Dynamics of Economic Networks

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in collaboration with:

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Economic Networks

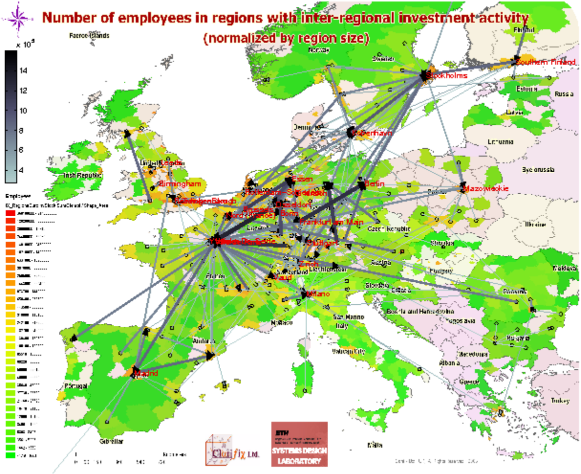
- ... one example (from Amadeus database)
  - networks reflect structure of economic control
- some types of economic networks:
  - ownership networks between firms (investments)
  - networks of board members of firms (decisions)
  - R& D networks (transfer of knowledge)
  - supply networks (transfer of goods)
  - credit networks (transfer of risk)

Download Tools for Network Vizualization (M. Geipel)

from our homepage `www.sg.ethz.ch/research/graphlayout`

Ownership Networks and Geography

- how does geography impact the structure of ownership control?



Economic Networks

- consist of nodes (⇒ firms) and links (⇒ interactions)

- *Physics perspective:* focus on the links
  - topological features, degree distribution, path length
  - centrality, modularity, clustering, cliquishness, ...
  - dynamics (preferential attachment)

- *Economics perspective:* focus on links *and* nodes
  - eigendynamics of nodes (e.g. growth, R&D, entry/exit)
  - eigendynamics of links (adaptation, creation/removal)
  - different time scales of link and node dynamics
  - quality of links (unidirectional, weight, costs)
  - feedback of links on the node dynamics
  - utility maximization vs. boundedly rational behavior

Costs and benefits

- economic system: large number of *interacting agents*
- agent i: *utility* from economic interaction with agents j:

$$\text{utility}_i(t) = \sum_j \text{benefits}_{ij}(t) - \text{costs}_{ij}(t)$$

  - aim: (i) increase benefits, (ii) reduce costs, (iii) do both
- **benefits:**
  - reach a common goal (optimal use of resources)
  - exchange of knowledge (R&D network)
- **costs:**
  - exploration costs (search for partners)
  - transaction costs (costs for interaction)
  - friction from differences in 'behavior', 'opinion', ...
  - costs for *maintenance* of connections
  - (indirect: 'dissipation', 'saturation')

Application: Emergence of Local Cultures

- economics: localized producer networks (clusters)
  - need of a shared understanding on what constitutes acceptable business practice ⇒ *local cultures* (= social norms)
- benefits of local cultures
  - avoid coordination dilemma among firms (alignment of quantities produced, investment incentives for research and training)
  - ⇒ foster positive externalities: knowledge spillovers, pooled labour markets
- existing studies: game theoretic analysis
  - require "known" optimum behaviour and a notion of "oughtness" for co-operation
- our model: investigates which behaviour comes to be shared
  - no ex-ante best behaviour (many strategies → business success)

Convergence toward shared behavior

agent i: 'economic' behavior $x_i(t) \in [0, ..., 1]$

1. *assumption:* utility increases if everyone shares same behavior
   - benefit: $b = \text{const.}$, costs: $\sim \Delta x$

$$u_i(t) = \sum_j b - c\,|x_i - x_j|$$

2. *assumption:* interaction ij occurs only iff $u_{ij}(t) > u_{\text{thr}}$

$$|x_i - x_j| < \varepsilon = (b - u_{\text{thr}})/c$$

   - possibility of interaction depends on *'open-mindedness'* ε
   - bounded confidence model (Deffuant *et al.*, 2000)

3. *assumption:* interaction leads to more similar behavior

$$x_i(t+1) = x_i(t) + \mu\,[x_j(t) - x_i(t)]$$
$$x_j(t+1) = x_j(t) + \mu\,[x_i(t) - x_j(t)]$$

