Modeling of socio-economic systems: A new branch of physics?

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Is Economics the Next Physical Science?

An emerging body of work by physicists addressing questions of economic organization and function suggests new approaches to economics and a broadening of the scope of physics.

J. Doyne Farmer, Martin Shubik, and Eric Smith

In the past decade or so, physicists have begun to do academic research in economics. Perhaps a hundred people are now actively involved in an emerging field often called econophysics, and two new journals and frequent conferences are devoted to the field. At least ten books have been

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Physics Today, September 2005, pp. 37-42

Some historical notes

- involvement of physicists in economics/social sciences
  - Daniel Bernoulli: "utility" (1738)
  - Pierre-Simon Laplace: statistics of dead (1812)
  - Adolphe Quetelet (1796-1874) ("body mass index")
    - introduced the term "social physics" (1835)
- economist Vilfredo Pareto: "scaling laws" $y \sim x^{-\alpha}$ (1897)

...

- "econophysics"
  - coined by H.E. Stanley (1995) at Workshop in Kolcata, India
  - today: several hundred physicists involved (banks, insurance, ...)
- driving force: high-frequency data of transactions
  $\Rightarrow$ giant laboratory

Some recent activities

in Europe:

- Econophysics Forum http://www.unifr.ch/econophysics/
- COST P10 "Physics of Risk"
  - WG1: risk, WG2: agents, WG3: networks

in Germany:

- AKSOE: Focus section of the German Physical Society
  - AKSOE Conferences (part of DPG March meeting): 120 contributions (2006)
  - International Young-Scientist Award (about 35 nominations/year)
- International Conference "SocioPhysics" (ZIF Bielefeld, 2002)
  http://intern.sg.ethz.ch/fschweitzer/until2005/sociophysics/
- DPG Summer School: "Dynamics Of Socio-Economic Systems: A Physics Perspective" http://intern.sg.ethz.ch/events/Summerschool05/

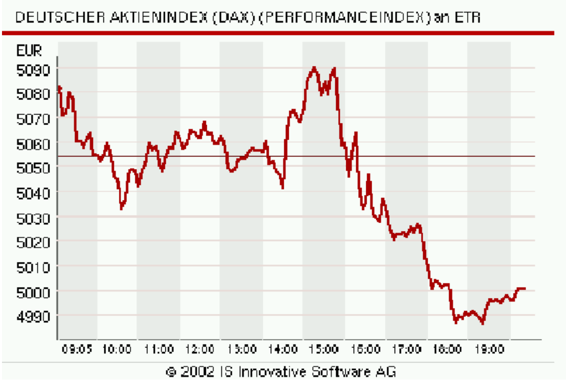
... Objection!

- *physics:* competence for non-animated world
  - "physical laws" for society, for economy?
- *theses:*
  - society/economy are subject to physical constraints (energy, ...)
  - dynamics governed by interaction of many similar elements $\Rightarrow$ *collective phenomena*
  - application of methods from many-particle physics, nonlinear dynamics, time series analysis, ...
  - detection of "universal" regularities valid also for socio-economic systems

I. Econophysics:
Stock market, growth of companies and organizations
II. Sociophysics:
Collective decision processes, network effects
III. Outlook and conclusions

... in the beginning was ...

- Louis Bachelier: *Théorie de la spéculation* (1900)
  - PhD Thesis (supervisor Henri Poincaré)
- random walk of asset prices

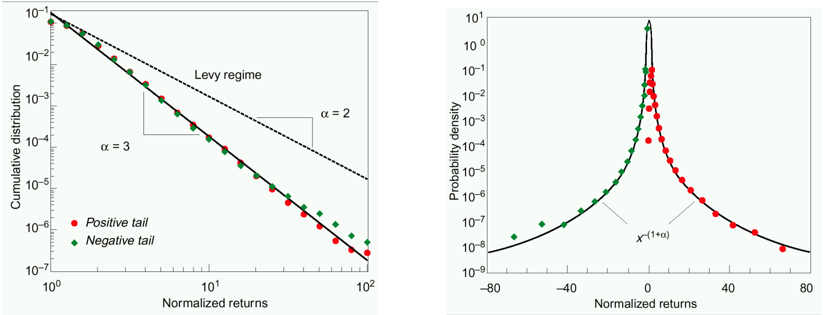


- developed the mathematics of Brownian motion

... and many years later ...

