System of systems architecture: Attraction Basins and Stability in Multi-stakeholder Preference Space

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Agenda

- Comments on SoS literature
- Maier's Heuristic of stable intermediate forms
- A network abstraction of SoS structure
- Example model of network formation
- Attraction basins as stable forms
- An SoS decision hierarchy
- Mechanism design as the "knobs" available to the SoS architect

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Existing state of SoS literature

- Dominated by case and experience based discussion of prior and current SoS
  - Generated many useful heuristics and guidance for practitioners but lacks rigor and consistency (Maier 1999, Krygiel 1999, Sage 2001, Keating 2003)
- Modeling of SoS is an emerging field
  - How can models be used to understanding the limits of these heuristics -- especially in cases where existing case literature is lacking? (DeLaurentis 2006)

Maier MW (1999) “Architecting Principles for Systems-of-Systems” *Systems Engineering*

Krygiel AJ (1999) *Behind the Wizard’s Curtain: An Integration Environment for Systems of Systems*

Sage AP; Cuppan CD (2001) “On the Systems Engineering and Management of Systems of Systems and Federations of Systems” *Information Knowledge System Management*

Keating C; Rogers R; et al. (2003) “Systems of Systems Engineering” *Engineering Management Journal*

DeLaurentis, D (2006) “Modeling and Simulation: Spanning the Life Cycle of a System of Systems” Methods for Designing, Planning and Operating Systems of Systems Workshop at Purdue University

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Maier's Heuristic

"Complex systems will develop and evolve within an overall architecture much more rapidly if there are stable intermediate forms than if there are not."

- Rechtin and Maier propose this heuristic for SoS architecture
- What does it mean?
- How can it be exploited?

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What are stable intermediaries?

Stable intermediate form:
Intermediate state of SoS construction that is *technically*, *economically*, and *politically* self-supporting

Technically: The intermediate form operates

Economically: The SoS could generate value for its stakeholders to justify said operation

Politically: The SoS has a stable governance structure that supports implementation

Maier 1999

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Problem Statement

- Mostly focused on the staged deployment for flexibility aspect
  - Silver and DeWeck (2007) propose a framework for choosing optimal paths between different sequences of intermediaries
- In collaborative SoS, the choice of path decision is distributed amongst the constituents

What are the path dynamics that occur when the choice of path is distributed?

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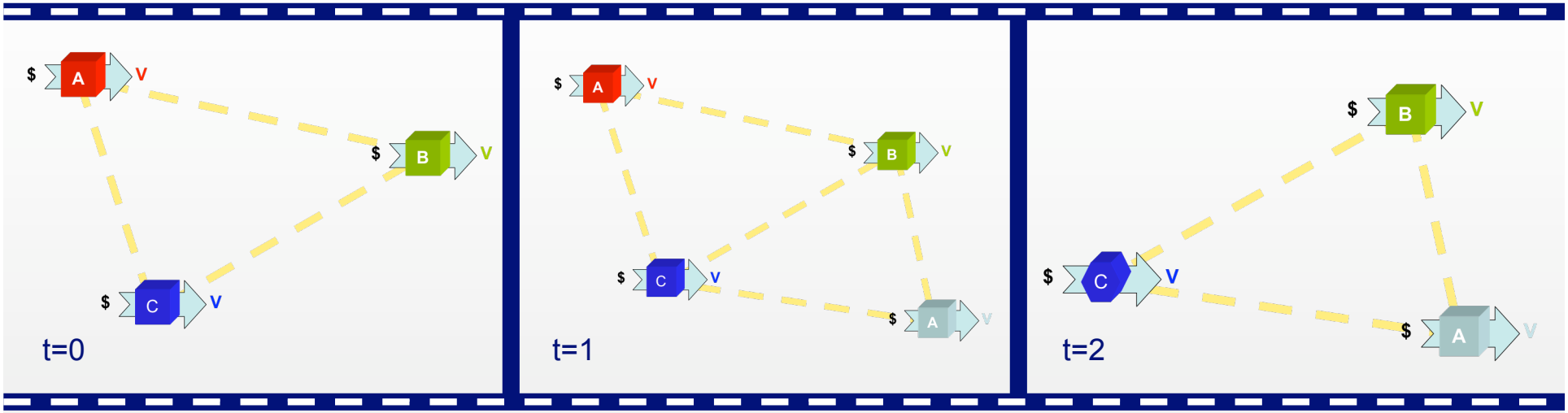
Network abstraction



