ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Systemic Instabilities and Disaster Spreading

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with Lubos Buzna, Karsten Peters, further team members from TU Dresden and ETH Zurich, and external collaborators

Challenges to Address

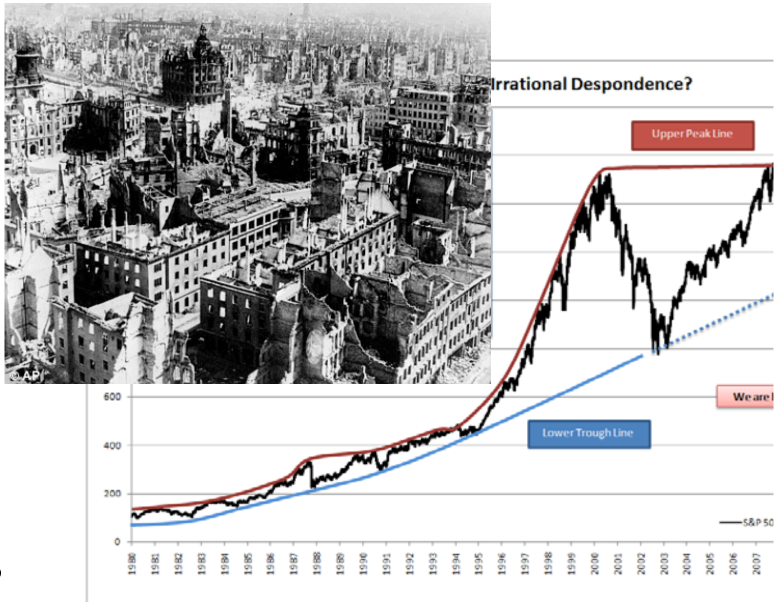
- Social and economic systems are rapidly changing, are in a transformation process, not in equilibrium
- Scientists need to be put in a better position to address the increasing number of socio-economic problems

As president of New York's Columbia University, Lee C. Bollinger formulated the issue as follows: "The forces affecting societies around the world ... are powerful and novel. The spread of global market systems ... are ... reshaping our world ..., raising profound questions. These questions call for the kinds of analyses and understandings that academic institutions are uniquely capable of providing. Too many policy failures are fundamentally failures of knowledge."

- We must close the gap between existing socio-economic problems and solutions, and get into a position to come up with solutions before a problem occurs
- The goal is to support politicians and business people in addressing practical problems

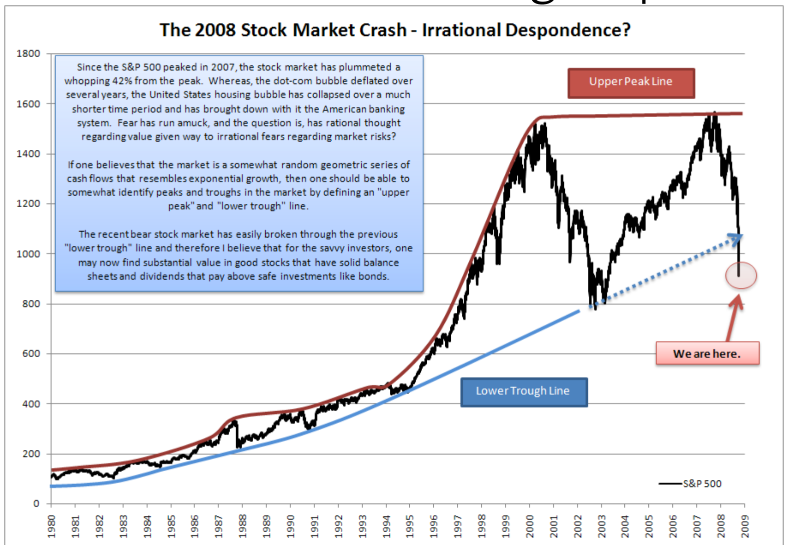
Socio-Economic Systems Imply Major Risks

- Conflicts: World War I (more than 15,000,000 victims); World War II (60,000,000 fatalities; cost of 1,000,000,000,000 1944 US$; destruction of 1710 cities, 70,000 villages, 31,850 industrial establishments, 40,000 miles of railroad; 40,000 hospitals 84,000 schools); Vietnam, Korea, former Yugoslavia, Afghanistan, Irak, Darfur…
- Financial and Economic Crises: estimated loss of 4-20 Trillion US$
- Climate Change will cause natural disasters conflicts for water, food, land; migration; social and political instability (estimated reduction of world gross domestic product by 0.6 12 Trillion US$ per year)
- Epidemics: Spanish Flu (20-40 Mio. Deaths), SARS (ca. 800 victims, 100 Billion US$ losses)



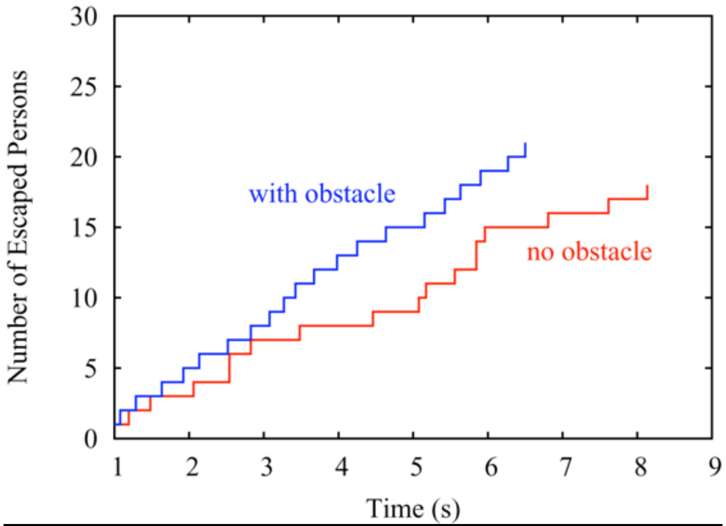
What are Complex Systems?