Econophysics

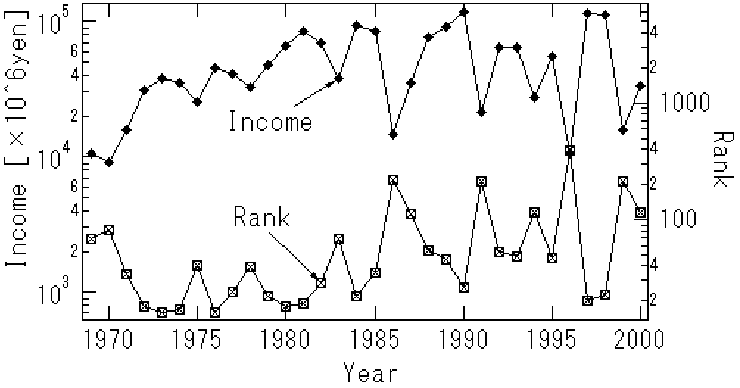
- basis: high quality "empirical" data (frequent, long term, ...)
- time series analysis: finding universal patterns ("laws") for
  - price increments: $\delta p_\tau(t) = p(t+\tau) - p(t)$
  - log returns: $r_\tau(t) = \log\{p(t+\tau)/p(t)\}$
  - volatility (variance): $\sigma^2 \Rightarrow$ fluctuations
  - autocorrelation: $\rho(\tau) \sim \langle r_\tau(t+\tau) r_\tau(t) \rangle$



Normalized log-returns r_τ of 1.000 US companies (1994-1995), τ=5 min (Plerou *et.al.*, 1999)

- short term ($\tau <$ month) fluctuations are non-gaussian
  - power law $f(r) \sim \langle r \rangle^{-\alpha}$, $\alpha \approx 3$
- "volatility clustering": positive correlations ...

Dynamics of companies



Takayasu et al '04: income of 15.000 US and 15.000 non-US comp., 80.000 Japanese comp. (income > 40 Mio Yen), before tax

Multiplicative stochastic processes

- set of companies: $i = 1, ..., N$, company "size" $x_i(t)$
- "Law of proportionate growth" (Gibrat, 1930)

$$x_i(t + \Delta t) = x_i(t)\Big[1 + b_i(t)\Big]$$

  - no interactions between firms
  - $b_i(t)$: independent of i, no temporal correlations (random noise)
  - *growth "rates":* $r(t) = x(t+1)/x(t)$, $t \gg \Delta t$, $\ln(1+b) \approx b$

$$\ln r(t) = \sum_{n=1}^{t} b(n)$$

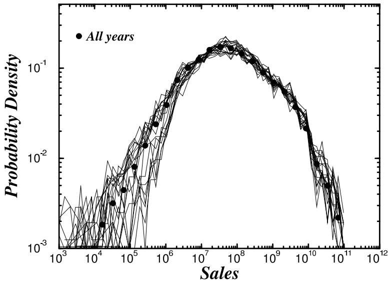
$\Rightarrow$ random walk for $\ln r(t)$ $\Rightarrow$ log-normal distribution for $x_i(t)$

Empirical Evidence?

- log-normal distribution of company sizes

$$P(x) = \frac{1}{\sqrt{2\pi}\,\sigma\, x} \exp\left[\frac{(-\ln x - \mu)^2}{2\sigma^2}\right]$$

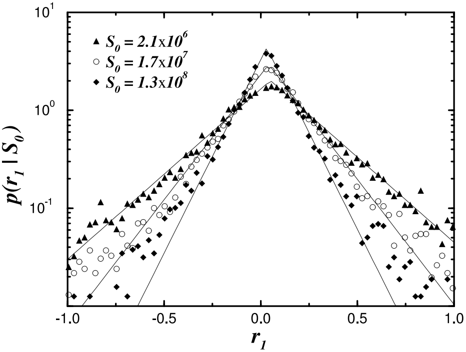
Fig. 2(a)



