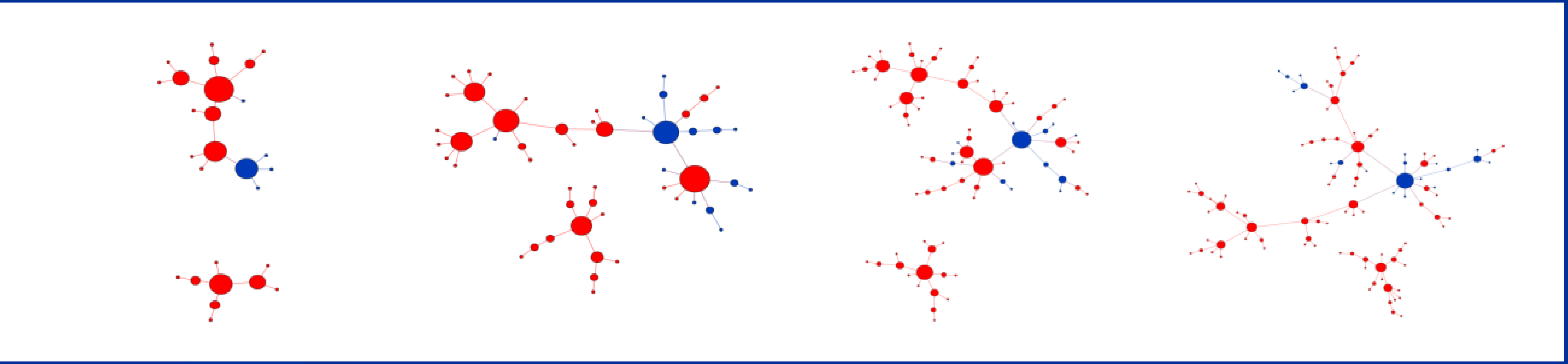
Modeling Dynamics *of* and *on* Networks Simultaneously

Theory-Driven and Data-Driven Approaches



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Modeling and Predicting State...

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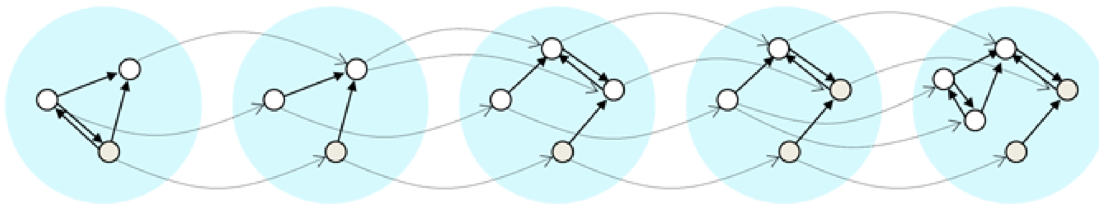

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CDI-Type I: Modeling and Predicting State-Topology Coevolution of Complex Adaptive Networks

Project Homepage

This project is supported by the NSF Cyber-enabled Discovery and Innovation Program (Award #: NSF BCS-1027752).
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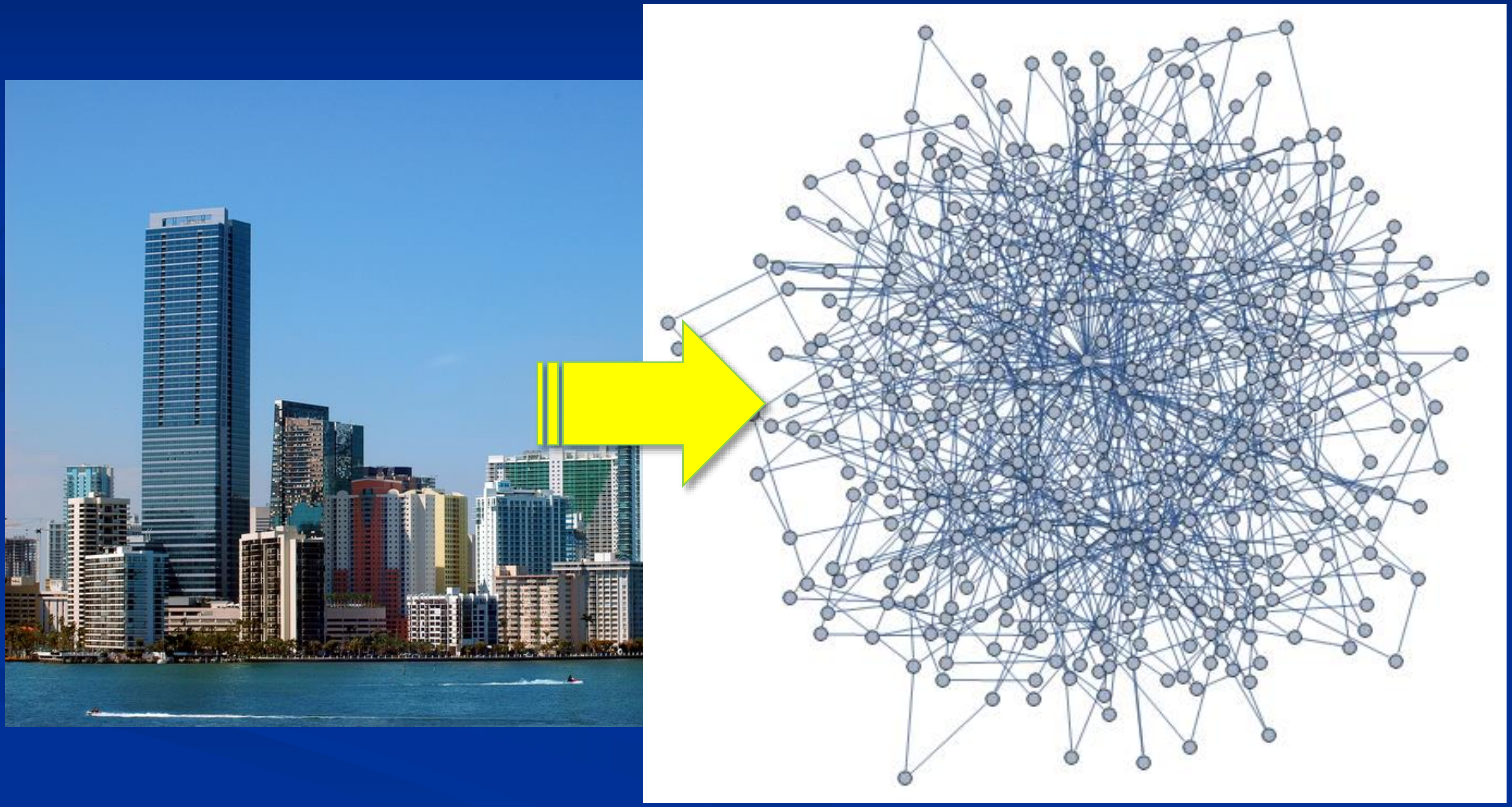
About the Project

The rapidly growing complex network science has presented novel approaches to complex systems modeling that were not fully foreseen even in a decade ago. It addresses the self-organization of complex network structure and its implications for system behavior, which holds significant cross-disciplinary relevance to many fields of natural and social sciences, particularly in today's highly networked social/political /economical circumstances.

Interestingly, complex network science has traditionally addressed either "dynamics on networks" (state transition on a network with a fixed topology) or "dynamics of networks" (topological transformation of a network with no dynamic state changes) almost separately. In many real-world complex biological and social networks, however, these two dynamics interact with each other and coevolve over the same time scales. Modeling and predicting state-topology coevolution is now recognized as one of the most significant challenges in complex network science.

The goals of this project are to establish a generalized modeling framework that can effectively describe state-topology coevolution of complex adaptive networks and to develop computational methods for automatic discovery of dynamical rules that best capture both state transition and topological transformation in empirical data. To achieve these goals, graph rewriting systems are used as a means of unified representation of state transition and topological transformation. Network evolution is formulated in two parts, extraction and replacement of

Complex Systems Modeled as Networks



Complex Systems Made Simple?

- Network = nodes + links
- Statistical properties
- Topological properties
- Dynamical properties

Dynamics *on* networks

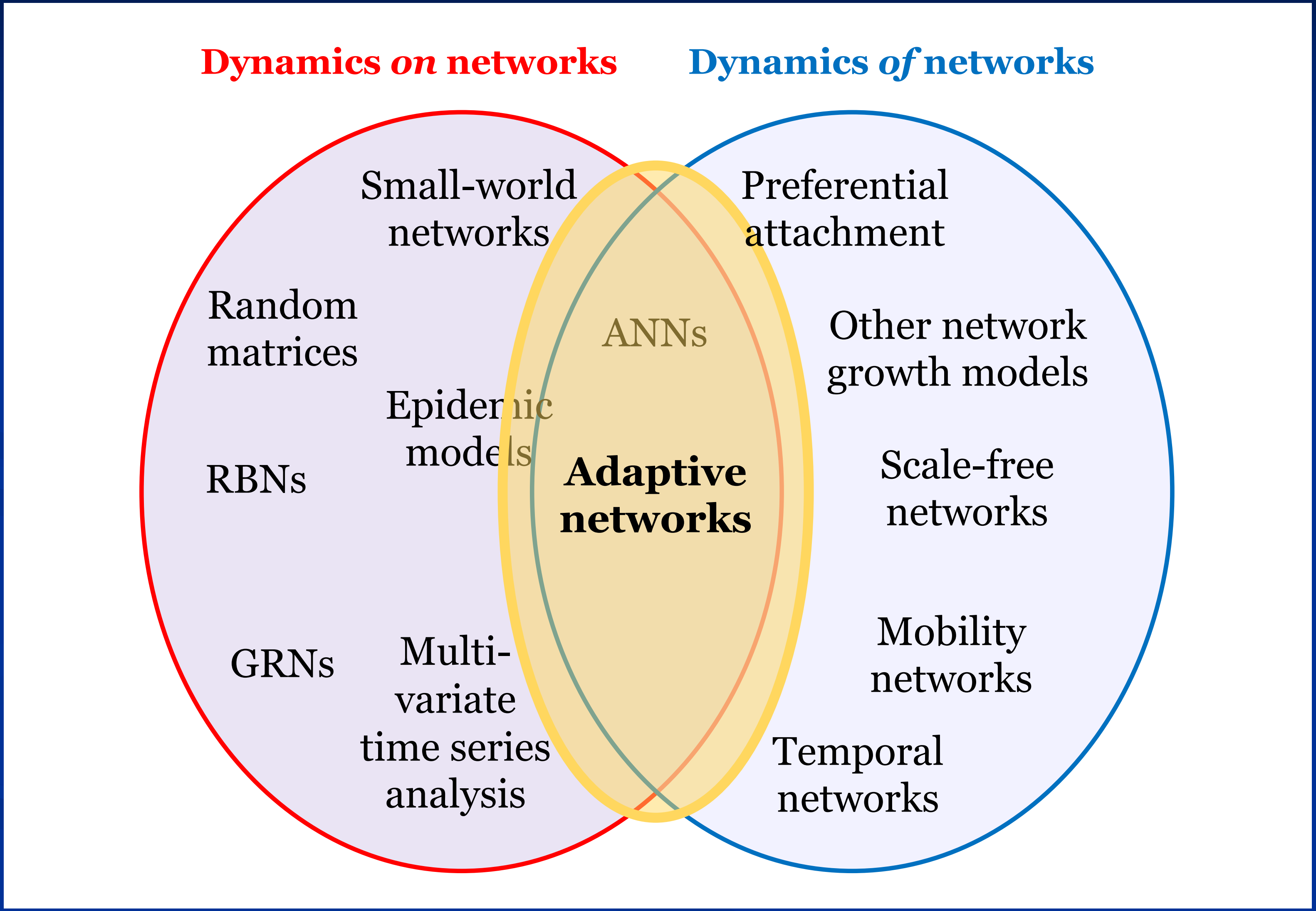
Dynamics *of* networks

What's Missing?