- Examples: Turbulent fluids; traffic flows; large supply chains; social, political, economic and ecological systems; financial markets; group dynamics and crowd behavior



A Daunting Class of Problems

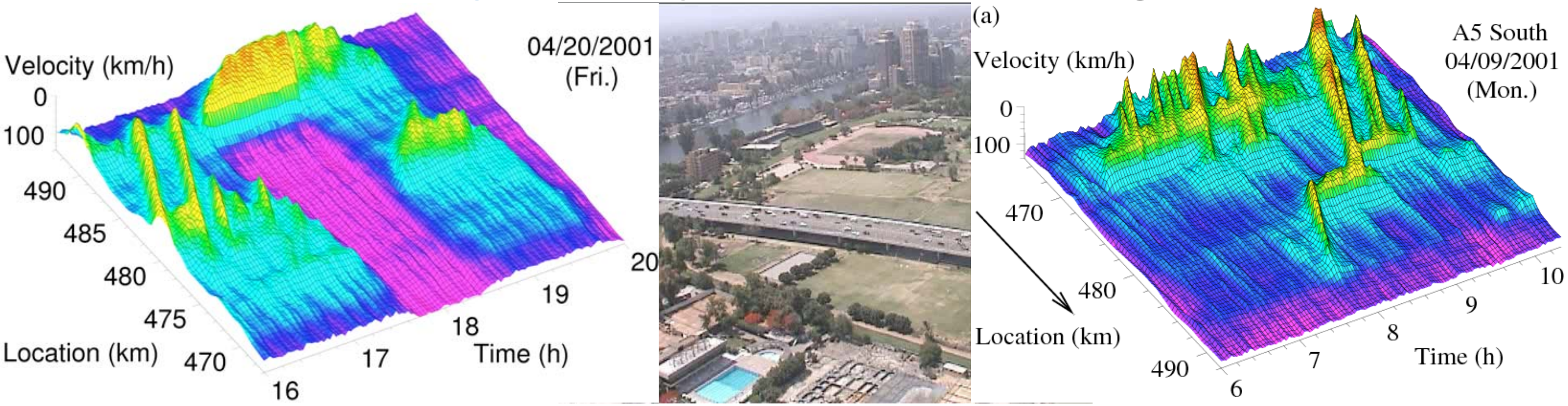
- Large number of interacting system elements (individuals, companies, countries, cars...)
- Non-linear or network interactions
- Rich system behavior
- Dynamic rather than static
- Probabilistic rather than deterministic
- Surprising, often paradoxical system behavior (e.g. slower-is-faster effects)
- Hardly predictable
- Seemingly uncontrollable
- Challenge our common way of thinking
- Almost everywhere around us
- Currently a nightmare for decision-makers



Complicated vs. Complex

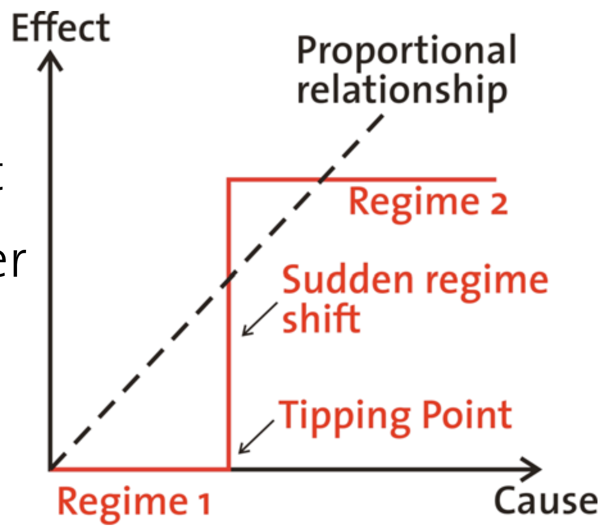
- Example: A car is a complicated system

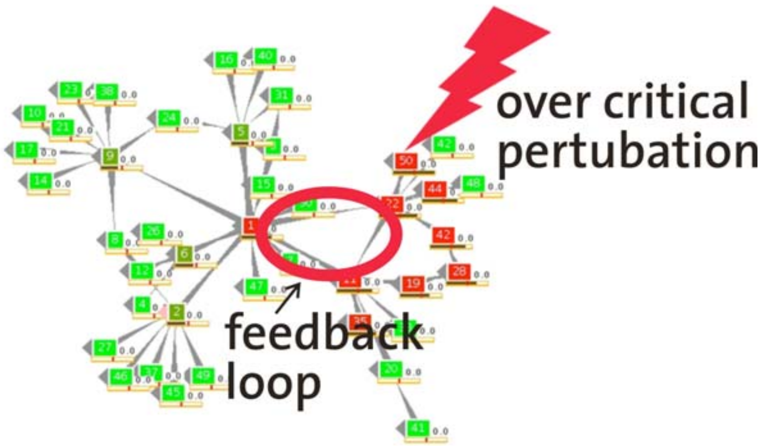
- Example: Traffic flows, involving the interaction of many cars, constitute a complex system
- Phantom traffic jams, many different kinds of congestion patterns



Non-Linear Interactions

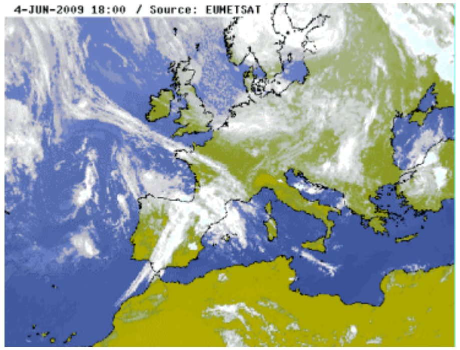
- Elements mutually adapt to each other
- They are influenced by their environment, but at the same time, they influence their environment
- Causes and effects not proportional to each other
- Unresponsive system or regime shifts
- Example: Sudden public opinion changes (pro vs. anti-war mood; public smoking ban; swiss banking secrecy; car sales, etc.)
- Network interactions are ubiquitous
  - Feedback loops, circuli vitiosi
  - Cascade spreading
  - Unwanted side effects (example: tabacco tax caused smuggle and criminal activity)