Empirical distribution of company sizes (1974-1993) (Amaral et al, 1997)

- Empirical distribution of growth rates
  $\Rightarrow$ depend on size tent-shape, exponential distribution

Fig. 3



(Amaral et al, 1997)

Explanation

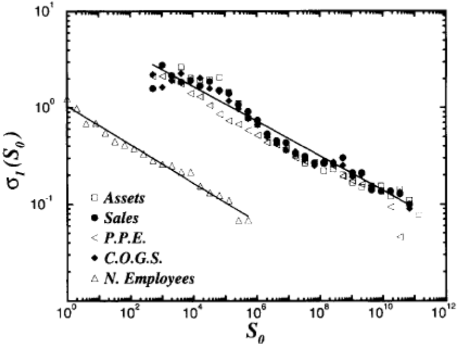
- correlations in the growth rates
  company is attracted to an "optimal size"

$$\frac{x_{t+\Delta t}}{x_t} = \begin{cases} k e^{\varepsilon_t}, & x_t < x^* \\ \frac{1}{k} e^{\varepsilon_t}, & x_t > x^*, \end{cases}$$

- result:

$$P(r_1|x_0) = \frac{1}{\sqrt{2}\,\sigma_1(x_0)} \exp\left[-\frac{\sqrt{2}\,|r_1 - \bar{r}_1(x_0)|}{\sigma_1(x_0)}\right]$$

- Empirical distribution of standard deviation of growth rates
  $\Rightarrow$ depend on size, power-law distribution



(Amaral et al, 1997)

Explanation

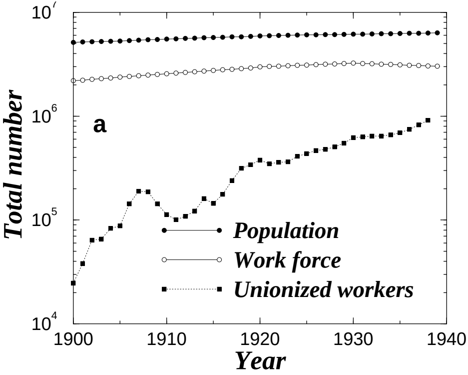
- growth depends on properties of management hierarchies
  n levels, z mean branching ratio, decisions on higher level are followed with prob π

$$\beta = \begin{cases} -\ln(\pi)/\ln(z) & \text{if} \quad \pi > z^{-1/2} \\ 1/2 & \text{if} \quad \pi < z^{-1/2} \end{cases}$$

- result:
  - $\sigma_1(x_0) \sim x_0^{-\beta}$; $\beta < 0.5$
  - β decreases in time $\Leftrightarrow$ companies better coordinated

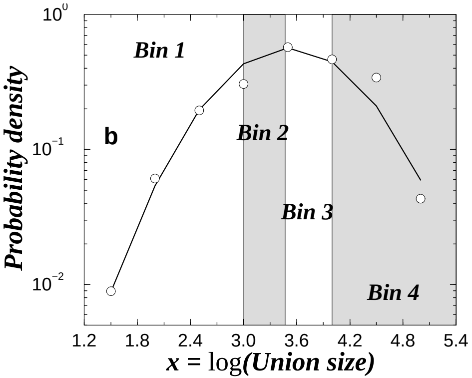
Growth in social organizations

- example: trade unions (Sweden 1900-1940)
  - 60 unions with ca 10.000 local chapters



F. Liljeros *et al.* (2003)

- statistical regularities for the size distribution? ⇒ *log-normal distribution*



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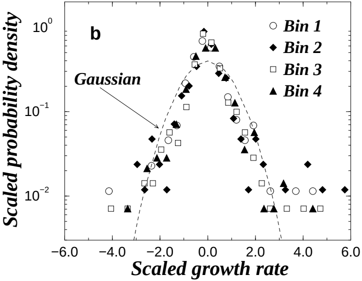
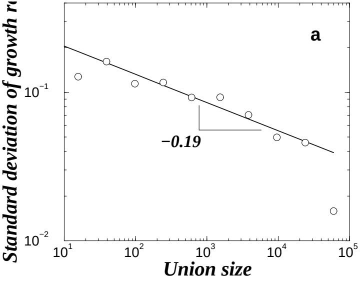
Growth dynamics: Gibrat's law

