SPHERA

Controlling networks while maintaining resilience

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CND' COMPLEX NETWORK DYNAMICS

BIU

NSF

Erasmus+

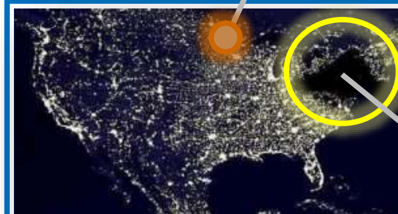
Bar-Ilan University
אוניברסיטת בר-אילן

Challenges


2003
NORTHEAST
BLACKOUT
5.5×10^7 People affected
10^2 Fatalities
6×10^9 USD in damages

Structure vs. dynamics

Structural perturbation (component failure)



Can we predict the point of Resilience loss?

Dynamic outcome (Resilience loss)

Dynamic framework

$$\frac{dx_i}{dt} = F(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} A_{ij} Q\big(x_i(t), x_j(t), \boldsymbol{\theta}_{ij}\big)$$

$x_i(t)$ State of a system component (node)

- Concentration of a protein/metabolite
- Probability of infection of an individual
- Load on power/communications component

Dynamic framework

$$\frac{dx_i}{dt} = F_i(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} A_{ij} Q_{ij}(x_i(t), x_j(t), \boldsymbol{\theta}_{ij})$$

Interaction mechanisms

For example (gene regulation)

$$\frac{dx_i}{dt} = -C_i x_i^{\beta_i} + \sum_{j=1}^{N} A_{ij} \frac{x_j^{\alpha_{ij}}}{k_{ij} + x_j^{\alpha_{ij}}}$$

F	**Self dynamics**
Q	**Interaction mechanisms**
$\boldsymbol{\varphi}_i, \boldsymbol{\theta}_{ij}$	**Distributed parameters**

Dynamic framework

$$\frac{dx_i}{dt} = F(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} A_{ij} Q(x_i(t), x_j(t), \boldsymbol{\theta}_{ij})$$

Interaction mechanisms

Example: population dynamics

$$\frac{dx_i}{dt} = x_i\left(1 - \frac{x_i}{C_i}\right) + \sum_{j=1}^{N} A_{ij} \frac{x_i x_j^{\alpha_{ij}}}{k_{ij} + x_i x_j^{\alpha_{ij}}}$$

Network structure

A_{ij}

Dynamic framework

$$\frac{dx_i}{dt} = F(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} A_{ij} Q(x_i(t), x_j(t), \boldsymbol{\theta}_{ij})$$

Interaction mechanisms

- Nonlinear
- Multi-parametric ($\boldsymbol{\varphi}_i, \boldsymbol{\theta}_{ij}$)
- Black-box: F_i, Q_{ij} sometimes unknown

Network structure

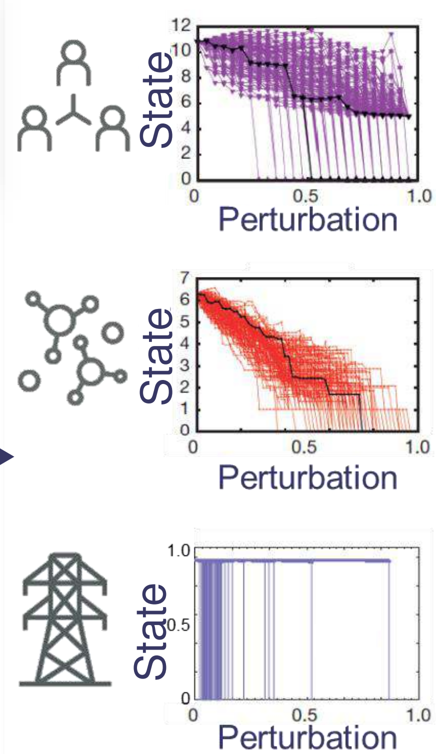
$\boldsymbol{A_{ij}}$

Weighted
Heterogeneous (Scale-free)

Diverse and unpredictable

Can we predict the point of Resilience loss?