- View the SoS as network of independent constituents that, through interfaces, create behavior that they could not achieve otherwise
- Network structure and the set of constituents changes over time

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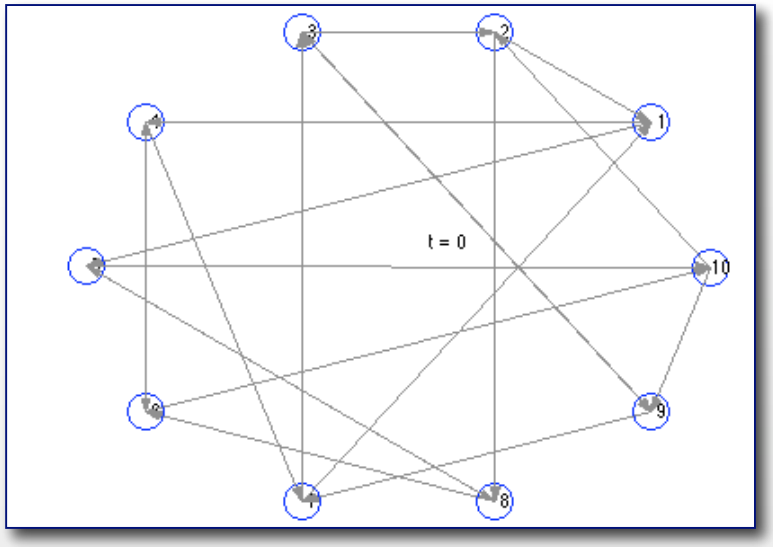
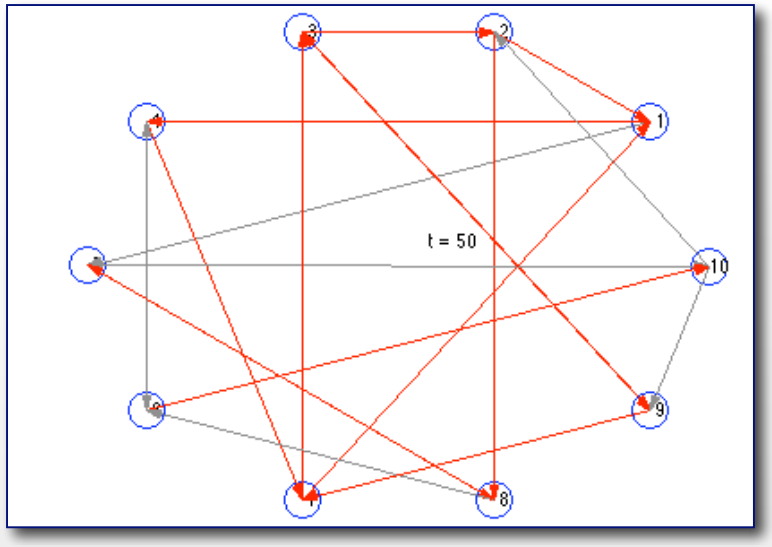
A network formation model





Key decision modeled is the formation / destruction of links

Woodard (2006) “Efficiency and Stability in Complex Value Networks” in *Architectural Strategy and Design Evolution in Complex Engineered Systems* PhD. Thesis Harvard University