- annual growth rate, standard deviation, scaled probability

$$g(t) = \ln\left\{\frac{x(t+1)}{x(t)}\right\} \; ; \; p(g|x) \sim \frac{1}{\sigma(x)}\mathcal{F}\left(\frac{g}{\sigma(x)}\right) \; ; \; \sigma(x) \sim x^{\beta}$$



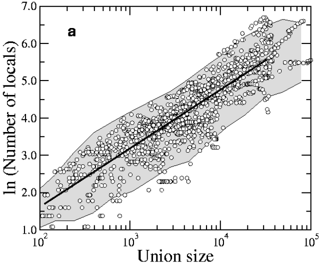


F. Liljeros *et al.* (2003)

Interal structure of organisations

- number of local chapters (n) that form a union of size x

$$n \sim x^{1-\alpha} \; ; \quad \alpha = 0.31 \pm 0.05$$



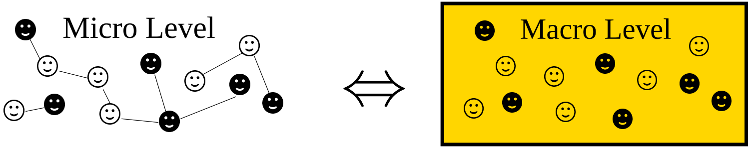
F. Liljeros *et al.* (2003)

- possibility of universal mechanisms for the structure of organisations

Challenges

- Complex socio-economic phenomena (stock market, company dynamics, social organizations, ...) reveal surprisingly simple empirical regularities ("laws") on the aggregated level. Why?
- Which interaction mechanisms lead to these "laws"?
- How do these simple findings relate to economic and social theory? What is their meaning?

The micro-macro link



- How are the properties of the elements and their interactions ("microscopic" level) related to the dynamics and the properties of the whole system ("macroscopic" level)?
- approach: agent-based models
  - agent: "particle" with "intermediate" internal complexity
  - collective phenomena in multi-agent systems

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Collective decisions

- population of agents: $i = 1, ..., N$
- each agent i: position $\mathbf{r}_i(t)$, opinion $\theta_i(t) \Rightarrow \{0, 1\}$
- "decision": to keep or change opinion $\theta_i(t)$

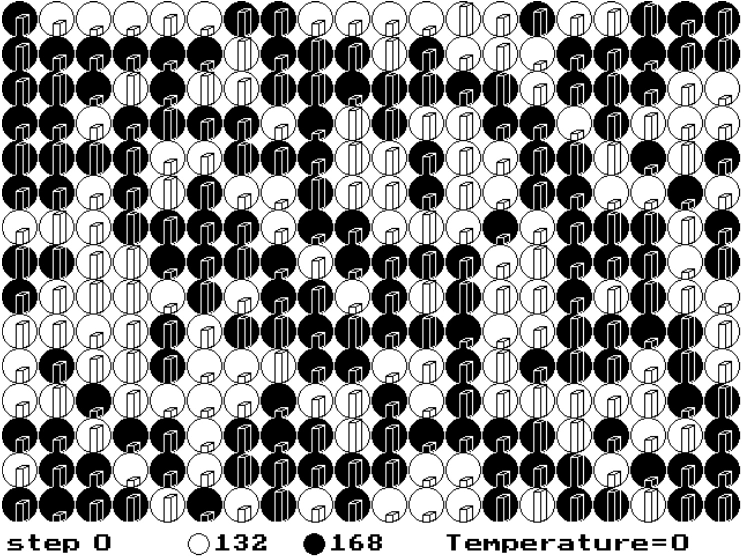
$$\theta_i(t+1) = \begin{cases} \theta_i(t) & \text{keep} \\ 1 - \theta_i(t) & \text{change} \end{cases}$$