   - $\mu = 0.5$: both agents adopt the 'mean' behavior

Influence of emerging in-groups

- interacting agents added to each other's in-group I_i and I_j
  - partnership relations from past interactions
- evidence that in-groups constrain agent behaviour
  - game theory (Fehr & Fischerbacher 2004)
  - group theory (French 1956, Lehrer 1956, Wagner 1978)
  - social impact theory (Latané 1981, Latané & Nowak 1997)
- influence of *emerging in-groups* on agent's i behaviour x_i?
  - *effective behaviour* x_i^{eff} considers *mean in-group behaviour* x_i^I

$$x_i^{\mathrm{eff}} = (1 - \alpha_i)x_i + \alpha_i x_i^I$$

  - group influence α_i increases with group size
- permanent influence of in-group on interaction: $\left| x_i^{\mathrm{eff}} - x_j^{\mathrm{eff}} \right| < \varepsilon$
  - search for new partners is costly $\rightarrow$ keep past partners
  - keep behavior close to past partners to allow further interaction

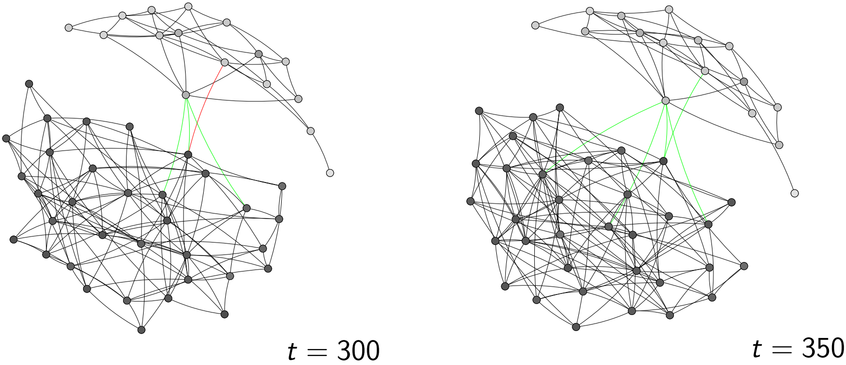
Co-evolution of economic network and behavior

- randomly choose agents i, j at time t

1. **link dynamics** (considers existing in-group)
   - $\Delta x^{\mathrm{eff}}(t) < \varepsilon \Rightarrow$ link formation (interaction)
   - $\Delta x^{\mathrm{eff}}(t) > \varepsilon \Rightarrow$ no link created or *existing link is removed*
2. **dynamics in individual behavior** (considers $x_i(t)$, $x_j(t)$)
   - interacting agents become more similar
3. **adjustment of effective behavior**
   - agent i, j: $x_i \rightarrow x_i^{\mathrm{eff}}$, $x_j \rightarrow x_j^{\mathrm{eff}}$
   - in-groups of i and j: x_i^{eff}, x_j^{eff} affected by changed $x^{I_i(t)}$, $x^{I_j(t)}$

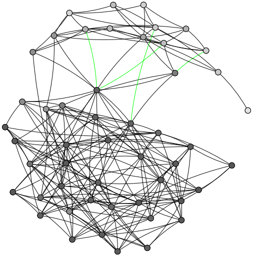
Result: *feedback between agents' behavior and their in-group structure* $\Rightarrow$ Computer simulation

Group Influence: two nearly separated components...

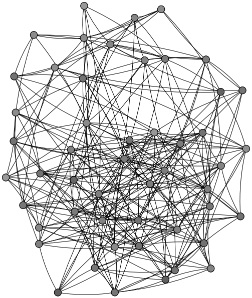


- 50 agents, $\varepsilon = 0.3$
  - green link: agents would not interact without group influence
  - red link: agents would not interact anymore

... finally united



$t = 400$

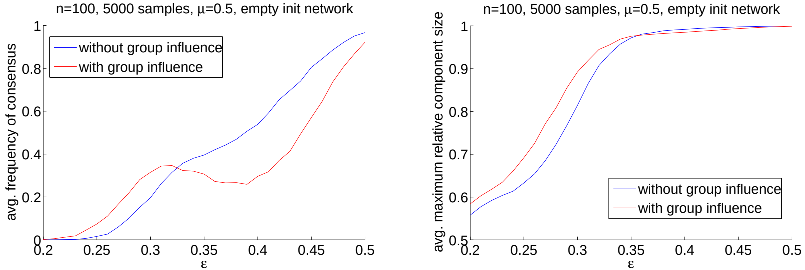


$t = 500$

- group influence (on average and a large range of ε)
  - fosters coalescence of components
  - increases maximum component size
  - $\Rightarrow$ consensus toward a common behavior

Influence of interaction costs on behavioral consensus?