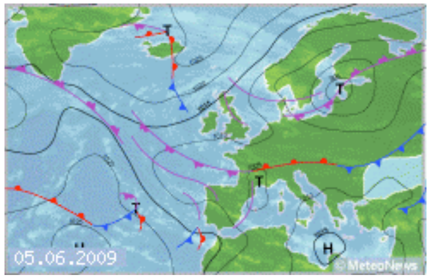


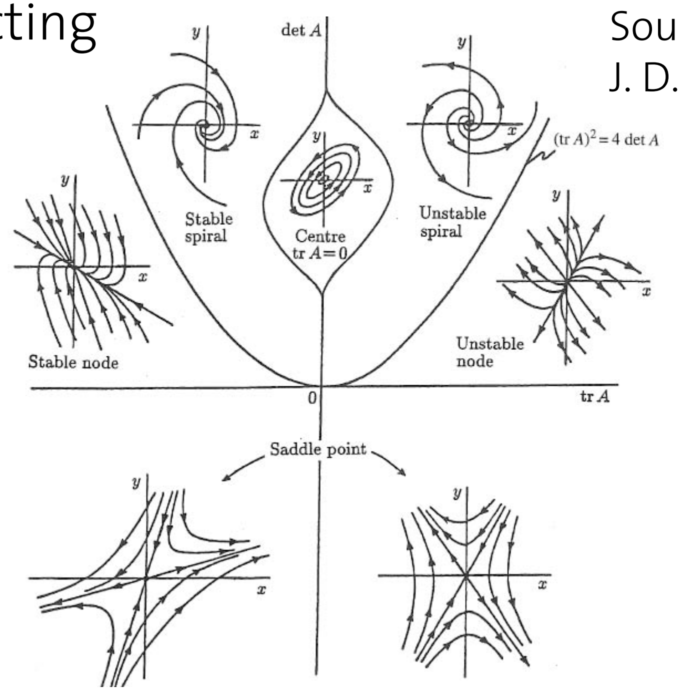


Limits of Predictability

- Large number of non-linearly interacting system components leads to complex dynamics





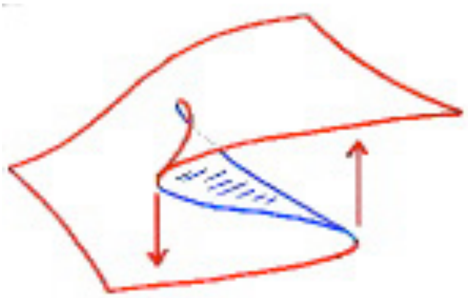


Source:
J. D. Murray

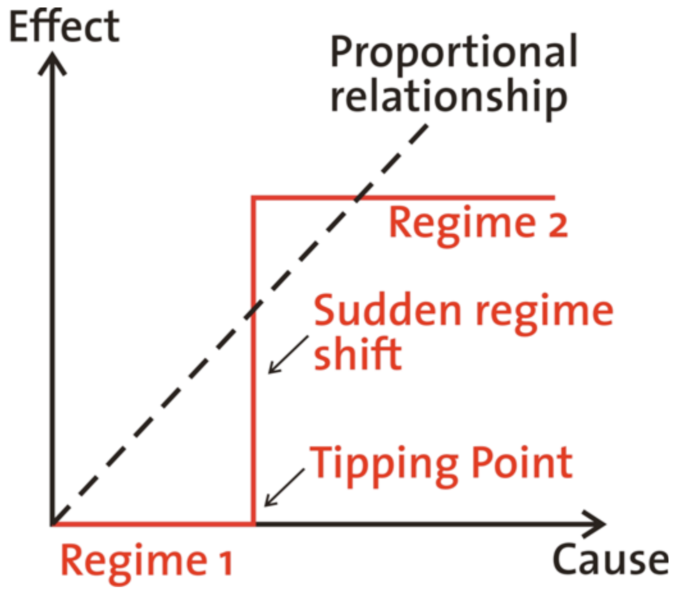
- Example: Weather forecast
- Chaotic dynamics/butterfly effect/ sensitivity: Small initial differences can cause very different behavior
- Self-fulfilling or self-destroying prophecy effects in socio-economic systems

Limits of Control

- Big changes may have small, no, adverse or unexpected effects
- Principle of Le Chatelier: A system tends to counteract external control attempts
- Irreducible randomness: A degree of uncertainty and perturbation that cannot be eliminated
- Delays may cause instabilities
- Regime shifts („phase transitions“, catastrophes): Sometimes small changes have a big impact