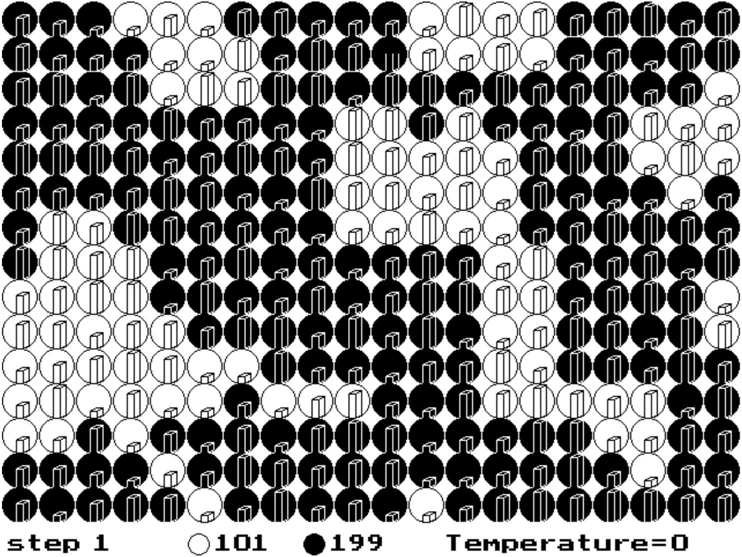
- fraction of opinions: $N = N_0 + N_1 \Rightarrow x = N_0/N$
  $x > 0.5$: majority with opinion 0, minority with opinion 1
- *note:* agents are "equally" capable, no ethnic or social minorities

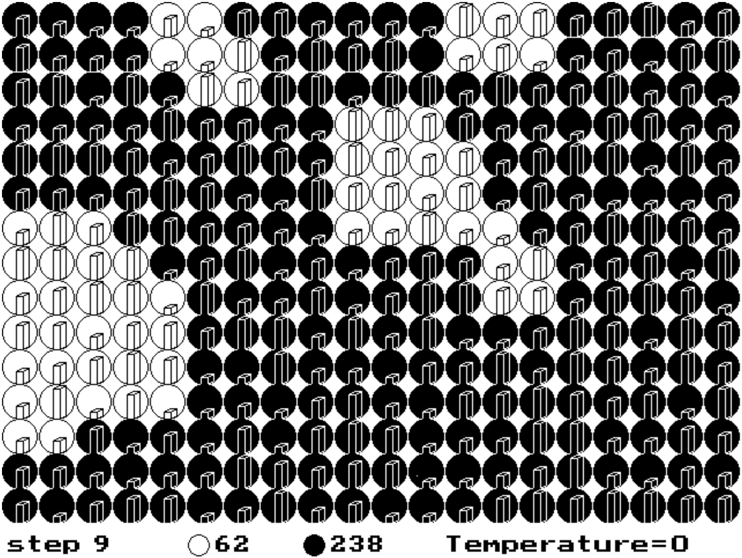
What drives the decision?

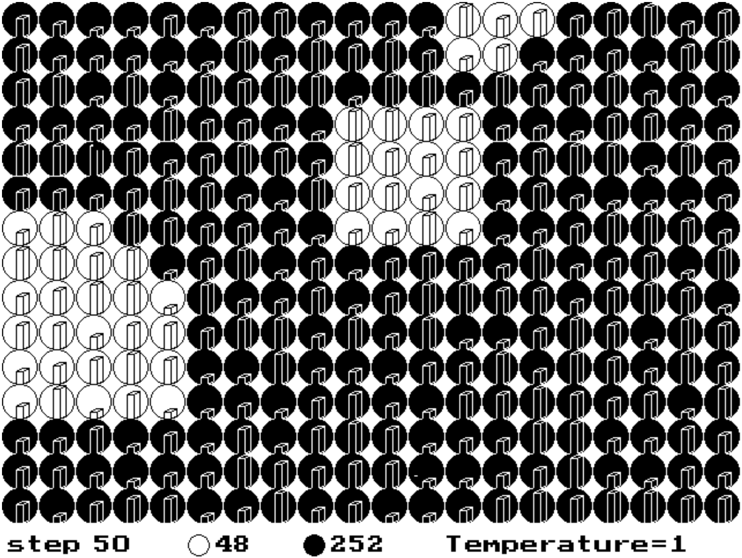
- utility maximization (based on complete information)
  - rational economic agents ⇒ predictable
- *social* elements: "information contagion", herding behavior
  - rules financial markets, mass panics, fashion, ...
  - ⇒ what is their effect on collective decisions?
- social impact theory (Latané, Holyst *et al*)