- Many real-world complex systems show coupling between "dynamics ***of*** networks" and "dynamics ***on*** networks"

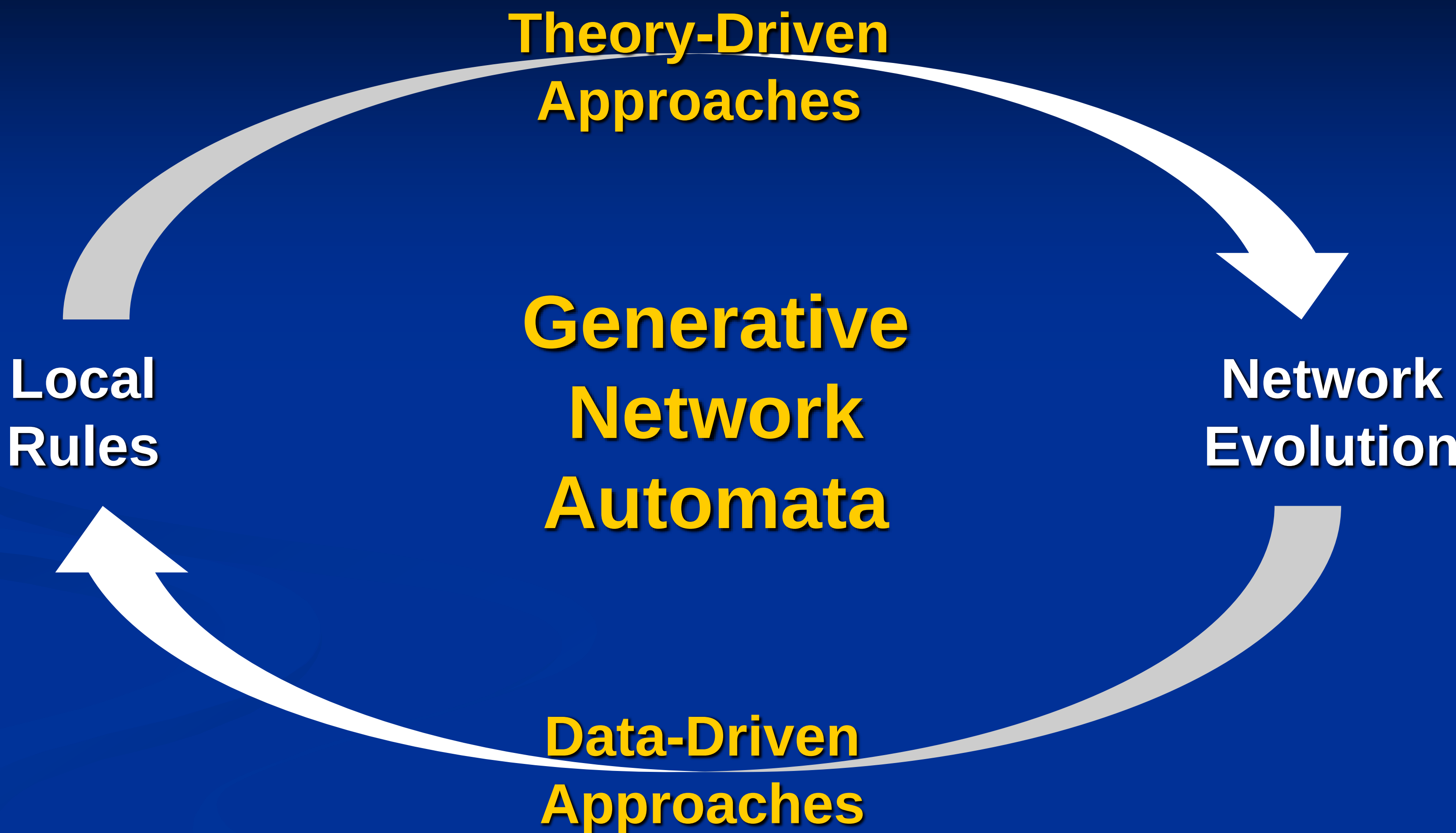
System	Nodes	Edges	States of nodes	Topological changes
Organism	Cells	Intercellular communication channels	Gene/protein activities	Fission and death of cells during development
Ecological community	Species	Interspecific relationships	Population	Speciation, invasion, extinction of species
Human society	Individual	Conversations, social relation-ships	Social, professional, economical, political, cultural statuses	Changes in social relationships, entry and withdrawal of individuals
Communica-tion network	Terminals, hubs	Cables, wireless connections	Information stored and transacted	Addition and removal of terminal or hub nodes

We Need Higher-Order Modeling Frameworks



Adaptive Networks

- Complex networks whose states and topologies co-evolve, often over similar time scales
  - Node states adaptively change according to link states
  - Link states (weights, connections) adaptively change according to node states



Sayama, Pestov, Schmidt, Bush, Wong, Yamanoi, & Gross, *Comput. Math. Appl.*, 65, 1645-1664, 2013.

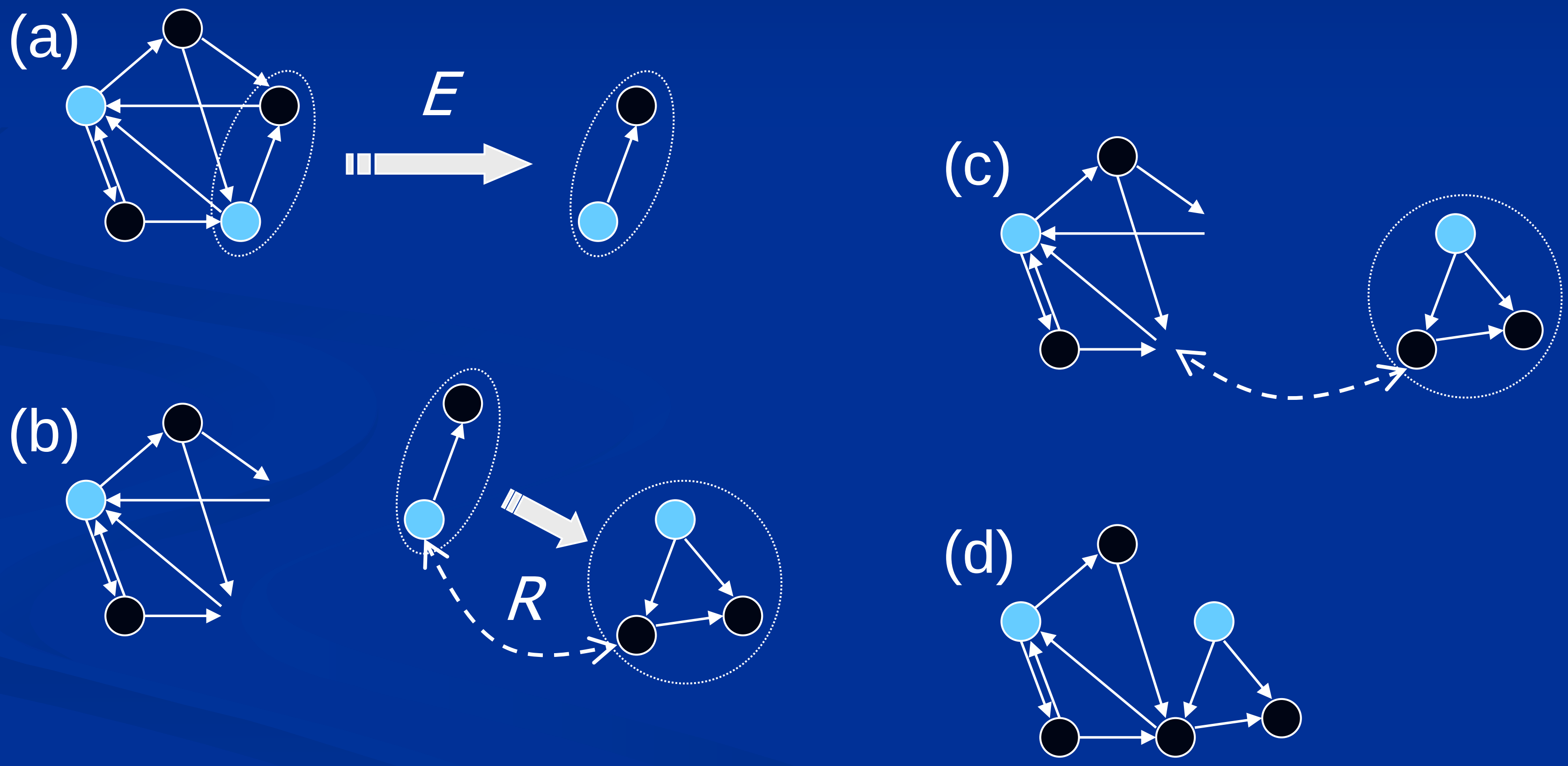
Generative Network Automata

- Unified representation of dynamics *on* and *of* networks using graph rewriting