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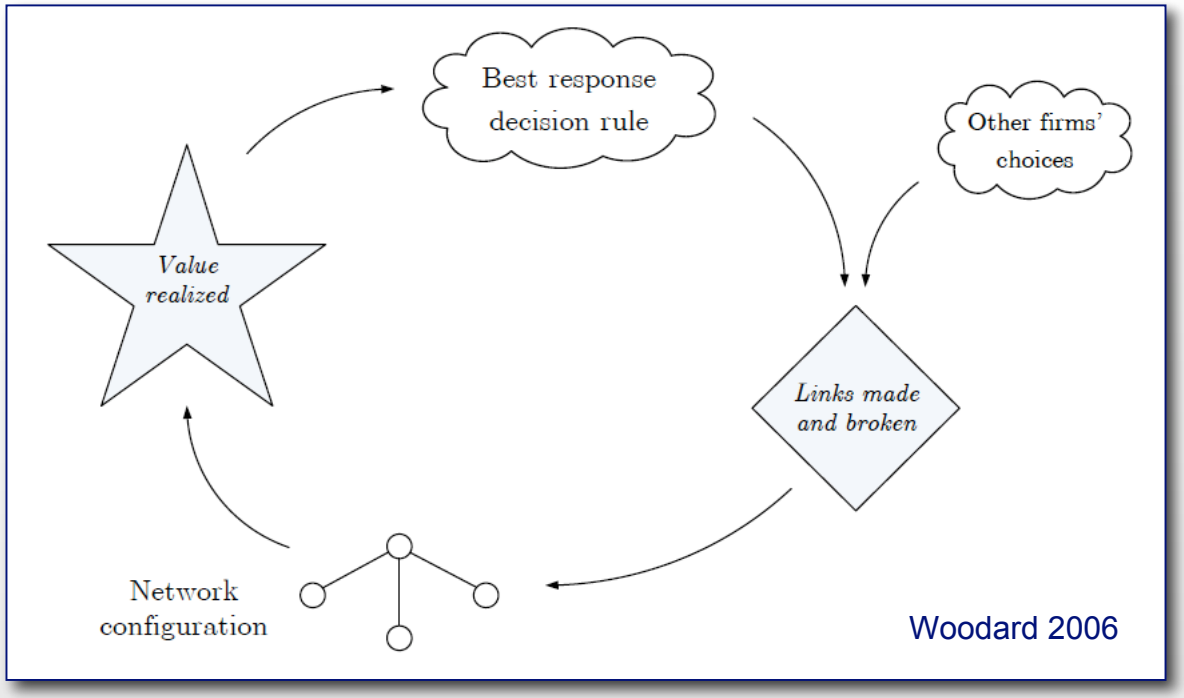
Collaborative decision loop



- SoS is a network of linked constituents
- In each round, constituents choose which links to operate
- Awarded payoffs depending on the network state

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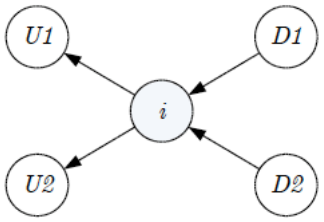
Link Formation



Woodard 2006

D1	D2	U1	U2	π_i
0	0	0	0	.37
0	0	0	1	.26
0	0	1	0	.59
0	0	1	1	**.92**

D1	D2	U1	U2	π_i
0	1	0	0	.11
0	1	0	1	**.83**
0	1	1	0	.50
0	1	1	1	.64

D1	D2	U1	U2	π_i
1	0	0	0	.49
1	0	0	1	**.66**
1	0	1	0	.20
1	0	1	1	.38

D1	D2	U1	U2	π_i
1	1	0	0	.02
1	1	0	1	.41
1	1	1	0	**.87**
1	1	1	1	.75

1. Observe prior states incoming links
2. Choose outgoing links that maximize payoff given observed incoming links
3. All constituents simultaneously change links based on choice in step 2

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Similar Real World Examples

Simplified routing: Observe incoming traffic, choose which outgoing routes to give priority

Supply networks: Firms payoffs depend on who offers to buy their finished goods and from whom they choose to purchase supplies (note that links in this case represent monetary flows, goods would flow in the opposite direction)

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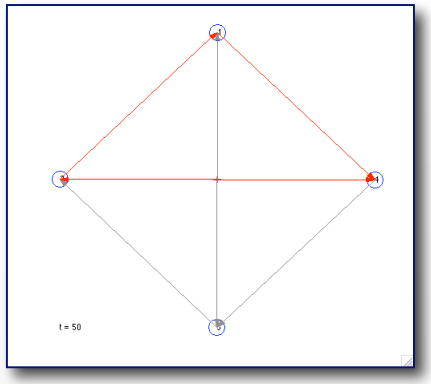
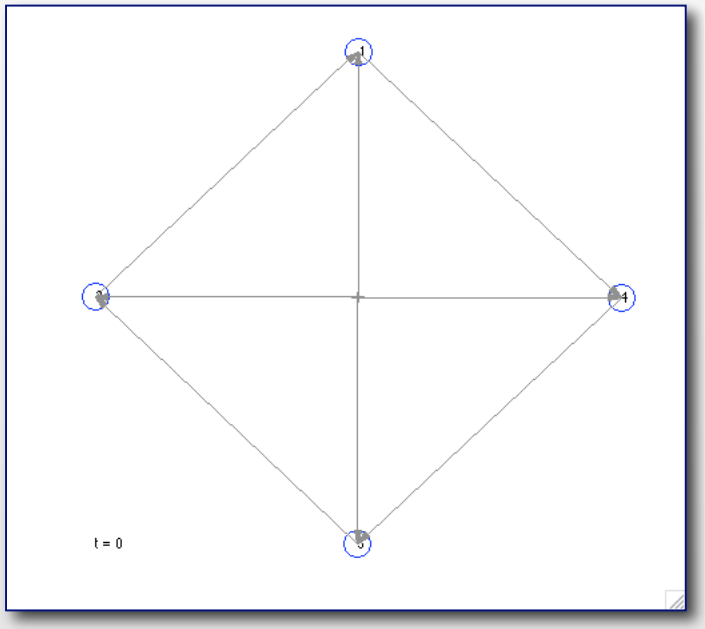
A small example run