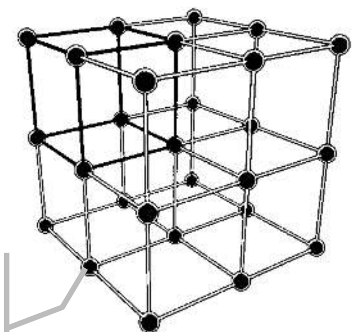
Diverse & unpredictable



Universal resilience patterns in complex networks. *Nature* **530**, 307 (2016)

A physicists nightmare

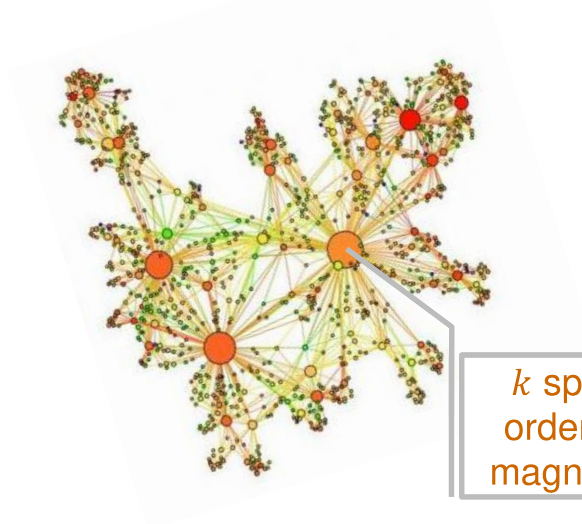
Current nonlinear dynamics theory:



Each node has $k = 6$ nearest neighbors

- Low dimensional
- Symmetric structures (lattice or lattice-like)

Where real networks are:

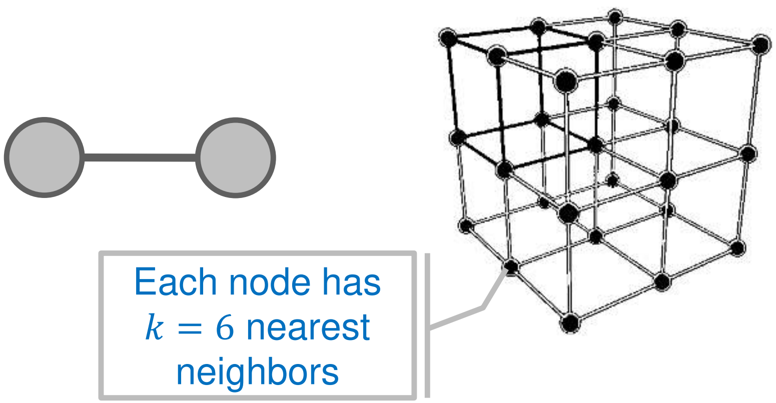


k spans orders of magnitude

- Disordered and weighted
- Extremely heterogeneous
- Scale free: $P(k) \sim k^{-\gamma}$