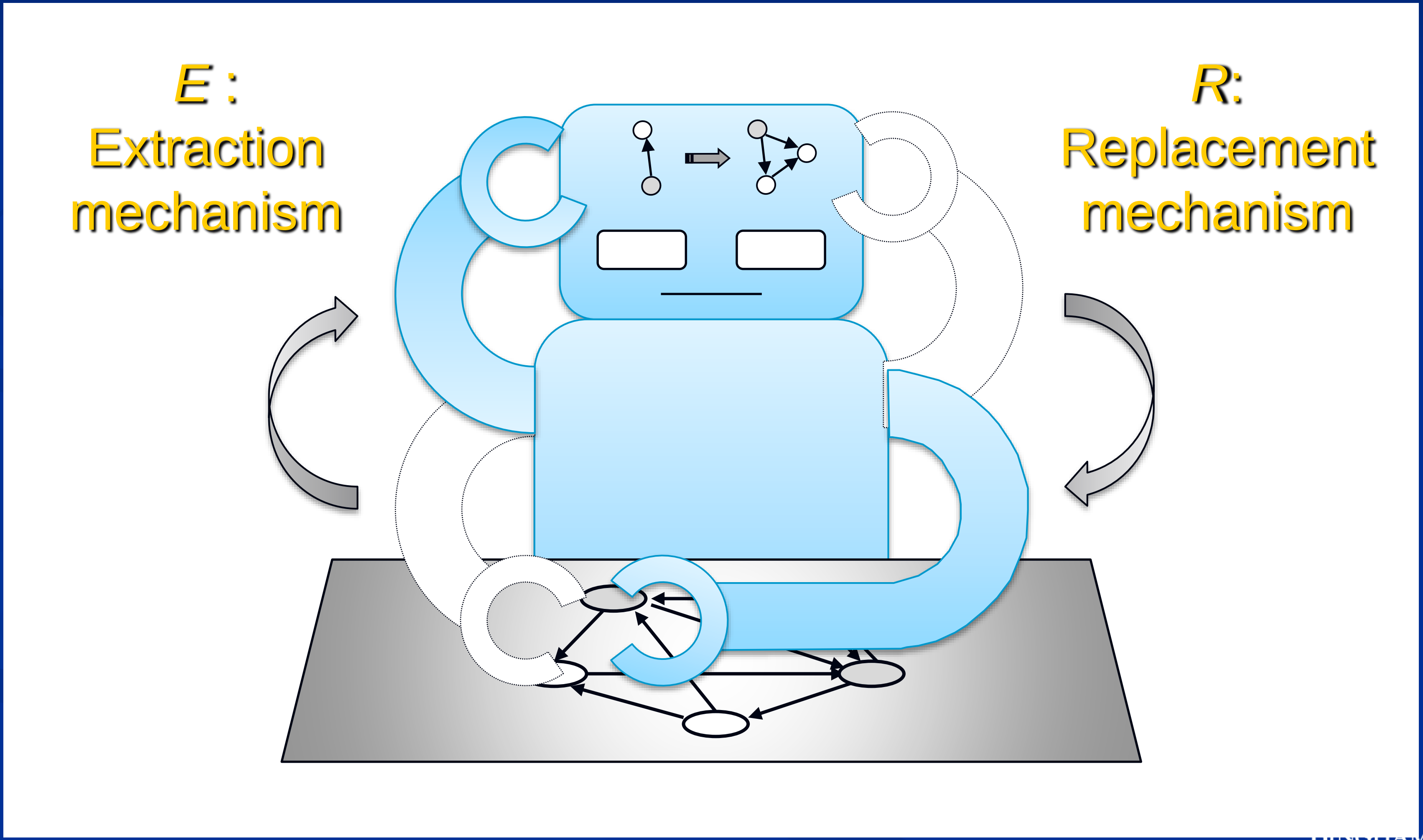
- Defined by <*E*, *R*, *I*>:
  - *E* : Extraction mechanism — When, Where
  - *R* : Replacement mechanism — What
  - *I* : Initial configuration

Sayama, *Proc. 1st IEEE Symp. Artif. Life,* 2007, pp.214-221.

GNA Rewriting Example



Actually, It's a Generative Network Automa~~ta~~-on



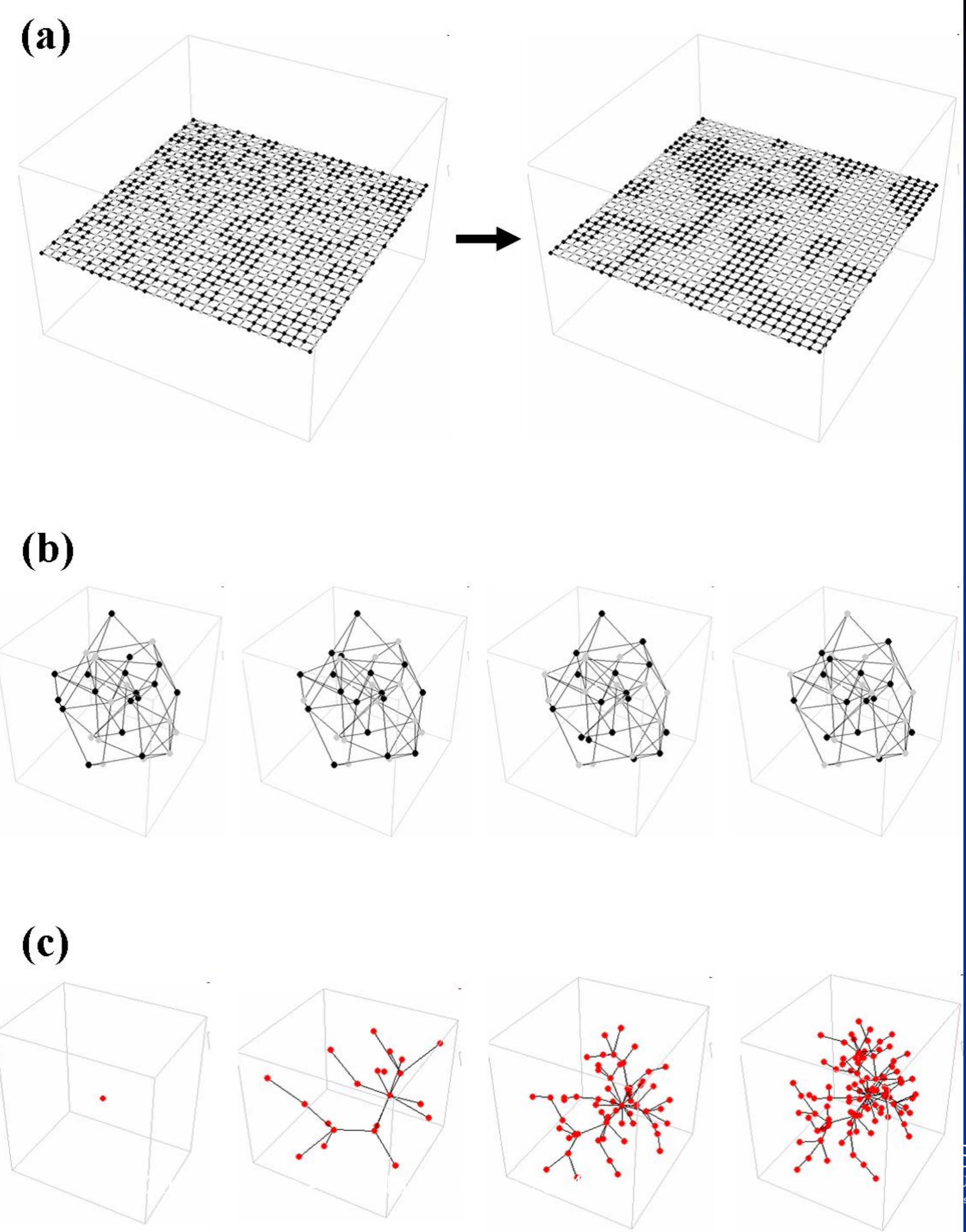
Generality of GNA

- GNA can uniformly represent in <*E*, *R*, *I*>:
  - Conventional dynamical systems models
    - If *R* always conserves local network topologies and modifies states of nodes only
    - E.g. CA, ANNs, RBNs
  - Complex network growth models
    - If *R* causes no change in local states of nodes and modifies topologies of networks only
    - E.g. small-world, scale-free networks