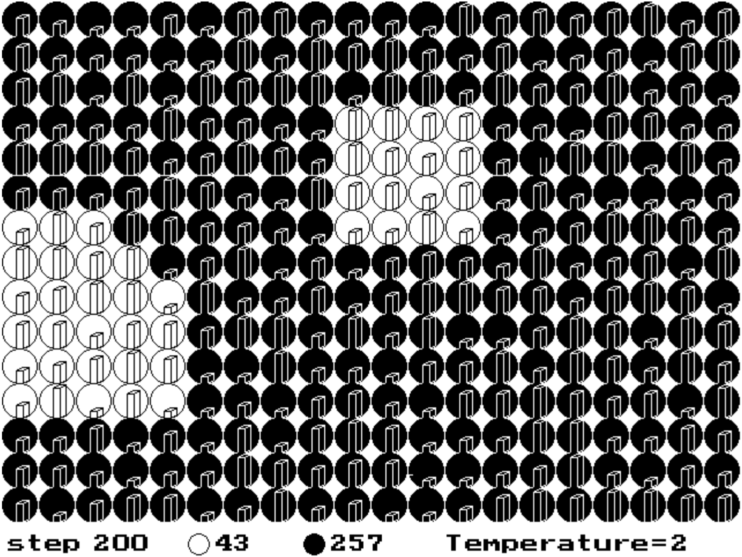
$$
\begin{aligned}
w(\theta_i'|\theta_i) &= \eta \exp\{I_i/T\} \\
I_i &= -\theta_i \sum_{j=1, j\neq i}^{N} s_j \theta_j / d_{ij}^n - \sigma s_i + e_i
\end{aligned}
$$

