled by a [54] accepted, presented at CESUN 2014.
Assessing competition and coordination

Network effects participation as size and embedding increases

Network becomes a factor in competition increase here

Manuscript in preparation for the journal of Health Affairs
Takeaways

- Design of connectivity structure is an important mechanism to govern the behavior of socio-technical systems.

- There are many interesting R&D projects to bridge the gap between complex network science and engineering of socio-technical systems.

- Careful design of team networks can lead to getting desired team-level behavior in organizations.
Research Themes @ CENS

- Emergence and evolution of collective behavior in social and socio-technical networks
  - Evolution of Trust and Cooperation as a function of Social Network Structure
  - Emergence of Fairness as a function of Social Network Structure
  - Coordination in Complex Team Structures
- Architecture Decision for Complex Socio-Technical Systems
  - Modularity Decisions for Complex Systems
  - Open Modular Systems and their Business Ecosystems
  - Efficient and Stable Complex Network Structures
- Resource Sharing Mechanisms in Socio-Technical Systems
  - Incentive-compatible resource sharing mechanism
  - Resource Sharing Mechanisms through Network Design
- Data-Driven Policy Analysis
  - Spatial Diffusion of Risky Behavior in Teenagers
  - Post-ACA Healthcare Competition

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UPCOMING TOPICS:

What Were the Top Issues and Opportunities from the SERC Model-Centric Design and Acquisition Forum?
Dinesh Verma, Stevens Institute of Technology
August 3 | 1:00 pm ET

What Lives at the Intersection of MOSA and Set-Based Design?
Gary Witus, Wayne State
October 5 | 1:00 pm ET

Why is Human-Model Interactivity Important to the Future of Model-Centric Systems Engineering?
Donna Rhodes & Adam Ross, MIT
December 7 | 1:00 pm ET