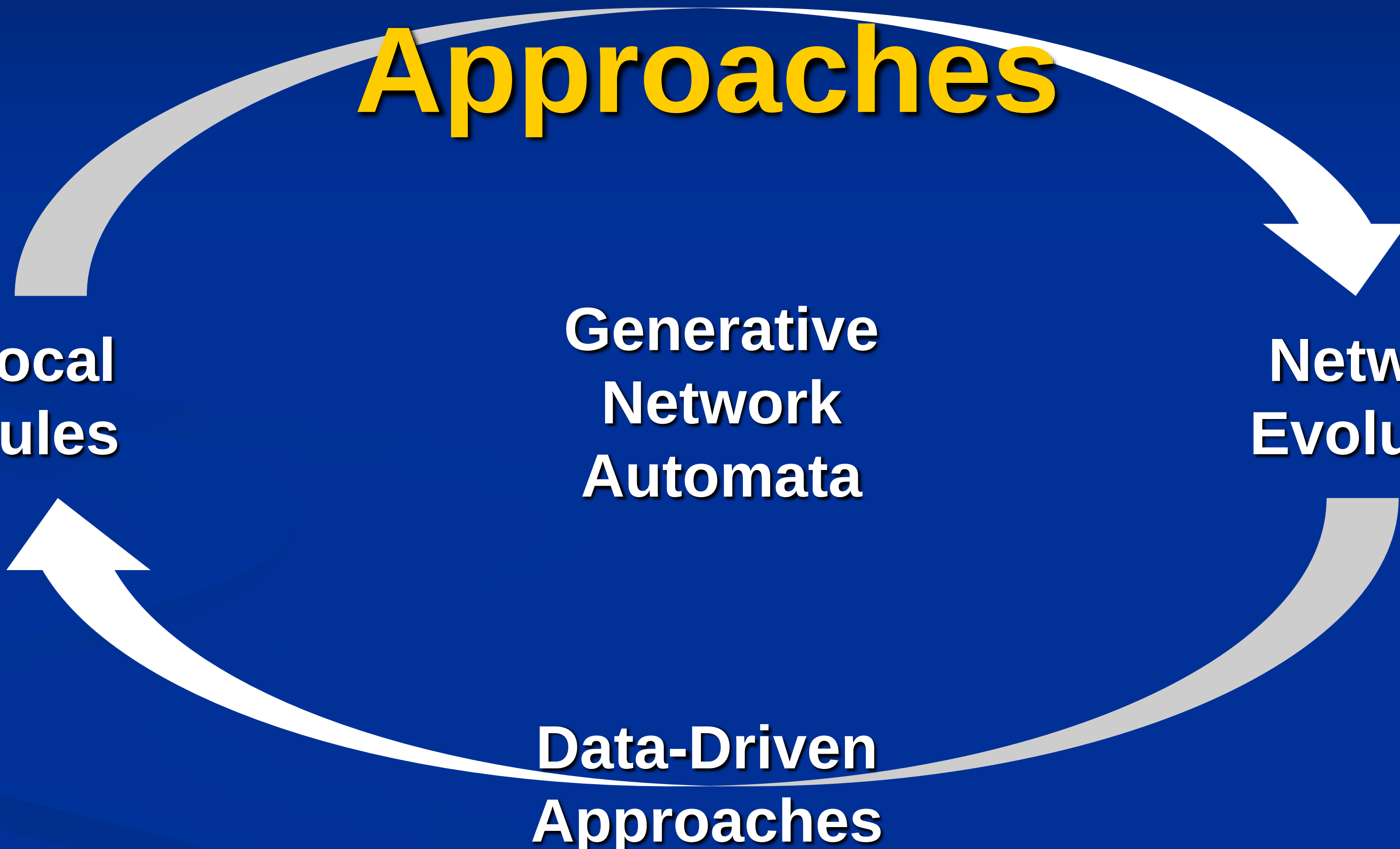
Cellular automata

Random Boolean network

BA scale-free network



Theory-Driven Approaches



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Exhaustive Search of Rules

- *E* samples a node randomly and then extracts an induced subgraph around it
- *R* takes 2-bit inputs (states of the node and neighbors) and makes 1-out-of-10 decisions
  - Total number of possible *R*'s: $10^{2^2} = 10{,}000$
- "Rule Number" *rn*(*R*) is defined by

$$rn(R) = a_{11}\,10^3 + a_{10}\,10^2 + a_{01}\,10^1 + a_{00}\,10^0$$

  - $a_{ij} \in \{0, 1, \ldots 9\}$: Choices of *R* when state of *u* is *i* and local majority state is *j*

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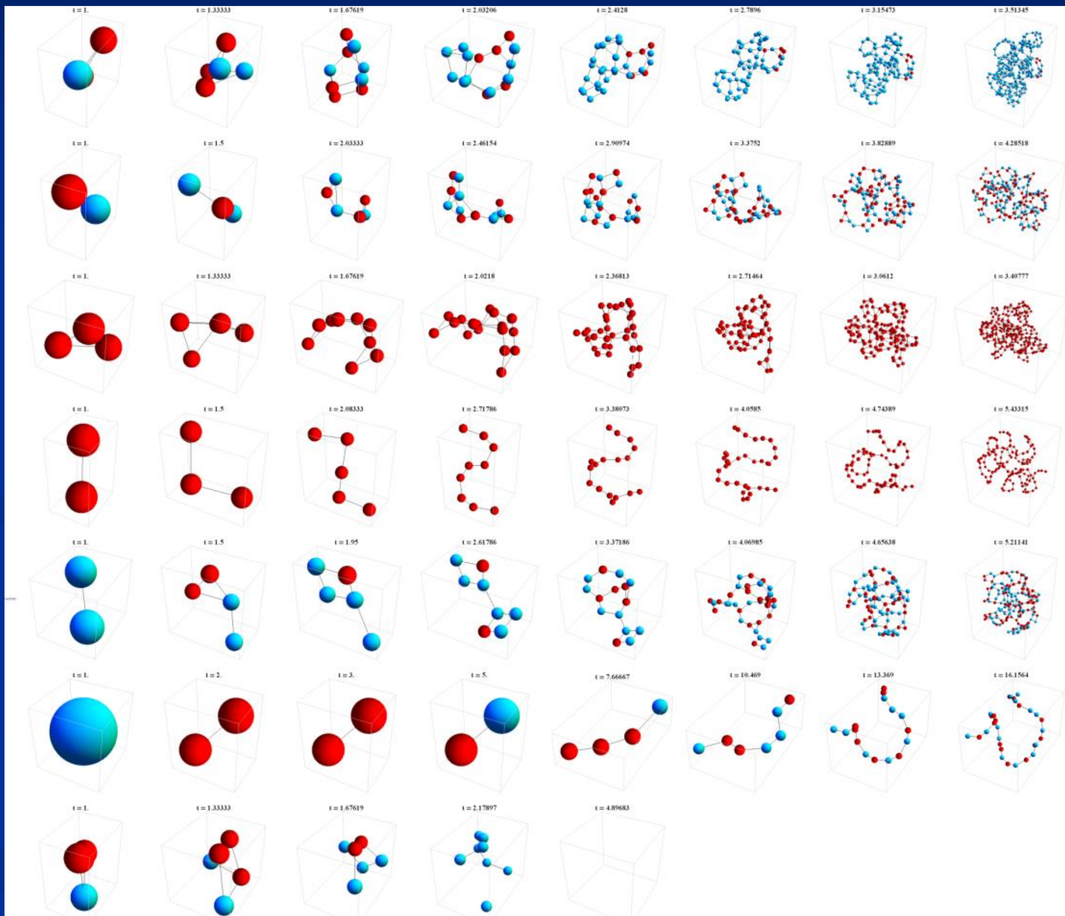
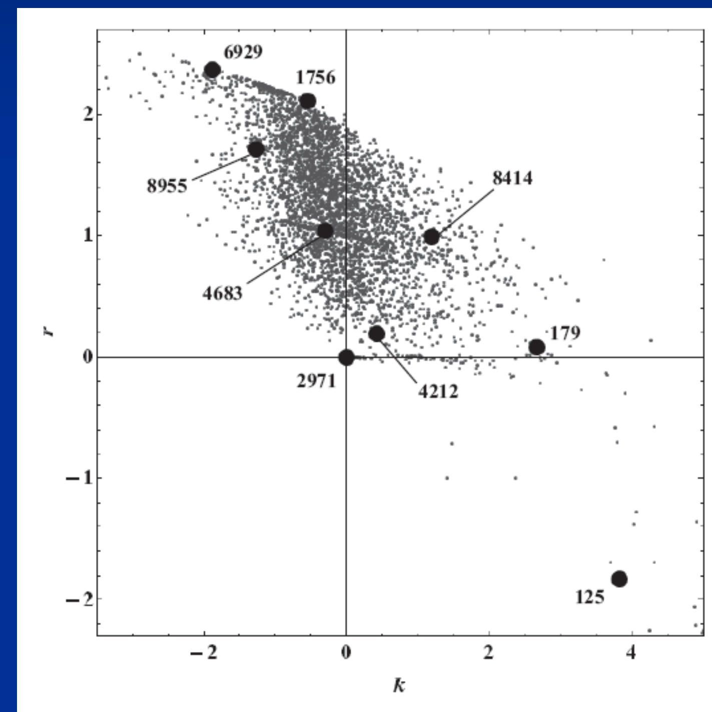
Exhaustive Search of Rules

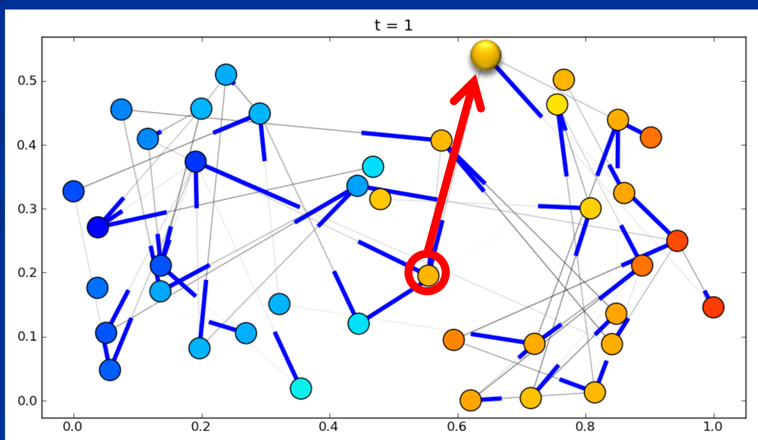


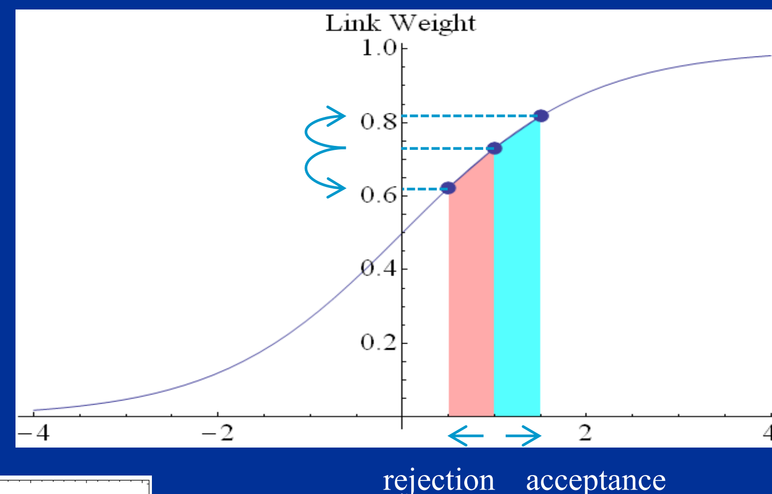


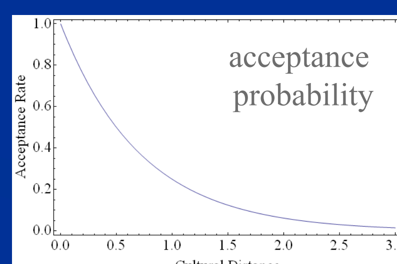
Sayama & Laramee, *Adaptive Networks,* Springer, 2009, pp.311-332.

Application to Computational Organizational Science

- Modeling and simulation of cultural integration in two merging firms







Yamanoi & Sayama, *Comput. Math. Org. Theory* 19, 516-537, 2013.