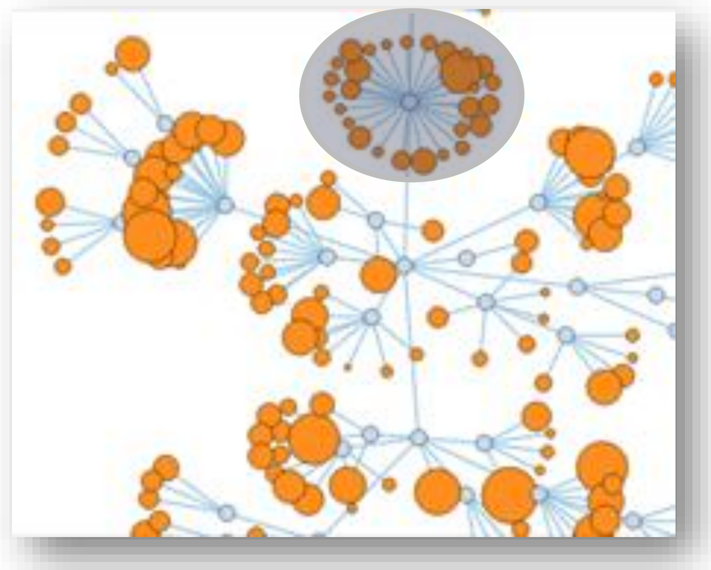
Symmetry

Zero order symmetry



All nodes identical

n-order symmetry

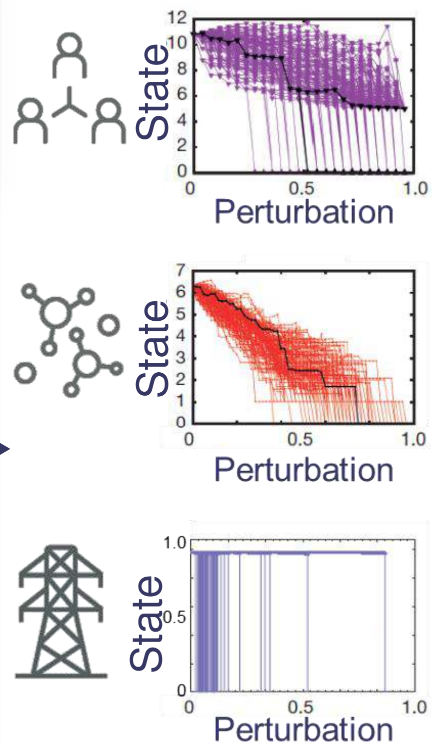


All environments identical

Global control parameter

Can we predict the point of Resilience loss?

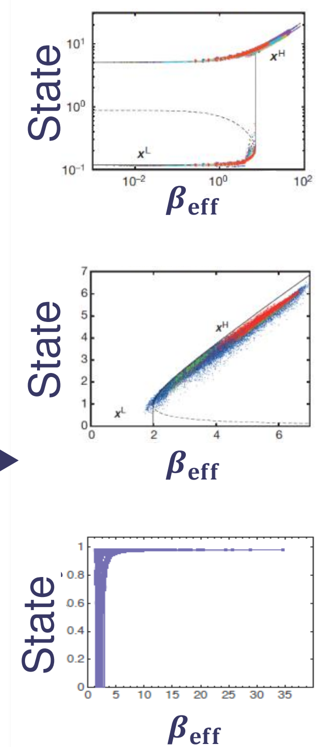
Diverse & unpredictable



Universal parameter
β_{eff} universally predicts the critical transition points of resilience loss

$$\beta_{\text{eff}} = \frac{\mathbf{1}^{\top}A^{2}\mathbf{1}}{\mathbf{1}^{\top}A\mathbf{1}}$$

Universal



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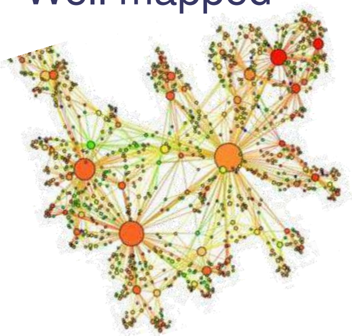
Global control parameter

Structure A_{ij}

Well mapped



Control parameter

$$\beta_{\mathrm{eff}} = \frac{\mathbf{1}^\top A^2 \mathbf{1}}{\mathbf{1}^\top A \mathbf{1}}$$