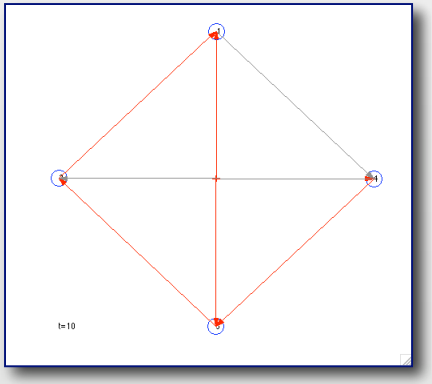
N = 4 firms
K = 2 outgoing links per firm
Simultaneous moves
No bargaining
No global incentives



Converged State #1



Initial State



Converged State #2

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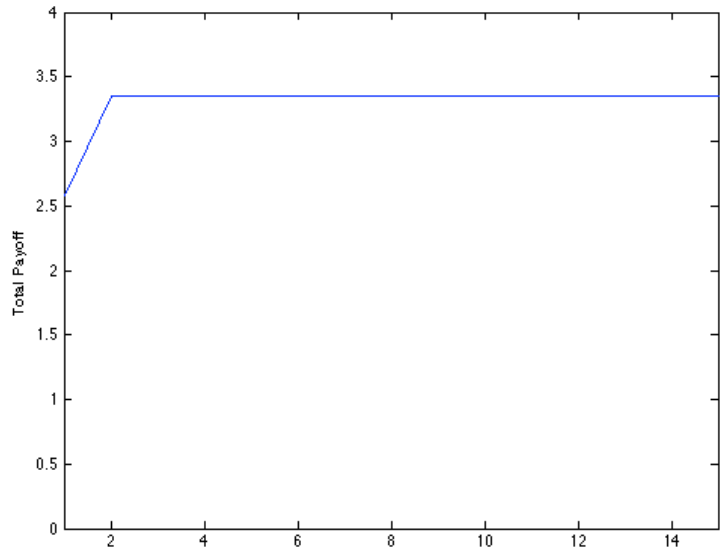
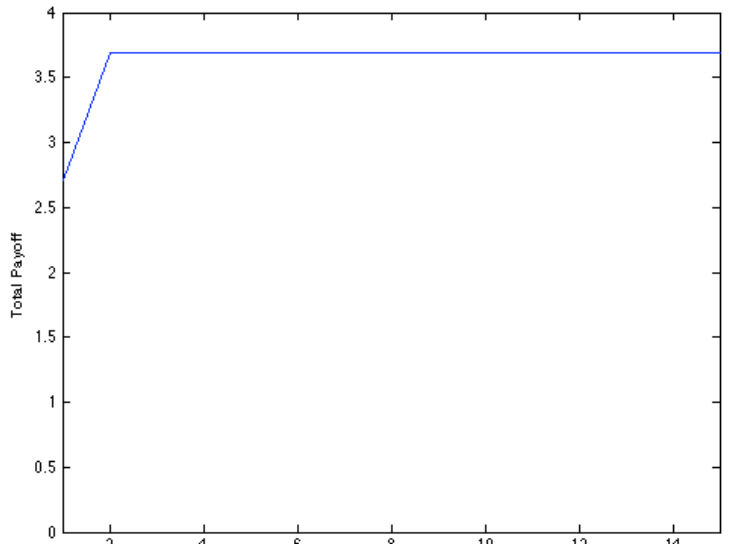
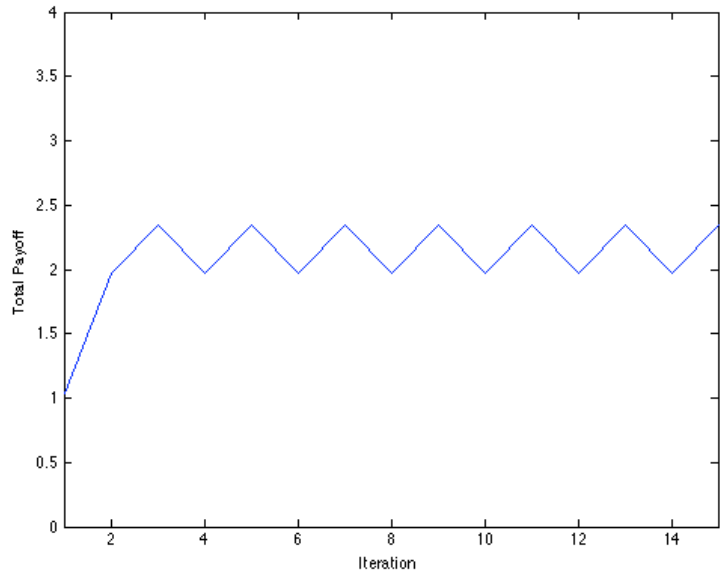
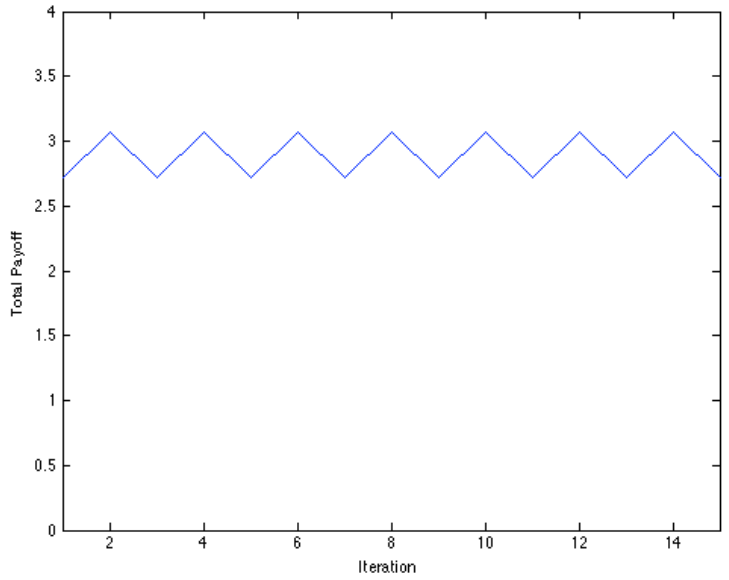
Time traces of total payoff