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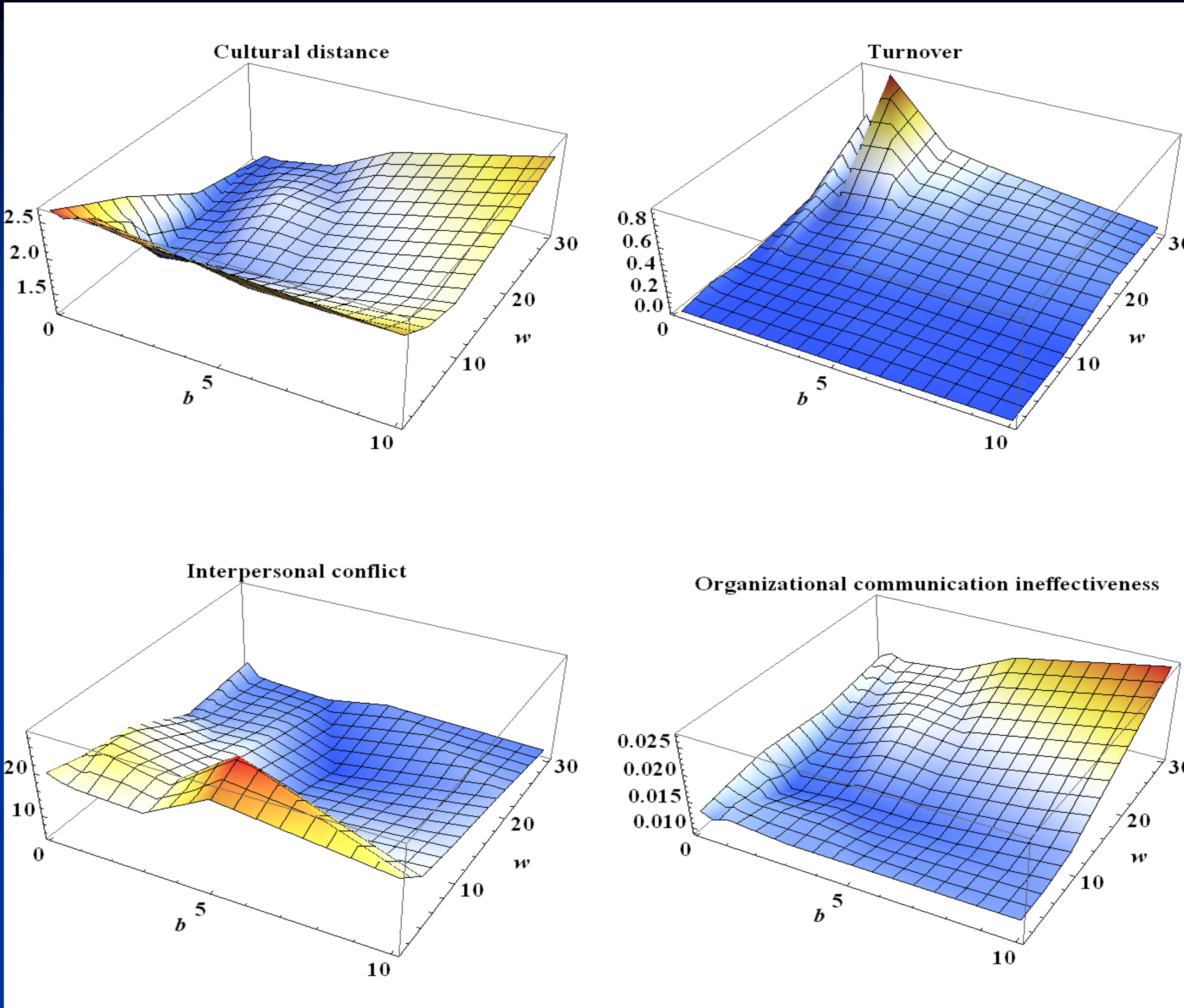
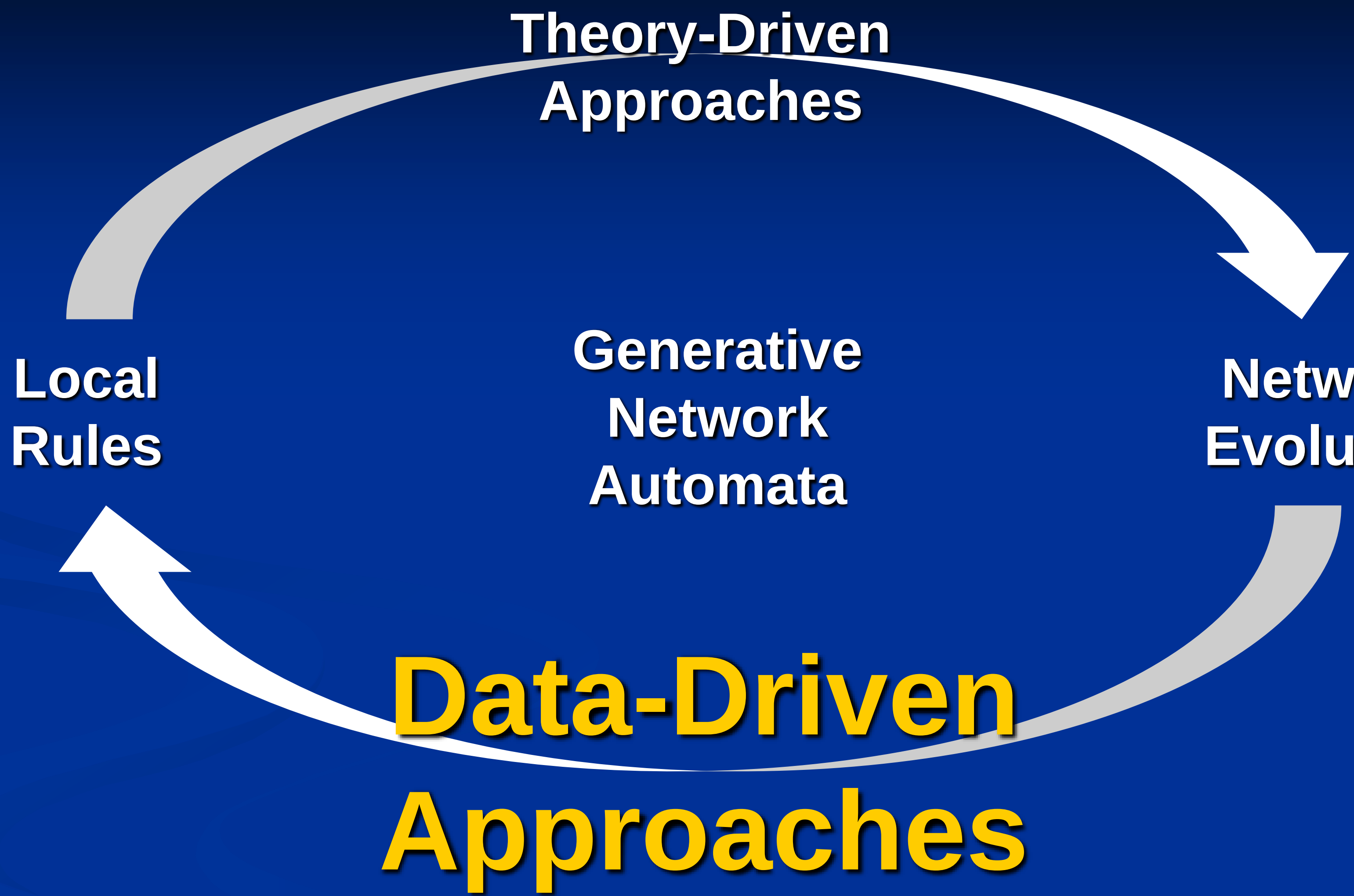


Cultural distance
2.5
2.0
1.5
0
b 5
10
w
10
20
30
Turnover
0.8
0.6
0.4
0.2
0.0
0
b 5
10
w
10
20
30
Interpersonal conflict
20
10
0
b 5
10
w
10
20
30
Organizational communication ineffectiveness
0.025
0.020
0.015
0.010
0
b 5
10
w
10
20
30

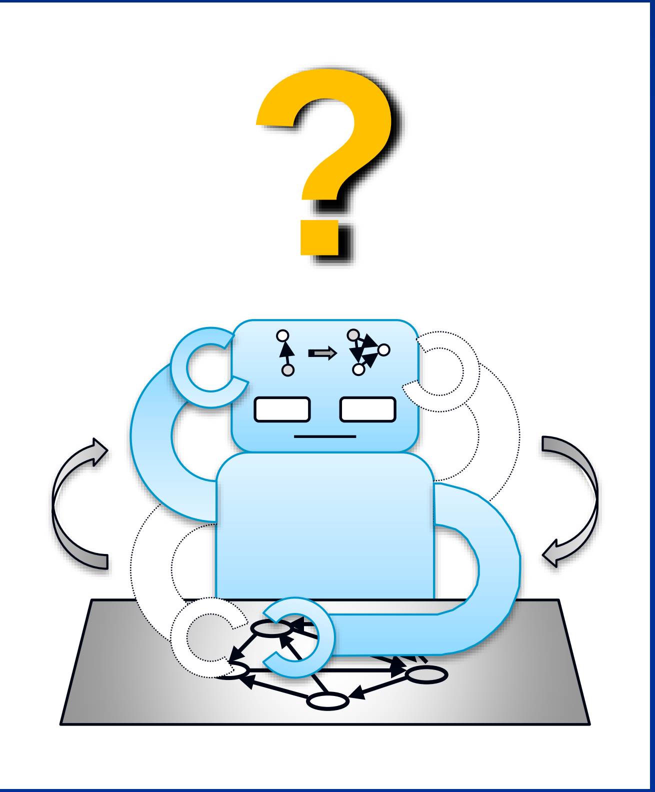

Theory-Driven Approaches
Local Rules
Generative Network Automata
Network Evolution
Data-Driven Approaches

A Challenge

- **Deriving a set of dynamical rules directly from empirical data of network evolution**
- Separation of extraction and rewriting in GNA helps the rule discovery

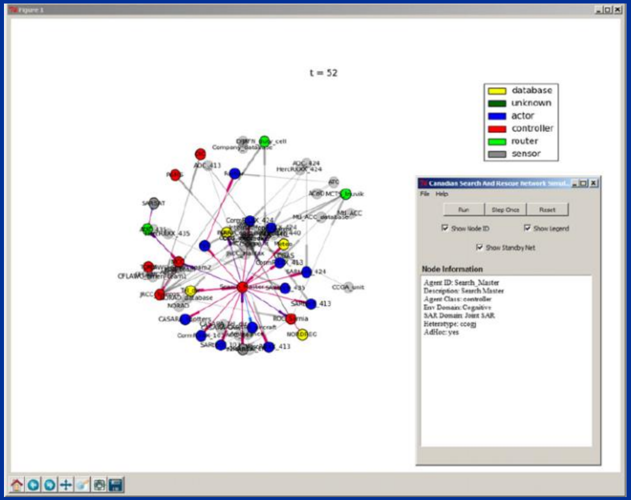
Pestov, Sayama, & Wong, *Proc. 9th Intl. Conf. Model. Simul. Visual. Methods*, 2012.