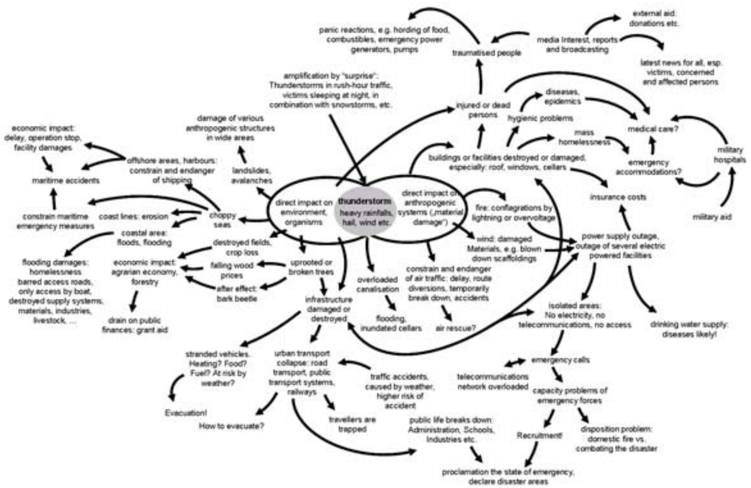


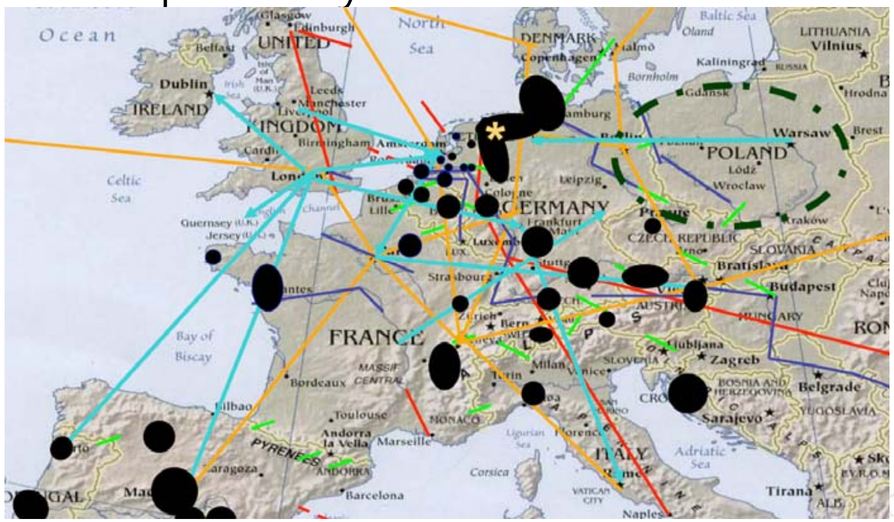
„Cusp catastrophe“

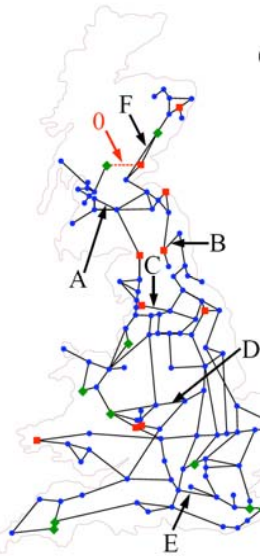


Cascade Spreading and Crises

- Systemic malfunctions, whenever the system state changes beyond a critical threshold („tipping point“)
- Example: Failure of interbank market
- Often caused by massive cascading effects („domino effects“, „avalanche effects“)
- Triggered by overcritical perturbation or coincidence of failures