Convergence

- Configuration converges either to a
  - Fixed point: Nash Equilibrium
  - Limit Cycle: Preference top cycle -- not equilibrium
- For small N, K can map entire space of possible network states and determine which connection decision will be made for each state

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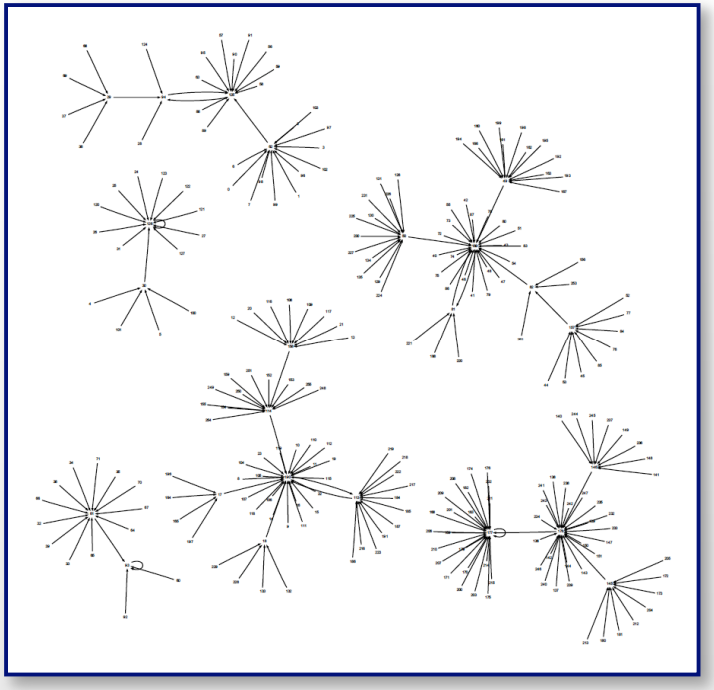
N = 4; K = 2 State Space