Translating **Structure** into **Dynamic observables** of interest

Resilience

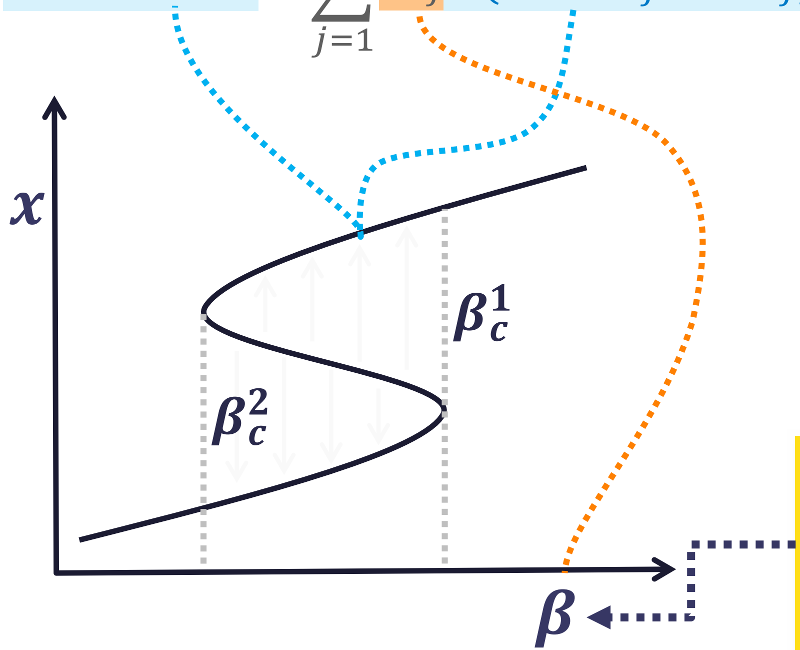
A Dynamic observable of the system that we seek to predict, understand and influence

Example: Using the **Structure** of the power network to determine its **Dynamic resilience** against local failures or load perturbations

Universal resilience patterns in complex networks. *Nature* **530**, 307 (2016)

Top-down - Global control parameter

$$\frac{dx_i}{dt} = F(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} A_{ij} Q(x_i(t), x_j(t), \boldsymbol{\theta}_{ij})$$



Bridges between **Topology** and **Dynamics**

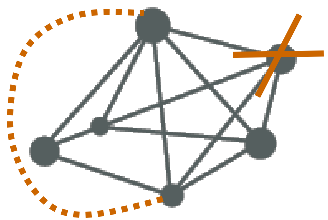
Sets guidelines for intervention

Bottom-up - Intervention

$$\frac{dx_i}{dt} = F_i(x_i(t), \boldsymbol{\varphi}_i) + \sum_{j=1}^{N} \left[A_{ij} Q_{ij}\big(x_i(t), x_j(t), \boldsymbol{\theta}_{ij}\big) + B_{ij} S_j(t) \right]$$