- Examples: Epidemic spreading, disaster spreading, congestion spreading, blackout of electrical power system







Cascade Spreading and Systemic Crises

- Network interactions are ubiquitous
  - Feedback loops, circuli vitiosi
  - Unwanted side effects
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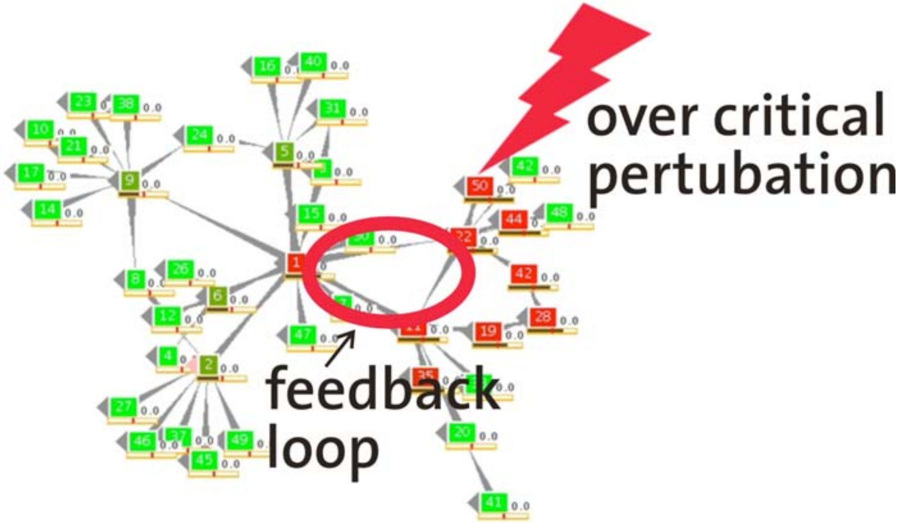
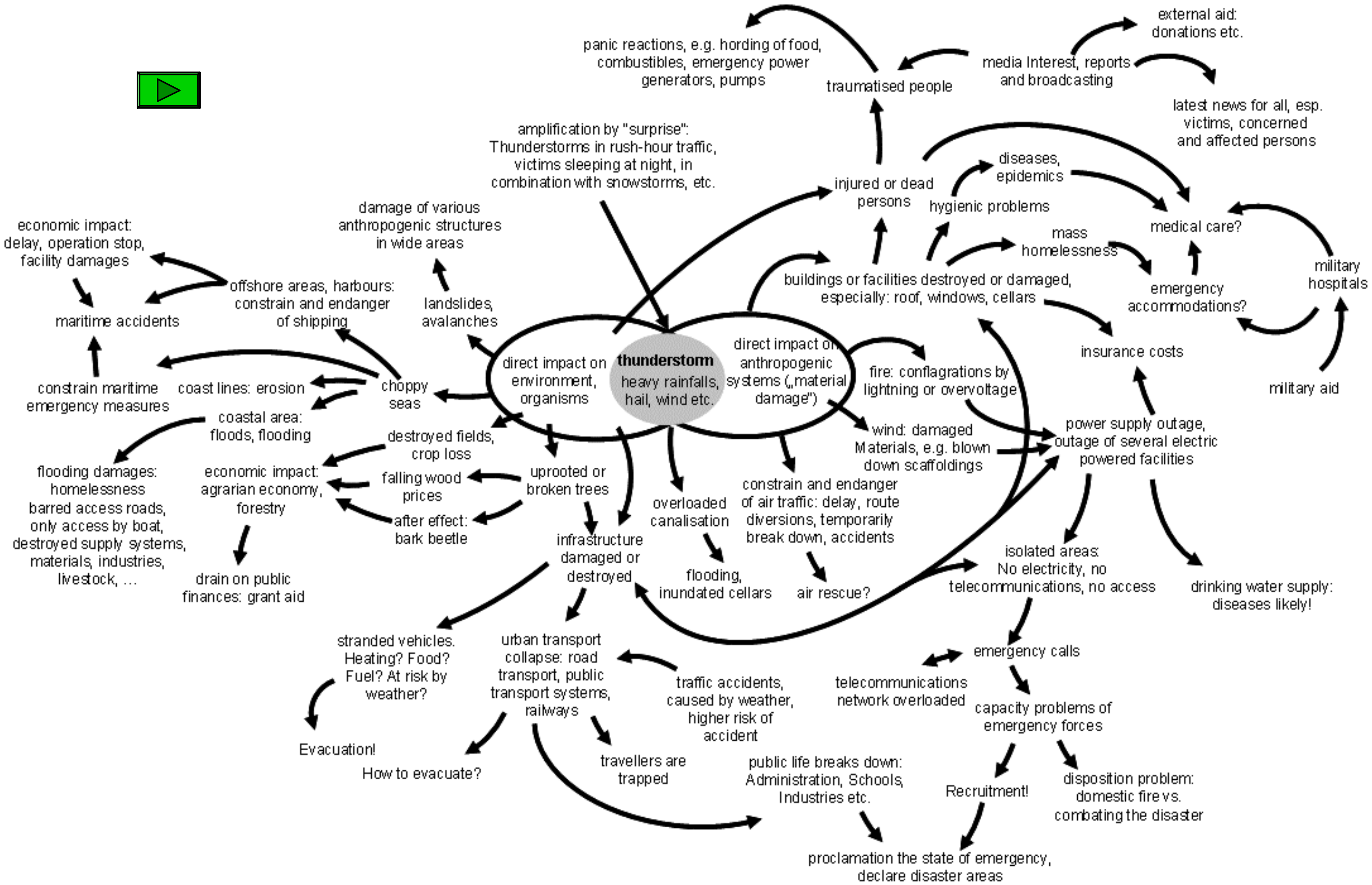
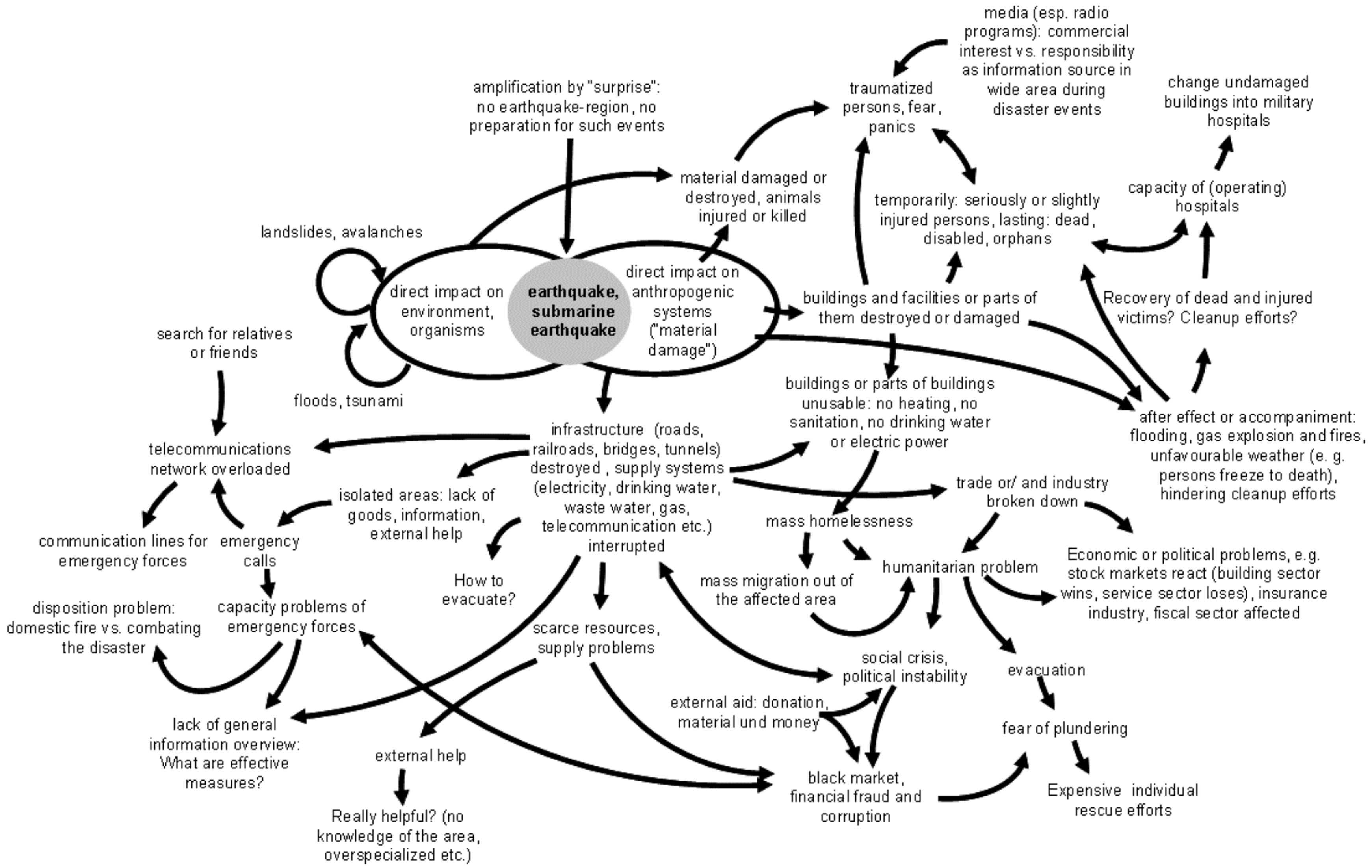