- For a given N, K, institutions and payoff structure…
- Each network configuration maps to an integer, one bit per link
- An arrow connecting two states means that if the network is in the tail state, it will transition to the head state in the following round



This structure provides an overall map of the collective preference space of all constituents

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Attraction Basins

- State space divided into several basins of attraction
- If the network state is in one of the basins, it will never leave, and will converge to the limit set of the basin (similar to Kauffman's (1993) Random Binary Networks)
- Limit sets are the stable intermediaries in collaborative decision space (i.e. political stability as Maier puts it)

Kauffman, SA (1993) The Origins of Order: Self-organization and Selection in Evolution. Oxford University Press.

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Implications

- Once the system is in an attraction basin, it cannot get out
- SoS stakeholders can use the limit sets as stable forms, providing incentive to move from one attraction basin to another
  - This is management of the SoS when incentive availability is uncertain
  - If an external SoS stakeholder wishes to keep the system in some desired state, they must encourage incentivize creation such that the preferred state is the equilibrium point under the implied payoff structure

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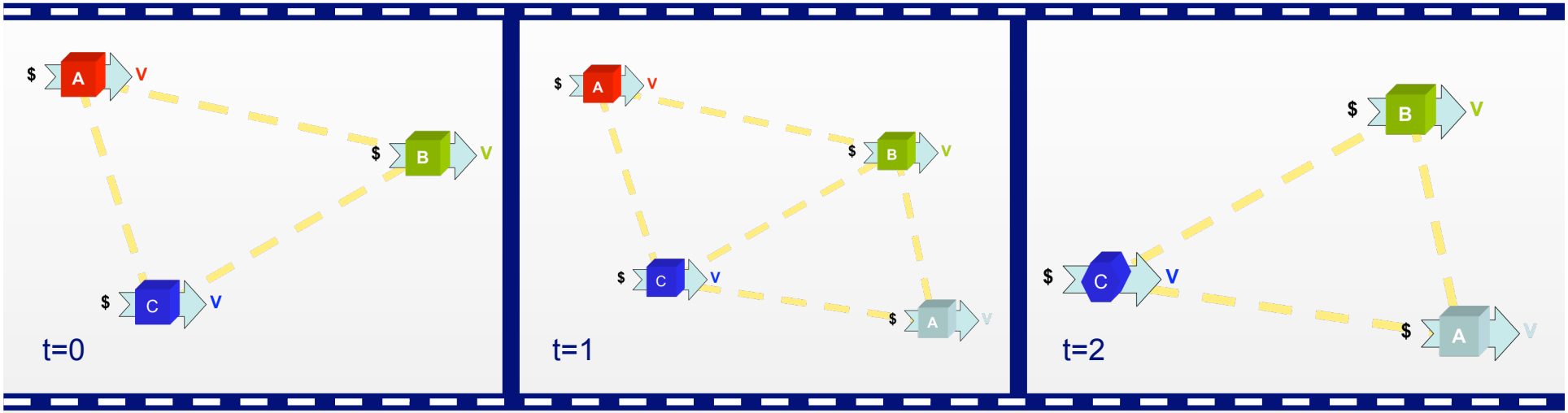
Network abstraction



SoS Agents value the behavior of the SoS as a whole. They directly control some sub-systems of the SoS and/or constituents

SoS Agents provide incentives to CAs to encourage beneficial formation interfaces and changes in constituents behavior that would not occur otherwise

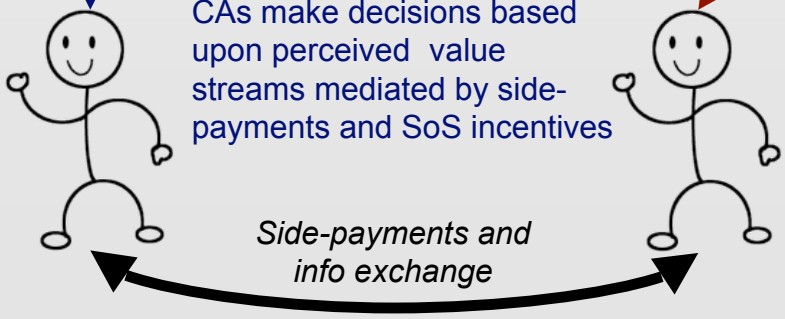
Interactions over time lead to varying SoS structure and behavior

Incentives

Competing SAs provide alternate incentives

Constituent Agents (CAs) control constituent systems and form interfaces with other constituents

CAs make decisions based upon perceived value streams mediated by side-payments and SoS incentives



Side-payments and info exchange

SoS architecture as mechanism design

Principal-Agent problem: A game in which one player's (the principal) payoff is determined by the action of another player (the agent) who also has preferences on those actions. The principal cannot take the action directly and must rely upon the agent in order to receive their payoff.