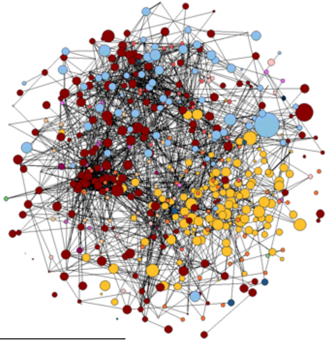
large costs ⇔ small 'open-mindedness' $\varepsilon = (b - u^{\text{thr}})/c$



- large costs $(0 < \varepsilon < 1/3)$
  - in-group influence increases probability to reach consensus
  - size of largest component increases
- small costs $(1/3 < \varepsilon < 1/2)$
  - with in-group influence, consensus becomes less probable
  - but size of largest component is not affected by in-group influence

Application: Innovation Networks

- complex technologies ⇒ firms must rely on knowledge transfers
  - Recent studies: relationship/performance of existing R&D networks
  - *emergence* of R&D networks, not just on existing networks



Picture from NEMO: Network Models, Governance and R&D collaboration networks, www.nemo-net.eu

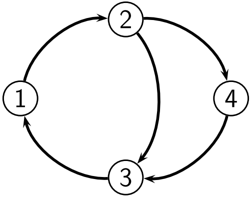
Costs and benefits in knowledge exchange

- agent i: knowledge stock $x_i(t) > 0$, knowledge growth:

$$\frac{dx_i}{dt} = B_i(\mathbf{A}, \mathbf{x}) - C_i(\mathbf{A}, \mathbf{x})$$

  - interaction (e.g. R&D collaborations) $\Rightarrow$ adjacency matrix $\mathbf{A}$
  - $B_i(\mathbf{A}, \mathbf{x})$: benefits (knowledge spillovers) $\Rightarrow \dot{x}_i = \sum_{j=1}^{n} a_{ij} x_j$
  - $C_i(\mathbf{A}, \mathbf{x})$: costs of collaborations $\sim$ number of links d_i

$$A = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$



- agent's 'profit' over certain time period: $u_i(t) = \lambda_{PF} - c d_i$
  - $\lambda_{\text{PF}} = \lim_{t \to \infty} \dot{x}_i / x_i$: largest real (Perron-Frobenius) eigenvalue of $\mathbf{A}$

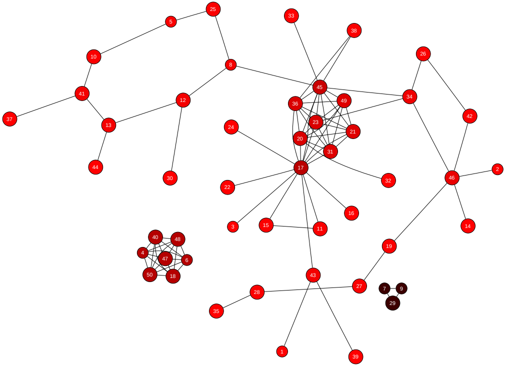
Evolution of the economic network

- Problem of maximizing u_i: optimize collaborations ($\to \lambda_{PF}$), network structure (d_i) $\Rightarrow$ minimize costs ($\sim c$)
- **network dynamics:** (initialization: empty graph)

1. **quasi-equilibrium**: fast knowledge growth
   A fixed $\to$ profits u_i reach balanced growth
2. **perturbation** of network: pair of agents (i, j) is selected at random
   - link $ij \notin E(G)$ is *created* if
     - either u_i or u_j is increased and none of u_i and u_j is decreased (*incremental improvement*)
   - link $ij \in E(G)$ is *deleted* if
     - at least one agent gains from the change (asymmetry!)
       link deletion involves severance cost: $v(\alpha, c) = (1-\alpha)c$ with $\alpha = c'/c$
       $\alpha \in [0, 1]$: $\alpha = 0$: full loss of investment, $\alpha = 1$: no loss
3. **stop** if network is pairwise stable, otherwise go to **1**

Example: Equilibrium network for $\alpha = 0.0$

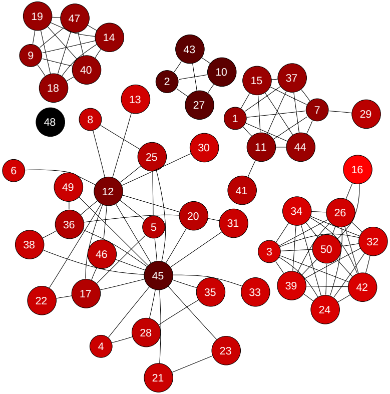
- heterogeneous degree distribution (hubs), giant component
- high severance cost prevent agents from further deleting links
- pairwise stability $\neq$ efficiency (suboptimal solution)