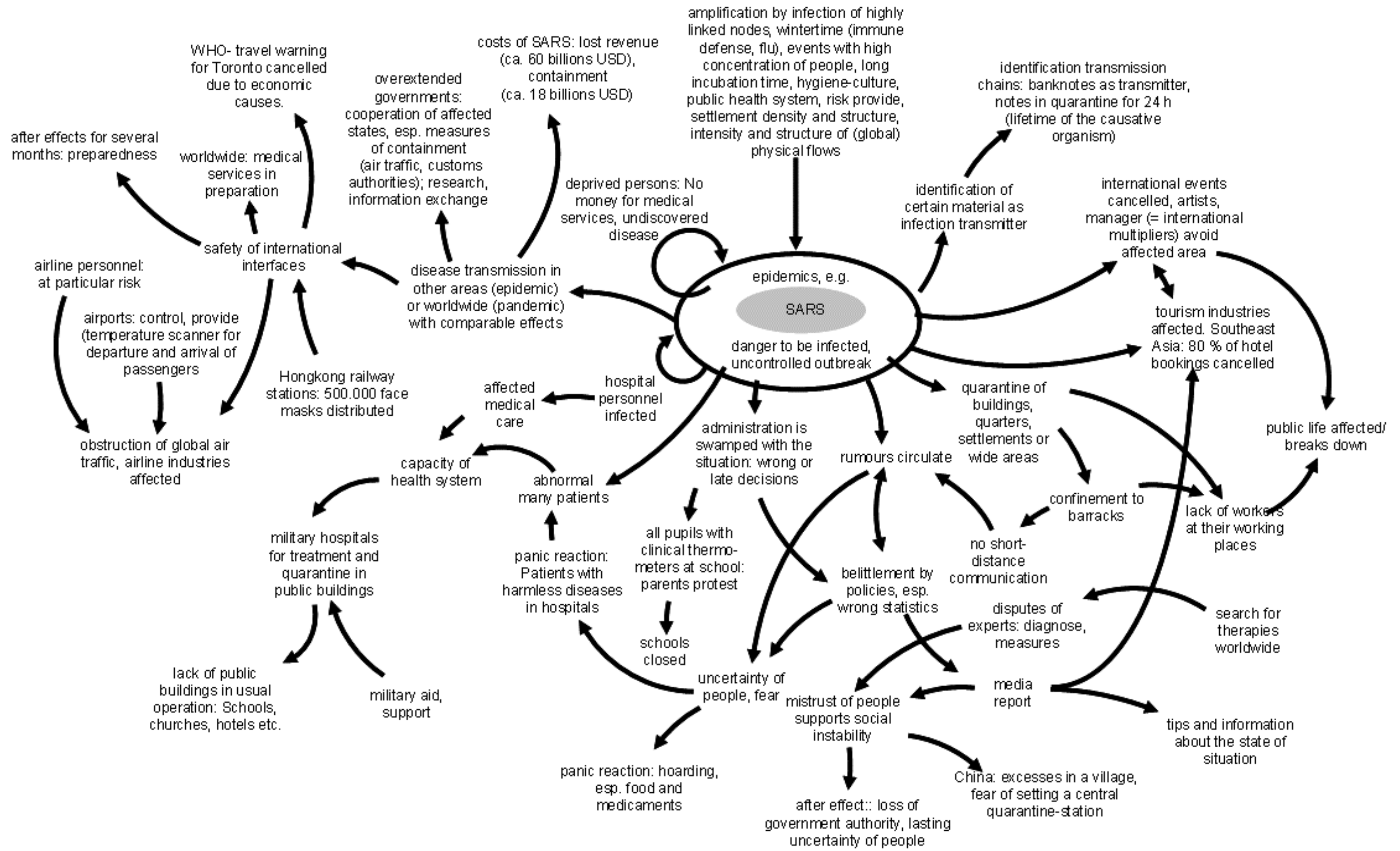
Causality Network for Thunderstorms



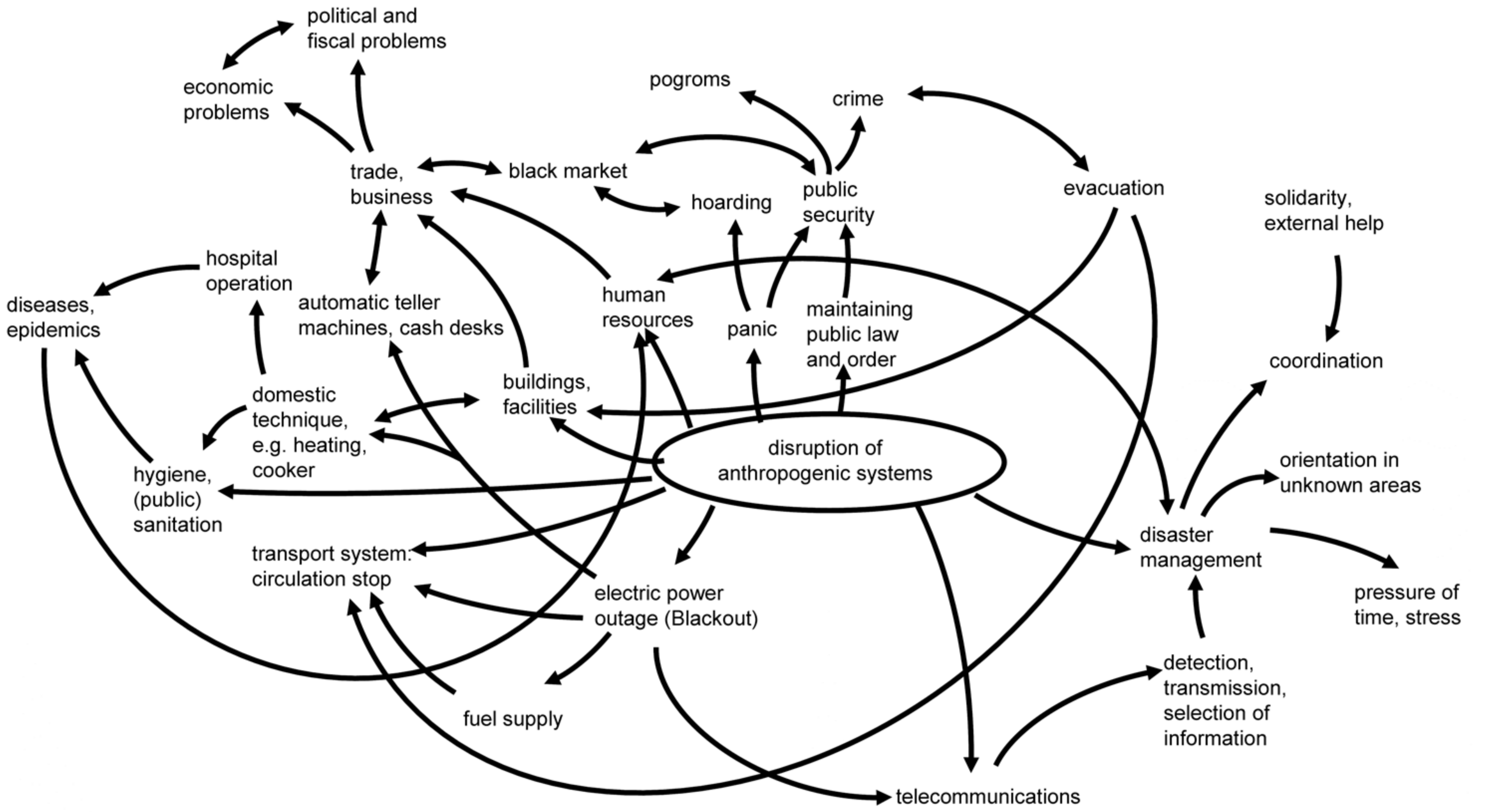
Cascade Failures due to Earthquakes



Impact of Epidemics