Mechanism design: "Mechanism design is the subfield of microeconomics and game theory that considers how to implement good system-wide solutions to problems that involve multiple self-interested agents, each with private information about their preferences."

DC Parks (1993) Iterative Combinatorial Auctions: Achieving Economic and Computational Efficiency. Ph.D. Thesis. University of Pennsylvania

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Potential Mechanisms for SoS

Approach	Examples from the Internet
Change the payoffs through **incentives** or penalties	Bundling of services at a discount
Change decisions by providing additional **information**	Publishing blacklists of spammers
Redefine the relationships between the constituents through **integration** or reallocation	Vertical integration of tier I and tier II network operators
Change the **institutions** under which the constituents interact and the system is operated	New TCP standard

Under managerial independence, mechanism such as these are the real “knobs” available to the SoS architect

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Limitations

- Accounting for delays and other temporal phenomena
- Computational / modeling complexity
  - Mega-models are often intractable
  - Can still be used to understand the mechanisms behind heuristics
  - May be able to build “flight simulators” so that architects can be sensitized to these issues
- Only one piece of the puzzle
  - Relies upon other work in systems modeling and design to provide inputs to the decision problems
  - Assumes that agents are rational and that their preferences can be characterized
  - Not all systems reach stable forms

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On-going work

- On-going work
  - Mathematical formulation of the mechanism design problem tailored for SoS
  - Transportation system model in progress
- Thesis with the formulation and examples of each of the four mechanism

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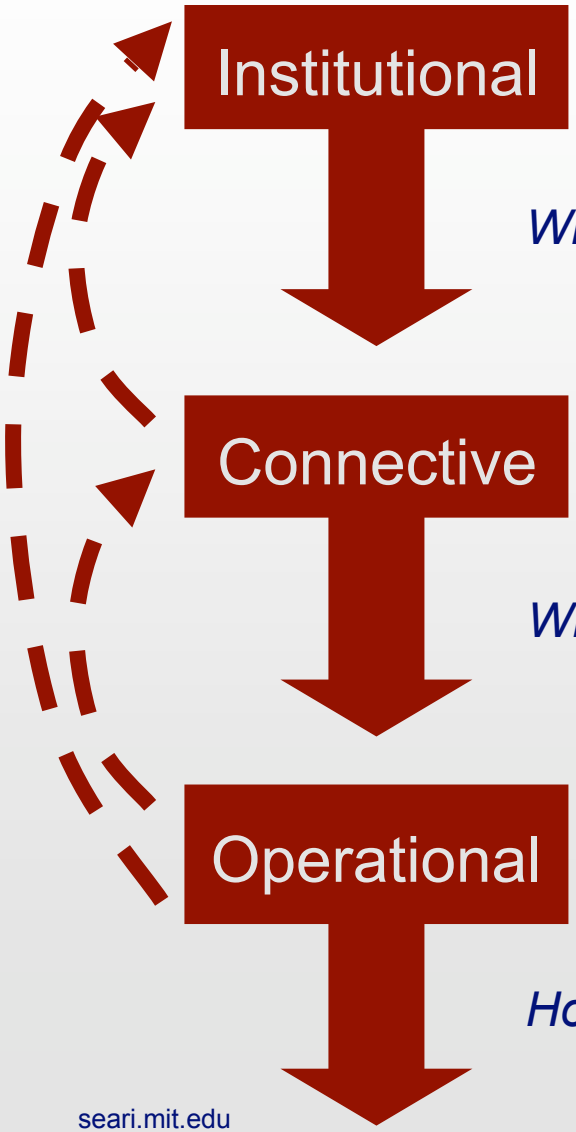
Decision making hierarchy



Standards, protocols, high level norms

Which connections are possible/allowed?

Connections between components to form SoS

Which connections are made?