Schmidt & Sayama, *Proc. 4th IEEE Symp. Artif. Life*, 2013, pp.27-34.



Application to Operational Network Modeling

- Canadian Arctic SAR (Search And Rescue) operational network
  - Rewriting rules manually built directly from actual communication log of a December 2008 SAR incident
  - OpNetSim developed to simulate hypothetical SAR operational network development



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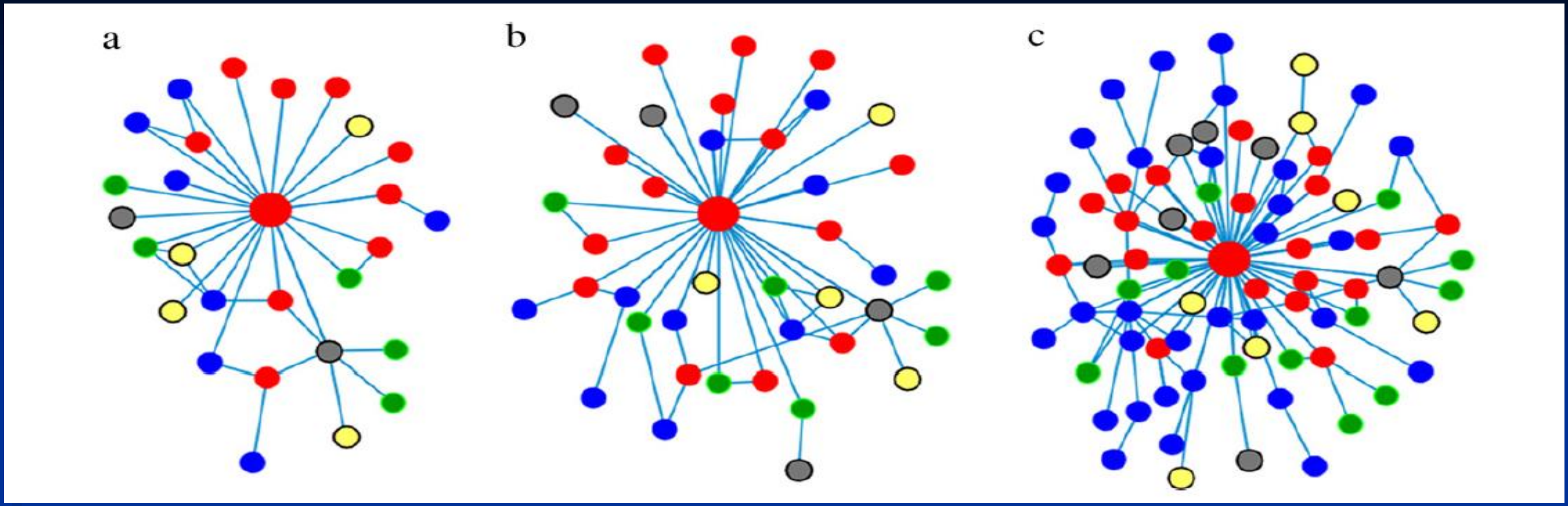

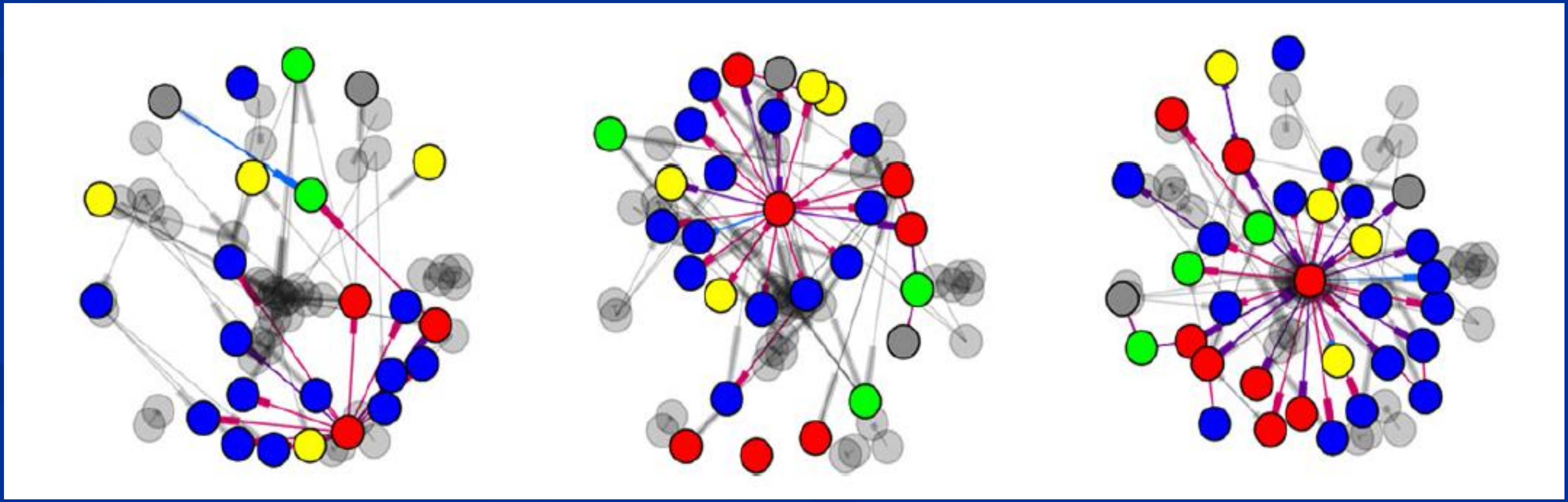

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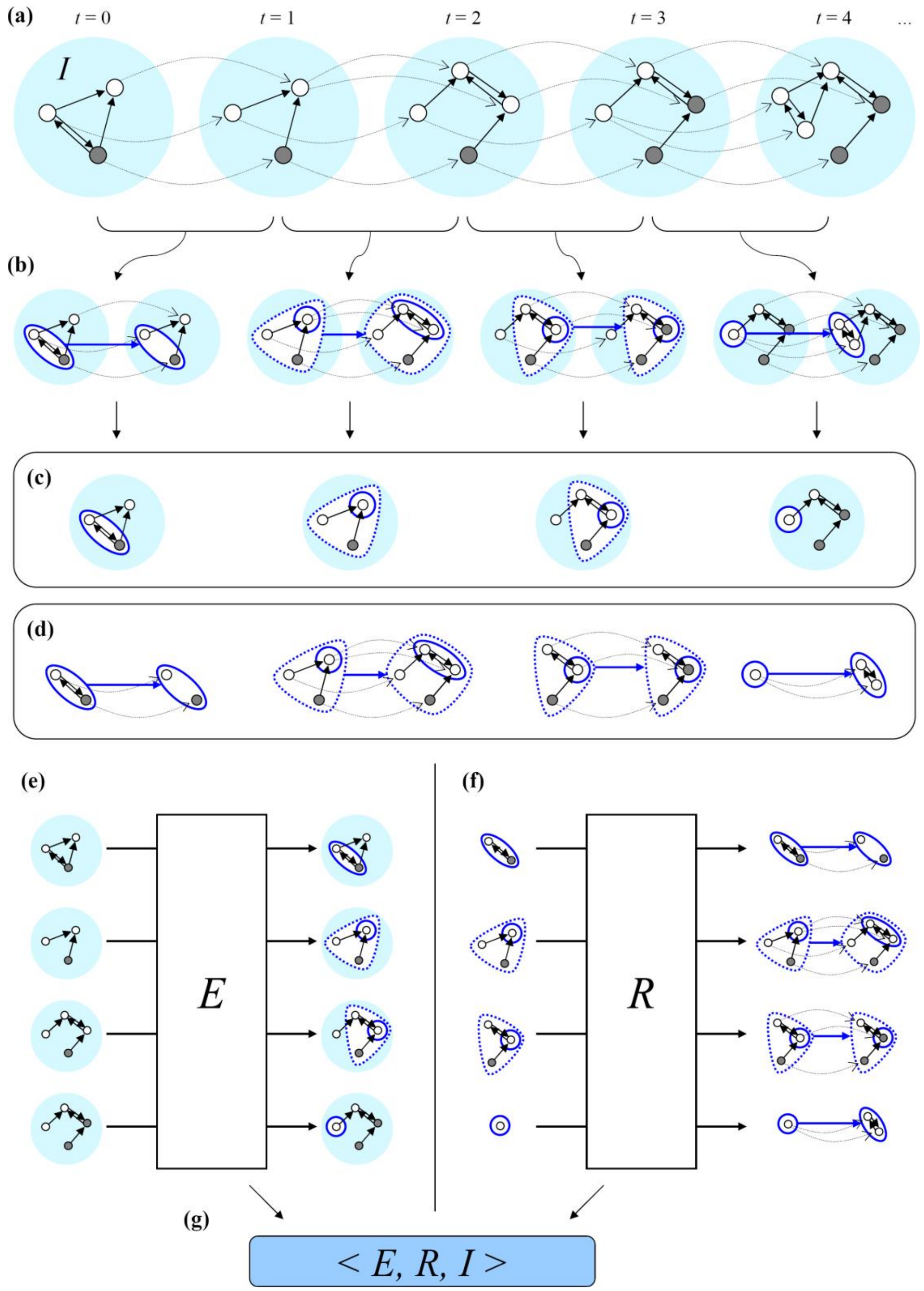
Automation of Model Discovery: PyGNA

- Adaptive network rule discovery and simulation implemented in Python with
  - NetworkX
  - GraphML

- Input: Time series of network snapshots
- Output: A GNA model that best describes given data
  - http://gnaframework.sf.net/