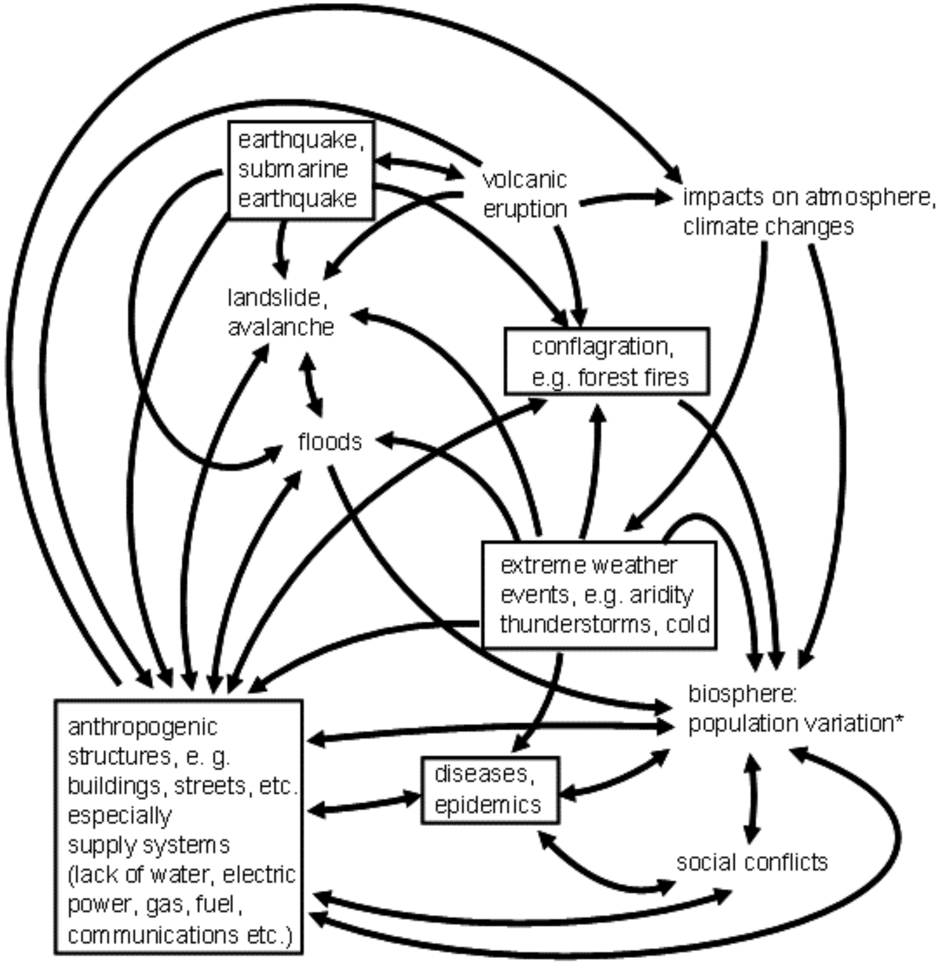


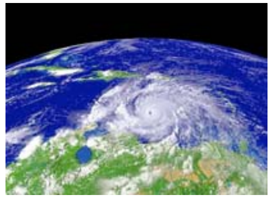
Common Elements of Disasters



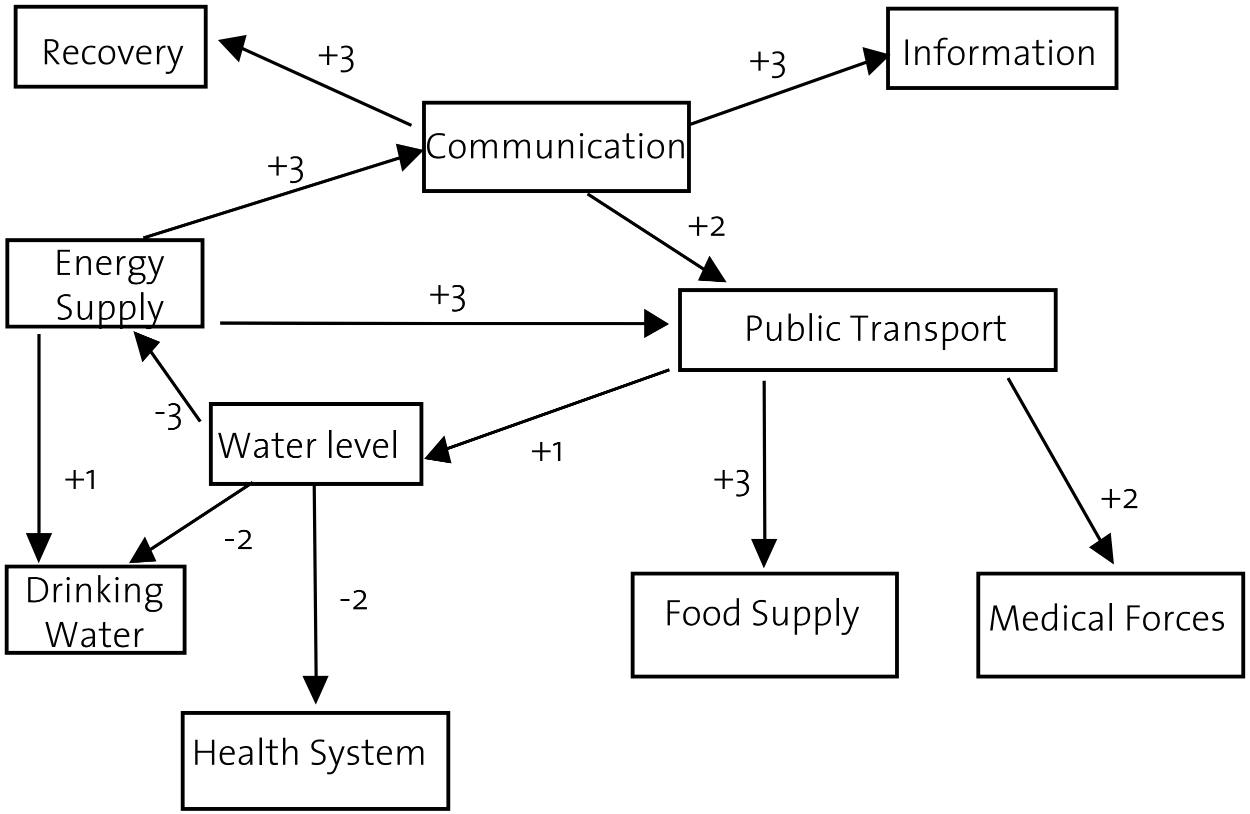
Causal Dependencies and Interaction Networks