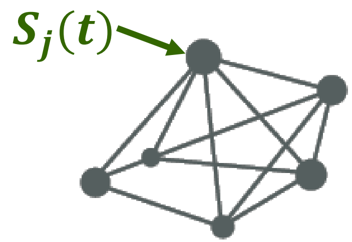
Structural interventions

Removing nodes, adding links, changing weights



Dynamic interventions

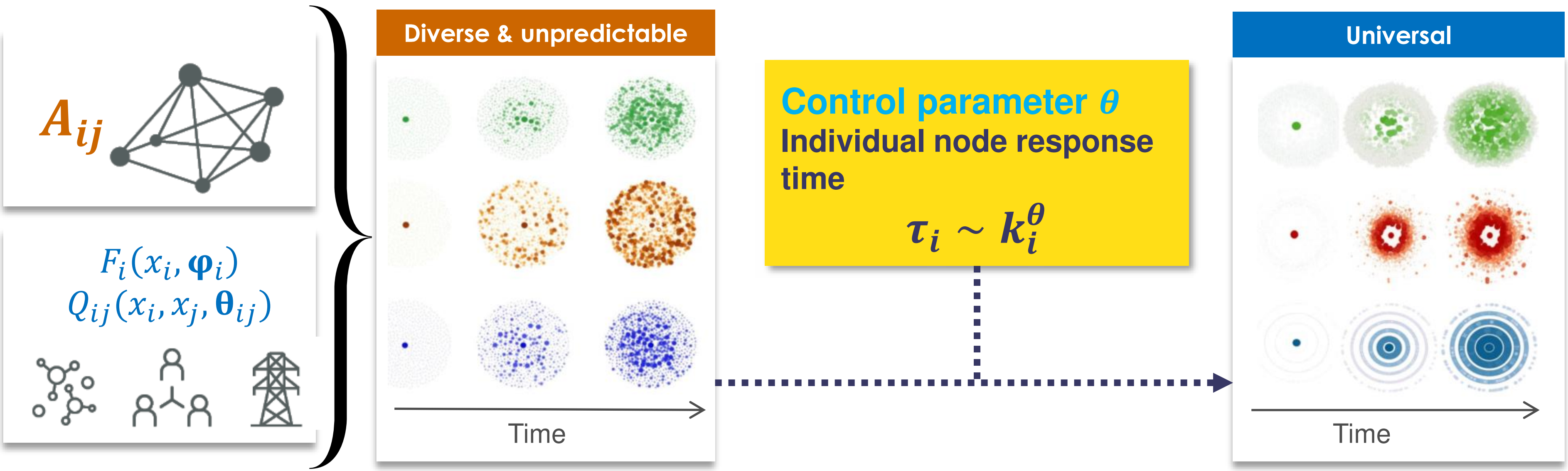
External signals $S_j(t)$ to selected nodes



Functional interventions

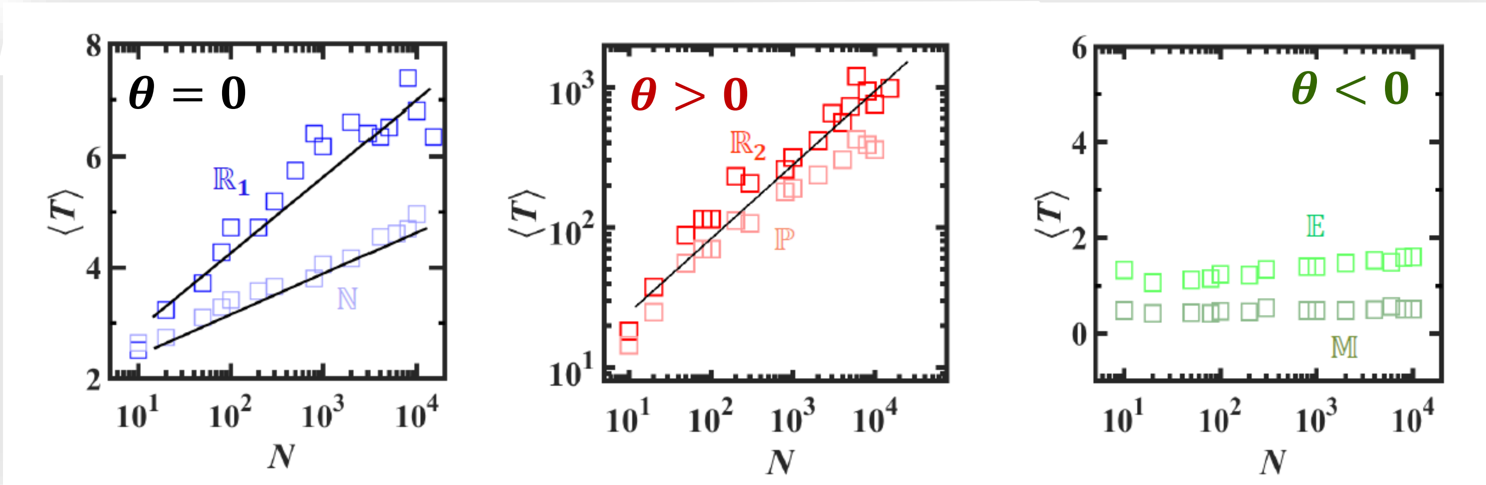
Manipulating F_i and Q_{ij} or their parameters