Management, maintenance and operation of SoS

How does the SoS operate to create SoS value?

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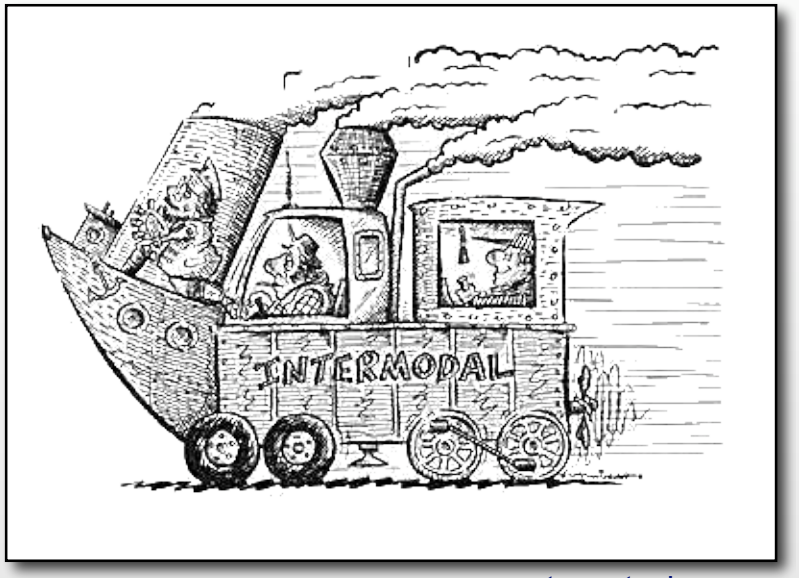
Example 1: Intermodal Transport

- Interconnection of transportation networks of different modalities
  - Rail-Road-Water-Air
- Interconnection points are ports
- Each mode maybe controlled by an independent authority
- The ports can also be independent



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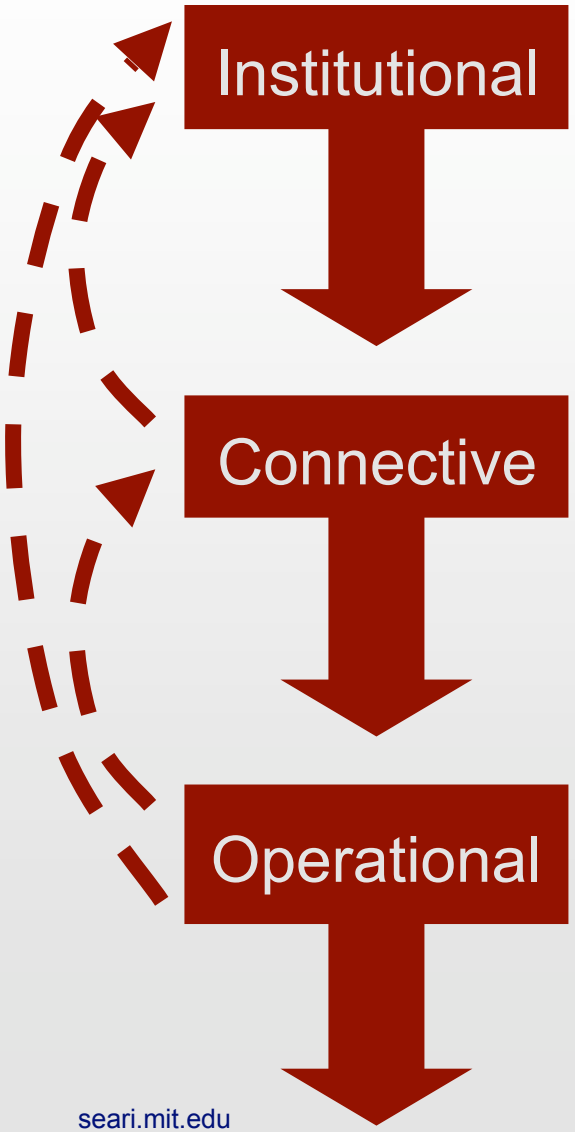
Example 1: Intermodal Transport



Rail/Road/Ship container standards
Regulations for Bills of Lading

Port construction

Port operation, route planning

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Examples

- **Construction:** Building a shopping complex one wing at a time
- **Space systems:** Staged deployment of constellation
- **Air Defense:** Multi-capability systems that have fallback states in the event of failure of part of the SoS

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