$n = 50$, $c = 0.15$, darker colours $\rightarrow$ higher profits

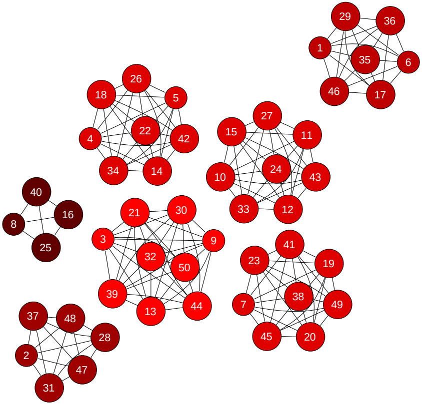
Example: Equilibrium network for $\alpha = 0.2$

- stronger clustering, disconnected components



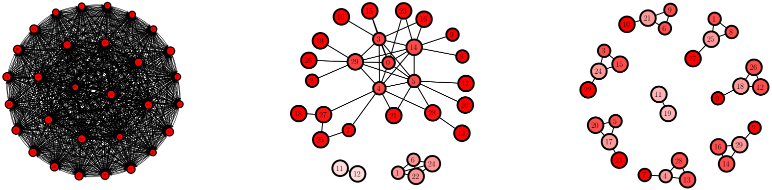
Example: Equilibrium network for $\alpha = 1.0$

- the smaller severence costs (loss after reconfiguration), the larger the tendency to form disconnected cliques (fully connected groups)



Simulations: Growing Networks with $\alpha = 0$

- intial setting: empty graph $\Rightarrow$ final setting: equilibrium network
- $0 < c < 0.5$: fully connected graph is efficient network



$c = 0.01$ $c = 0.2$ $c = 0.5$

- equilibrium networks more sparse and clustered with increasing c
- inefficient equilibrium networks are reached
  - for given cost, *multiple equilibria* exist
  - equilibrium network is *path dependent* (stochastic influences)

Knowledge Growth with Quadratic Costs

- node dynamics

$$\frac{dx_i}{dt} = -dx_i + b\sum_{i=1}^{n} a_{ji}x_j - c\sum_{i=1}^{n} a_{ij}x_i^2$$

- network dynamics:
  - pair of agents, *i* and *j*, is selected at random
  - different agent strategies
    - ⋆ unilateral link deletion/creation ⇒ *indirect reciprocity*
    - ⋆ bilateral link deletion/creation ⇒ *direct reciprocity*
  - decision are bounded rational
    - ⋆ locally bounded (no complete information on the system)
    - ⋆ temporarily bounded (finite time horizon)

M. König, S. Battiston, F. Schweitzer: Modeling Evolving Innovation Networks, in: Innovation Networks – New Approaches in Modeling and Analyzing (Eds. A. Pyka, A. Scharnhorst), Springer (2007)

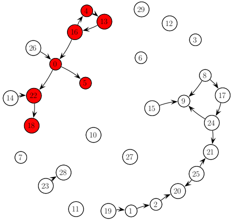
Baseline case: linear benefit and null costs

- node dynamics

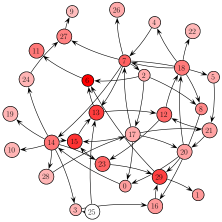
$$\frac{dx_i}{dt} = -dx_i + \sum_{i=1}^{n} a_{ji} x_j$$

- network dynamics: initial *random* network, remov least fit node, replacement with random links

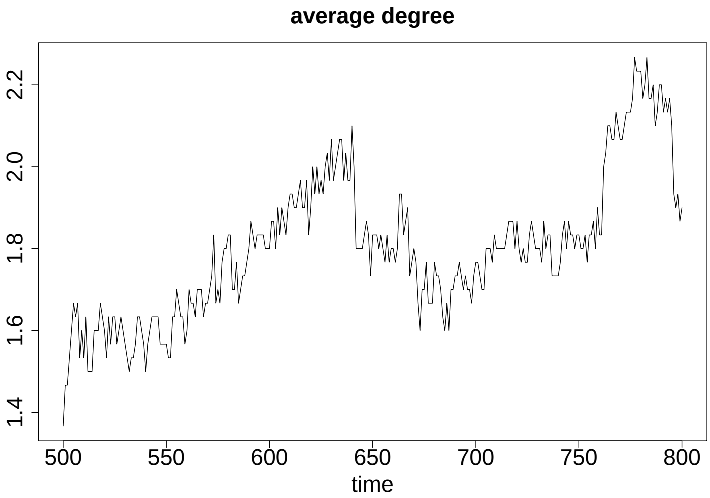
t=0



t=5.000



- emergence of a core of *cooperative* firms, and a *parasitic* pheriphery
- considerable crashes and recovery