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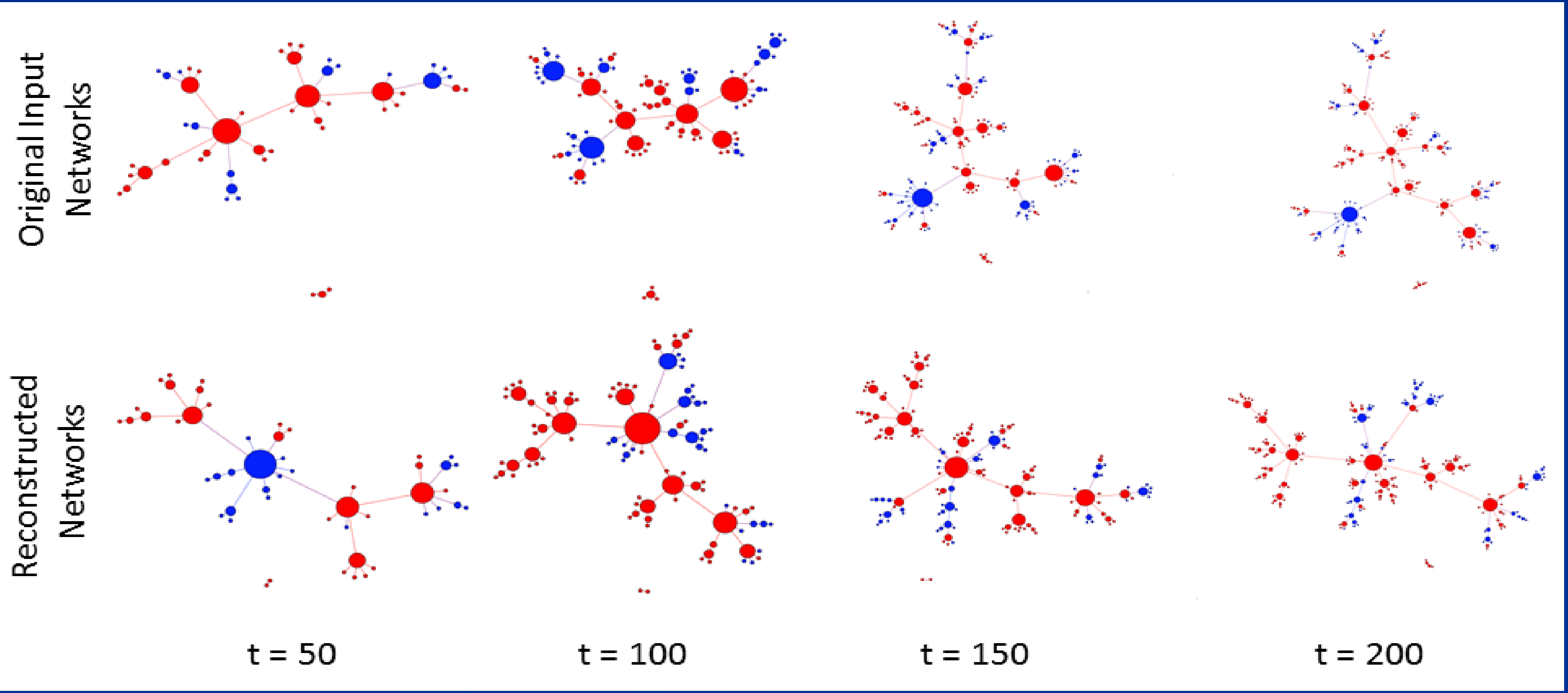
Results

- Example: "Degree-state" networks



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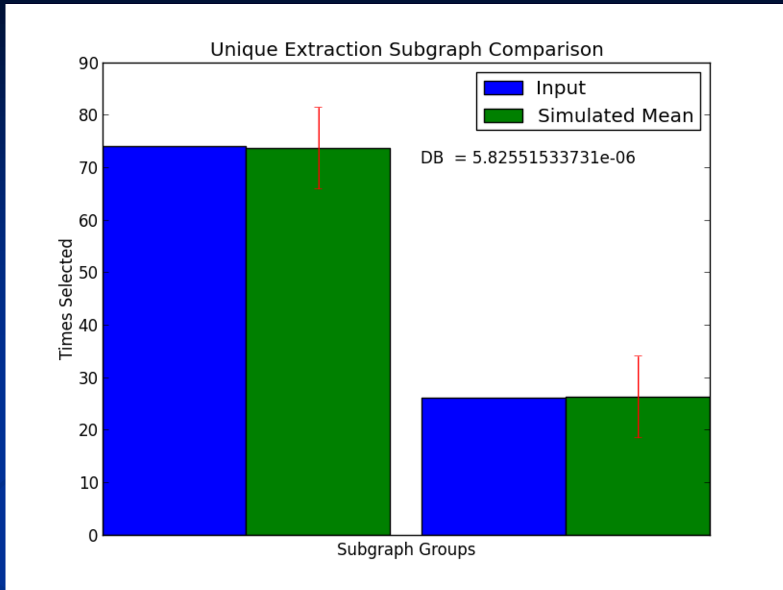
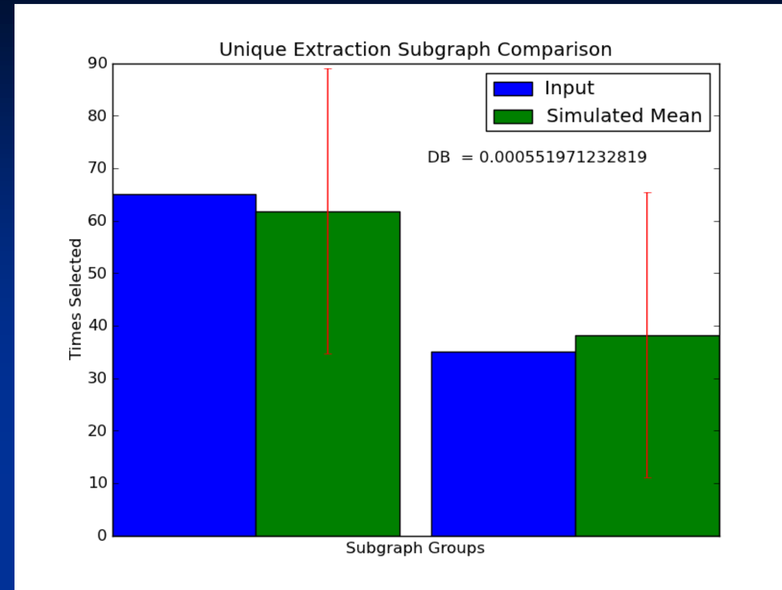
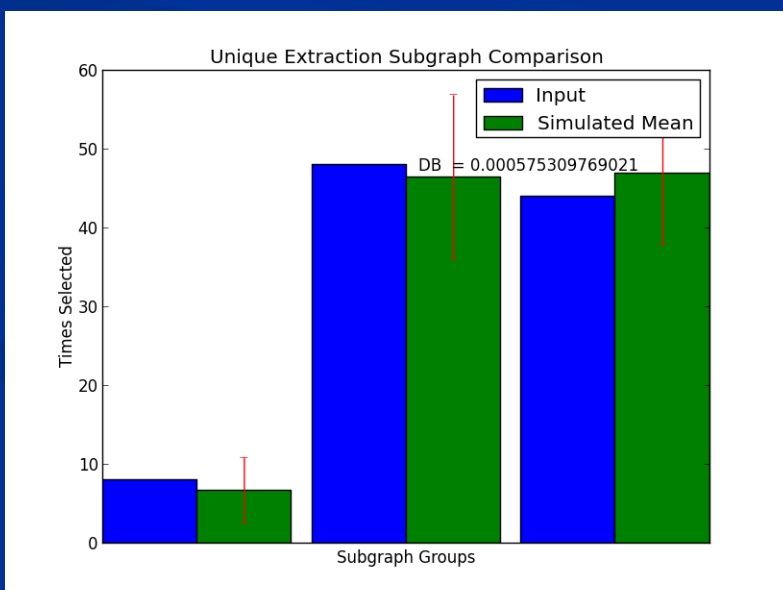
Barabási-Albert