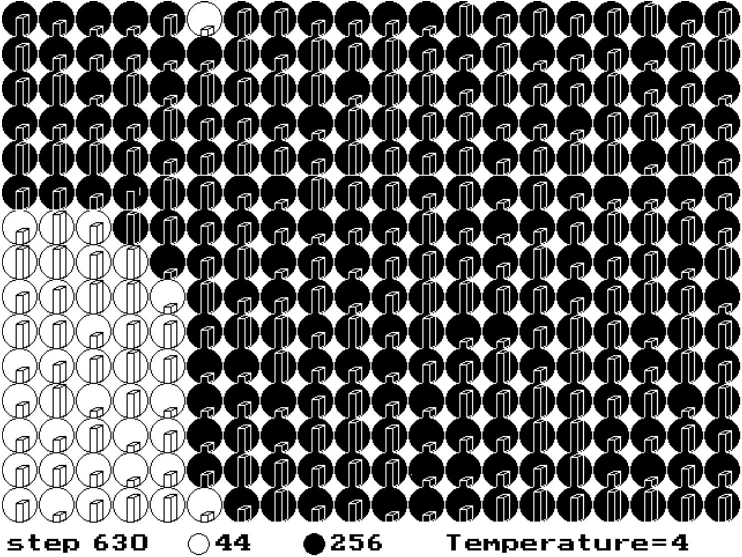

step 0
132
168
Temperature=0


step 1
101
199
Temperature=0


step 9
62
238
Temperature=0


step 50
48
252
Temperature=1


step 200
43
257
Temperature=2


step 630
44
256
Temperature=4

Local versus global trends

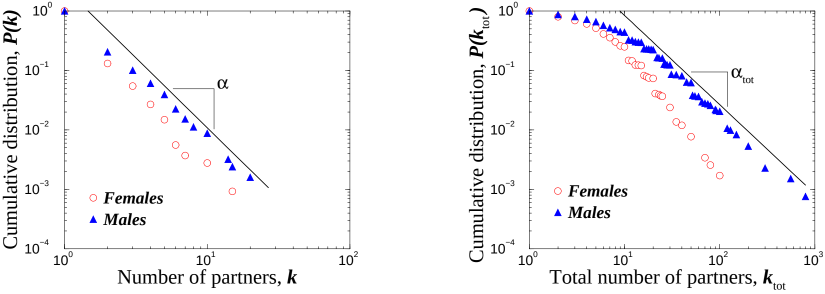
- agents exploit two different information
  - *local:* “do what your neighbors do” (be on the save side)
  - *global:* “do not follow the trend” (risky minority)
- dynamics: N agents on a lattice, two opinions $\theta_i \in \{-1, +1\}$

$$
\begin{aligned}
\theta_i(t+1) &= +1 \;\text{ with }\; p = \frac{1}{1+\exp\{-2\beta h_i(t)\}} \\
\theta_i(t+1) &= -1 \;\text{ with }\; 1-p \\
h_i(t) &= \sum_{j \in NN} J_{ij}\theta_j - \alpha\theta_i \left| \frac{1}{N} \sum_j \theta_j \right|
\end{aligned}
$$

Online Simulation (Bornholdt, 2001, cond-mat/0105224)

Social contact networks

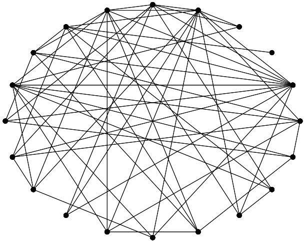
- social contacts: subjective, difficult to quantify ...
- rather unambiguous: sexual contacts
  - data: 2810 persons (age: 18-74) (Sweden, 1996)



F. Liljeros *et al.* (2001)

- result: $P(k) \sim k^{-\alpha}$
  - (w) $\alpha = 2.54 \pm 0.2$ $(k > 4)$, $\alpha_{tot} = 2.1 \pm 0.3$ $(k_{tot} > 20)$
  - (m) $\alpha = 2.31 \pm 0.2$ $(k > 5)$, $\alpha_{tot} = 1.6 \pm 0.3$ $(20 < k_{tot} < 400)$

What does this mean for the underlying interaction dynamics?



- scalefree network ⇒ links to nodes with already high number of links preferred ("the rich get richer")
- no distinguished scale ⇒ no separation of a "core group"

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Physics of socio-economic systems also deals with:

- risk management
  - dynamics of option prices $\Leftrightarrow$ transport equations (heat)
- macro economics
  - *wealth distributions*, production functions, GDP dynamics
- economic networks
  - innovation networks ("catalytic growth")
  - production networks, supply chains
- urban dynamics
  - location theory, spatial distribution of industrial centers
  - spatial urban growth
  - traffic dynamics

Challenge: Systems Design

- making use of of all of it
  - 1st step: *empirics*: facts, not fiction
  - 2nd step: *theory:* modeling, understanding
  - 3rd step: *design:* enhance system's performance
- example: *dynamics of human crowds*
  optimization of pedestrian areas, panics, evacuation
- example: *enhancing cooperation* (evolutionary game theory)
  - phase transition towards cooperation, coexistence of strategies
  - incentives and interaction rules to enhance cooperation
- example: *information filtering based on trust and reputation*
  - use social networks for targeted information
  - spontaneous formation of coalitions to reach certain goals

Concluding remarks

- physical methods and tools are applicable to collective phenomena in social sciences, economics, ...
- reductionist view ⇒ focus on particular questions
  no universal tool, no theory of everything
- data analysis: detection of "universal" (?) empirical "laws"
- minimalistic agent models capture essential (?) dynamics
- deeper understanding due to analytical methods
  no "blind" computer simulations

"Every theory, whether in the physical or biological or social sciences, distorts reality in that it oversimplifies. But if it is a good theory, what is omitted is outweighted by the beam of light and understanding thrown over the diverse facts."

Paul A. Samuelson