Spatio-temporal spreading patterns



Predicting the spatio-temporal propagation of signals in complex networks. *Nature Physics.* **Hopefully soon**

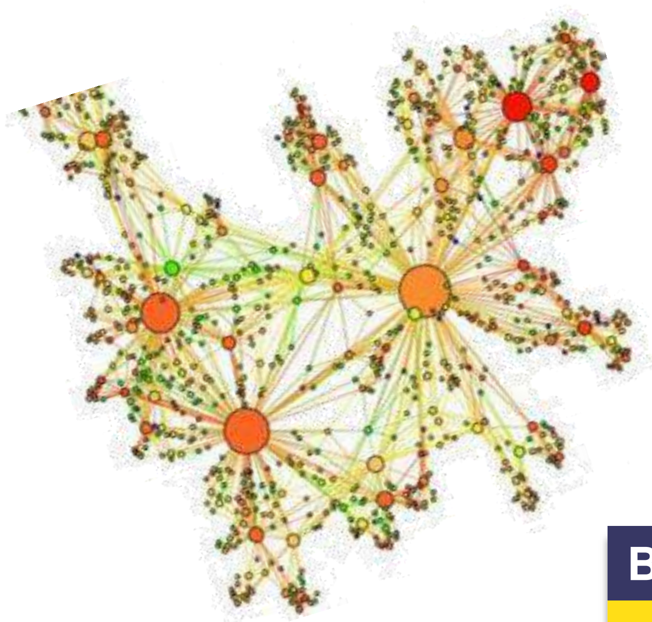
Soft stability



Beyond stability

How much time do we have before an undesired transition occurs

Optimizing functionality vs. resilience



Beyond stability

How much time do we have before an undesired transition occurs

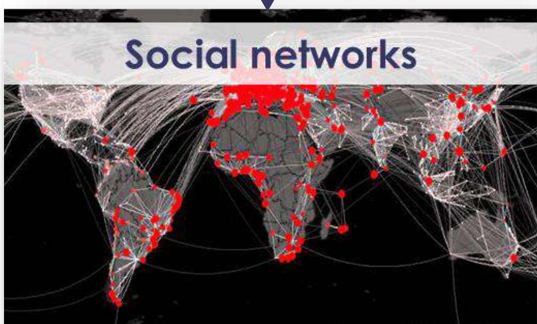
Open threads

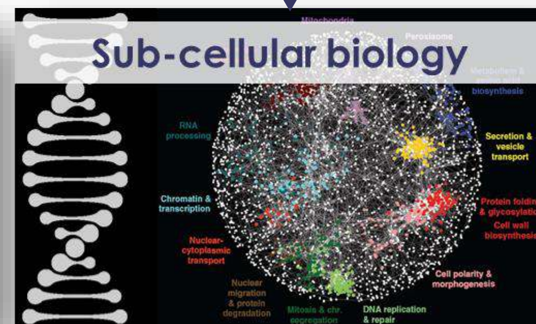
Top-down Identify macroscopic control parameters (β, θ)

Bottom-up Selecting nodes for intervention (real-time mitigation)

Stability vs. resilience Enriching the discussion on stability

Functionality vs. resilience Can we introduce balanced incentives





In the top-down approach systems are influenced by means of global control parameters. Quite often these act as boundary conditions for the system dynamics. To identify such control parameters is a challenge on its own. Often they can be derived from the known macroscopic, or system dynamics. As a major conceptual drawback, control parameters usually reflect limitations of stability, rather than of resilience.

• In the bottom-up approach systems are influenced by specifically targeting some of the system elements, e.g. agents in an agent-based model or nodes in a network representation. Again, two different possibilities exist: (i) the agents can be controlled in their internal dynamics, or (ii) the agent interactions can be controlled.

Can we identify general principles for the bottom-up control of socio-economic or ecological systems? How can driver nodes be identified based on data-driven methods?

Can we explain the breakdown of resilience in social organizations as a misallocation of resources? What is the relation between resilience and the natural tendency of systems to maximize their performance?