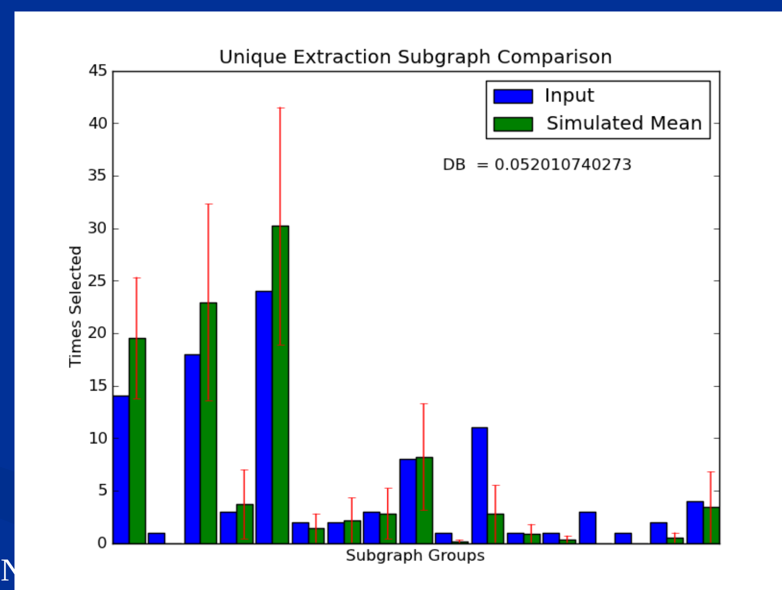
Degree-state



State-based

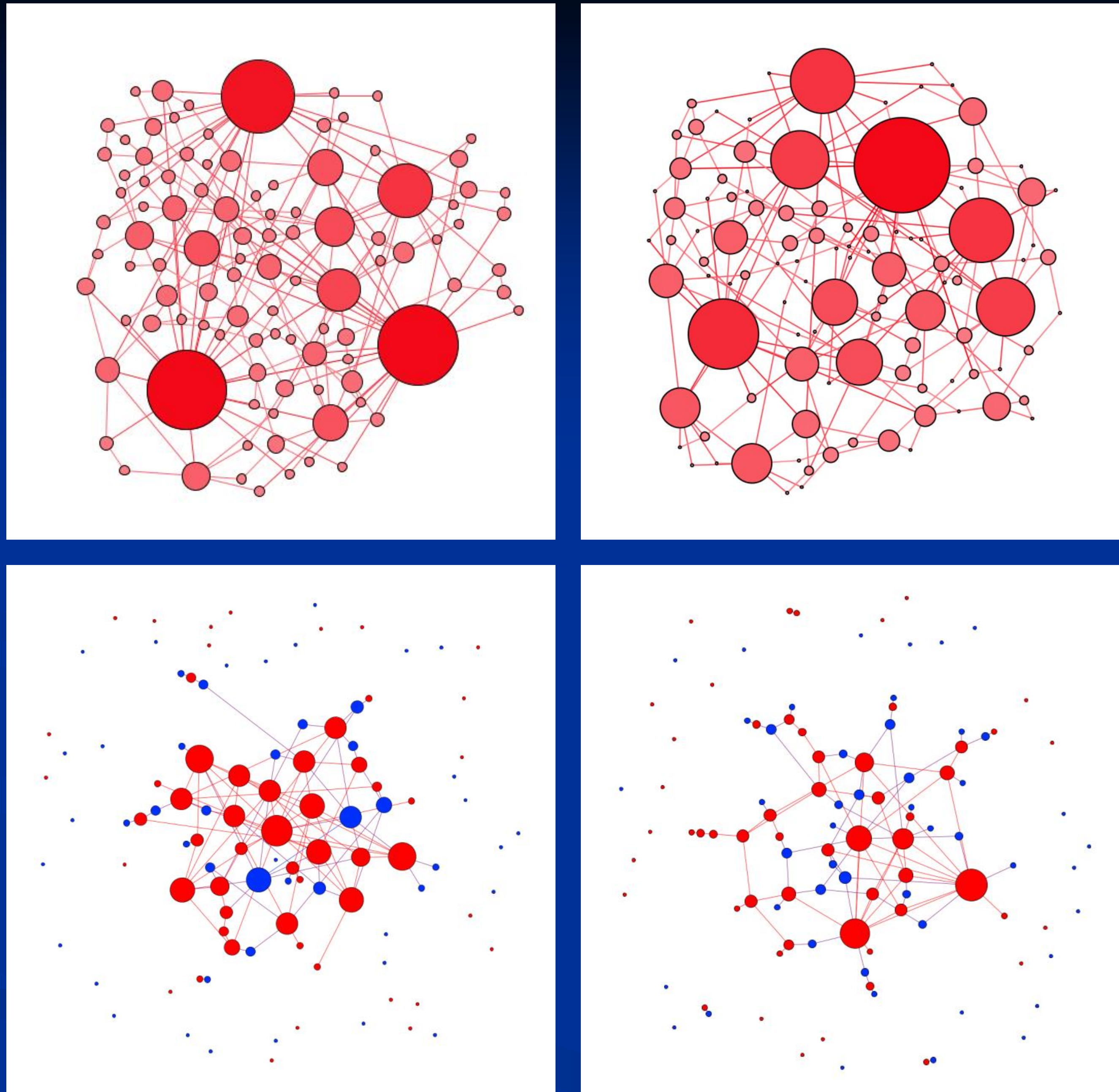


Forest Fire



Barabási-Albert

State-based

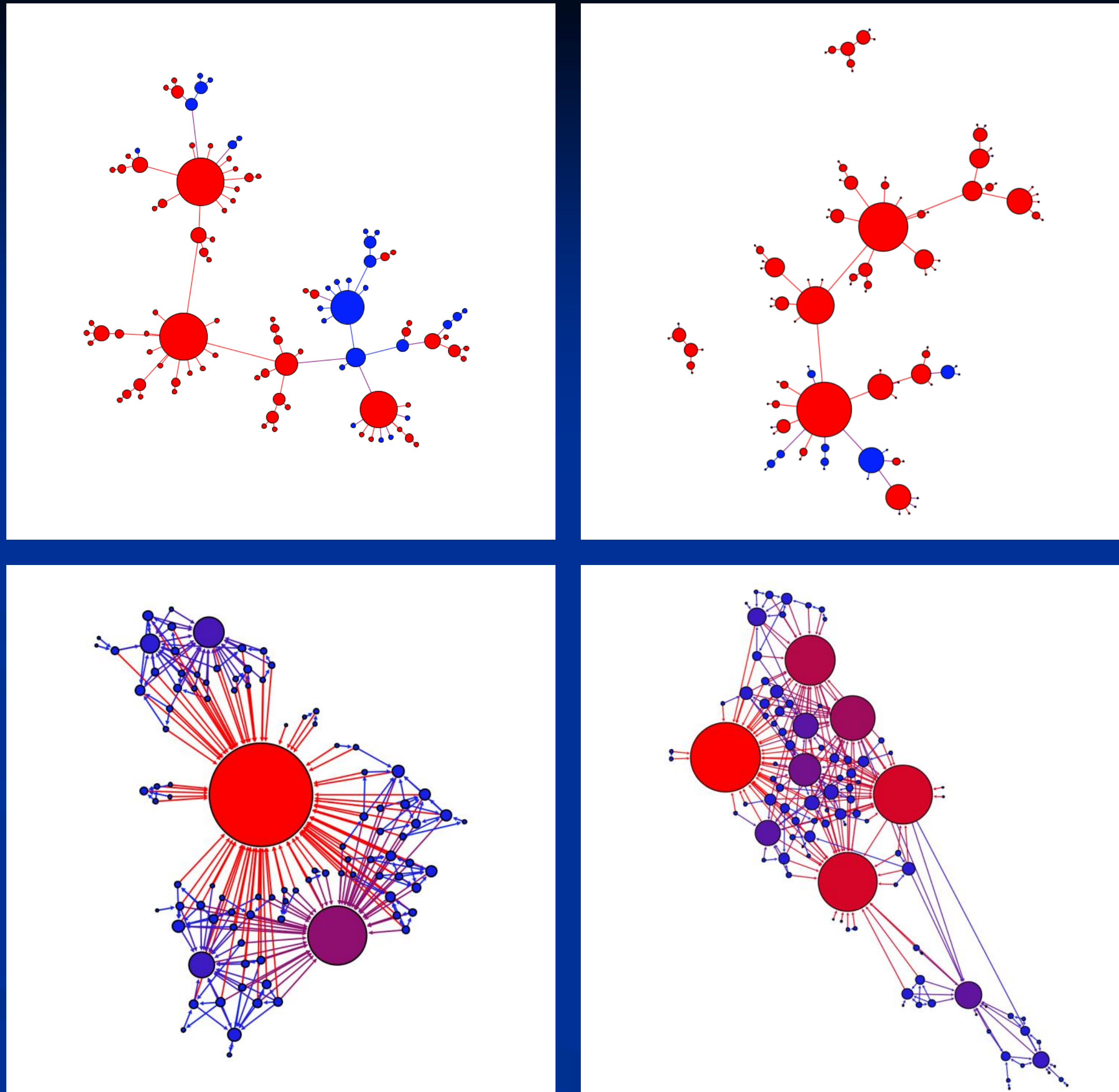


Input

Simulated

Degree-State

Forest Fire



Input

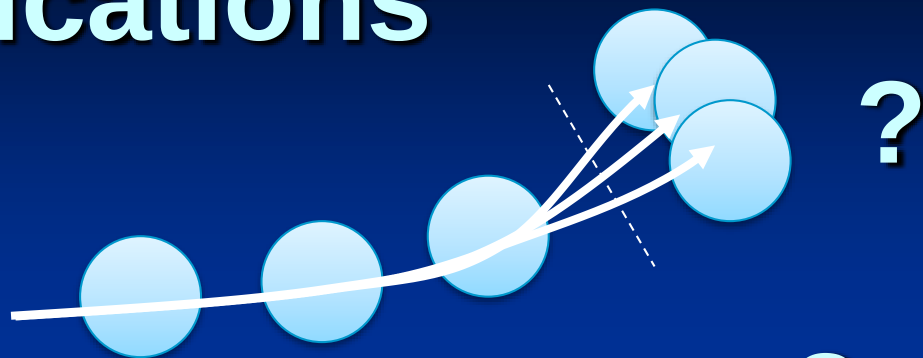
Simulated

Comparison with Other Methods

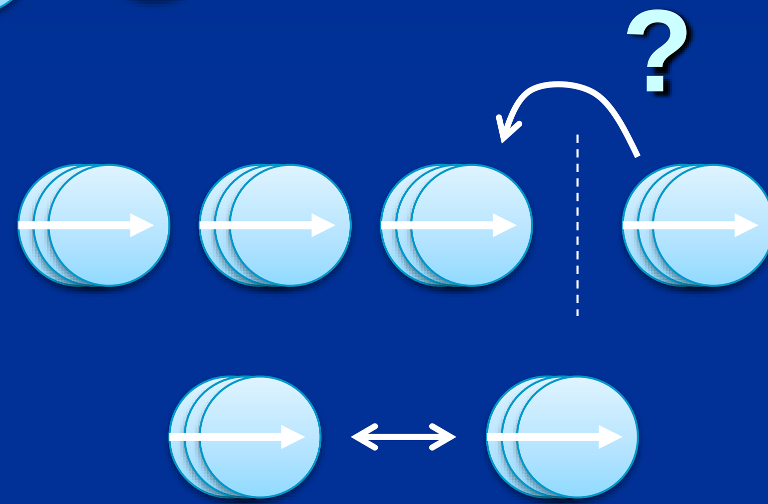
- PyGNA produces *generative models* using detailed state-topology information
  - Capable of generative simulation of an entire network which is not available in statistical approaches (e.g., Rossi et al. 2013)
- PyGNA models extraction and replacement as *explicit functions*
  - More efficient and flexible than graph-grammar approaches (e.g., Kurth et al. 2005)

Applications

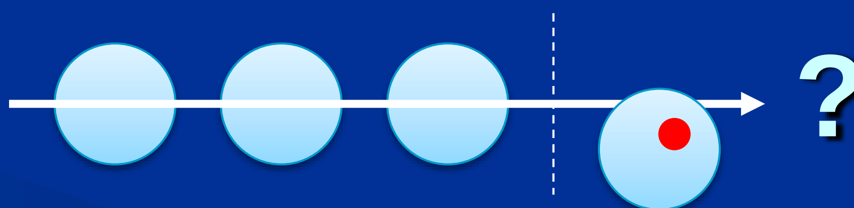
- Prediction



- Classification



- Anomaly detection



Summary

- Proposed GNA, a unified modeling framework for adaptive networks
- Explored behavioral diversity of GNA
- Applied to computational org. science
- Applied to operational network simulation
- Developed algorithms for automatic rule discovery from temporal network data

http://coco.binghamton.edu/NSF-CDI.html

Acknowledgments

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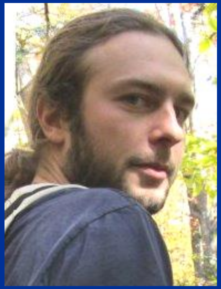
    Award # 1027752



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