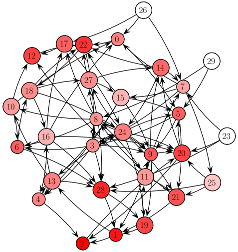


- considerable crashes and recovery

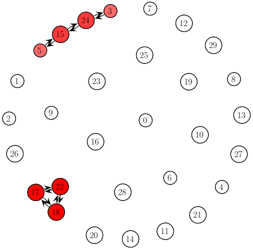
Case 1: indirect Reciprocity, linear benefit, squared costs

- agent i with time horizon T:
  - random unilateral link creation, optimal unilateral link deletion
  - accepted, if knowledge stock x_i increased

t=0



t=2.000

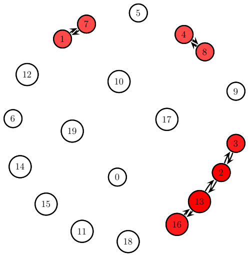


- initial links break down in favour of few bilateral cooperations
- free-riders get isolated

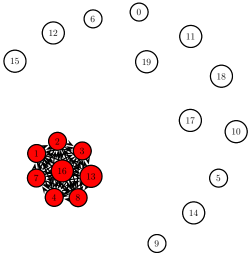
Case 2: direct reciprocity, linear benefit, squared costs

- agents i and j with time horizon T:
  - random bilateral link creation, optimal bilateral link deletion
  - accepted, if both knowledge stocks x_i and x_j increased

t=0



t=1.000



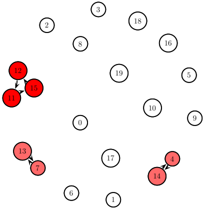
- initially connected agents evolve towards fully connected network
- initially isolated agents have nothing to contribute

Case 3: ind. reciprocity, weighted linear benefit, squared costs

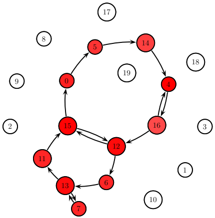
$$\frac{dx_i}{dt} = -dx_i + b\sum_{i=1}^{n} a_{ji}x_j + b_{\text{ext}}\sum_{i=1}^{n} w_{ji}x_j - c\sum_{i=1}^{n} a_{ij}x_i^2$$

- *externalities:* higher weights to
  - links providing shorter paths (Jackson, Watts 2002)
  - links contributing to cycles ⇒ feedback on technology

t=500



t=500



- cyclic externalities support emergence of indirect reciprocity

Conclusions

- important aspect of economic networks: link *and* node dynamics
- *example 1:* formation of local cultures ($\sim$ social norm)
  - common behavior reduces costs of interaction (friction, risk of failure)
  - in-group evolves $\rightarrow$ modifies firms behavior $\rightarrow$ feeds back to interaction, economic network
  - decreasing c does not increase probability of (full) consensus
- *example 2:* innovation networks
  - linear/nonlinear cost functions $\Rightarrow$ limits for connected networks
  - multiple equilibria: many stable, but inefficient equilibrium networks
  - different agent strategies for link creation/removal
  - if severance costs grow, agents stick to their suboptimal solutions
  - *both* analytical results *and* computer simulations

This research overview is based on the publications:

- P. Groeber, F. Schweitzer, K. Press: How groups can foster consensus: The case of local cultures, *J. Artificial Societies and Social Simulations* (2008, submitted)
- M. Koenig, S. Battiston, M. Napoletano, F. Schweitzer: The efficiency and evolution of R&D networks, *J. Economic Dynamics and Control* (2008, submitted)
- M. D. König, S. Battiston, M. Napoletano, F. Schweitzer: On Algebraic Graph Theory and the Dynamics of Innovation Networks, *Networks and Heterogeneous Media* Vol. 3, Num. 2, June 2008, http://arxiv.org/abs/0712.2752
- M. D. König, S. Battiston, F. Schweitzer: Modeling Evolving Innovation Networks, in: *Innovation Networks - New Approaches in Modeling and Analyzing* (Eds. A. Pyka, A. Scharnhorst), Heidelberg: Springer (2008, forthcoming), http://arxiv.org/abs/0712.2779
- **further publications:** `http://www.sg.ethz.ch/publications/`