Disasters cause disasters

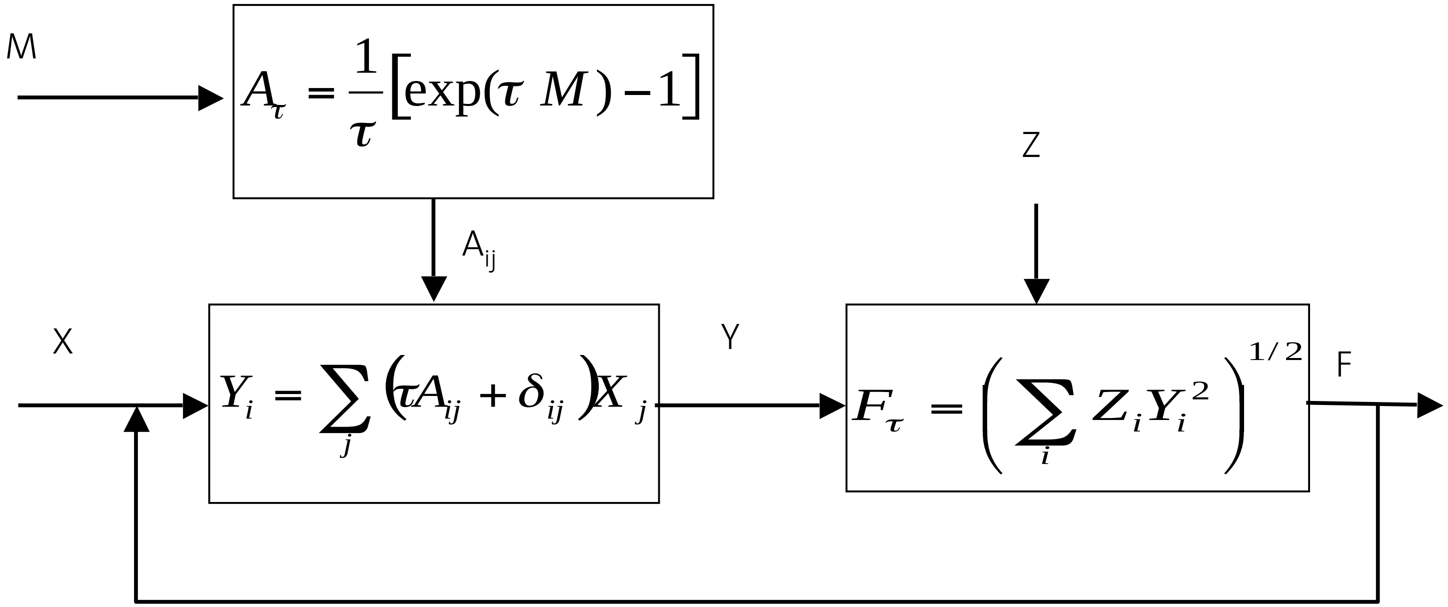




Causality Network of the Elbe Flooding 2002 (Detail)

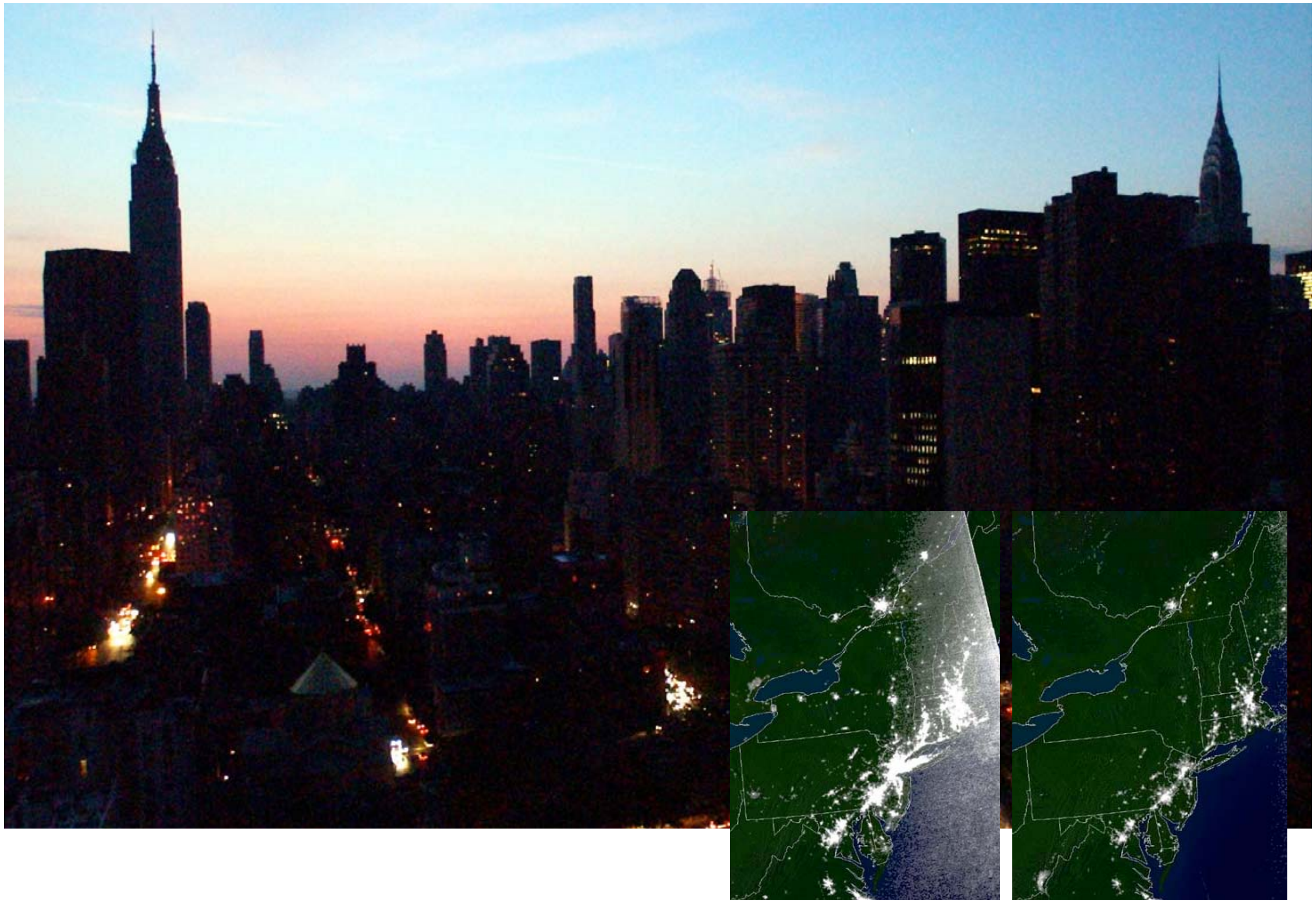


Quantitative Analysis of Causality Networks



Identify the elements of the matrix M. Consider quantitative (data) and qualitative interactions {-3, ..., +3} and thus functional and structural characteristics of the causal networks for different means of disaster!

Failure of Electricity Networks



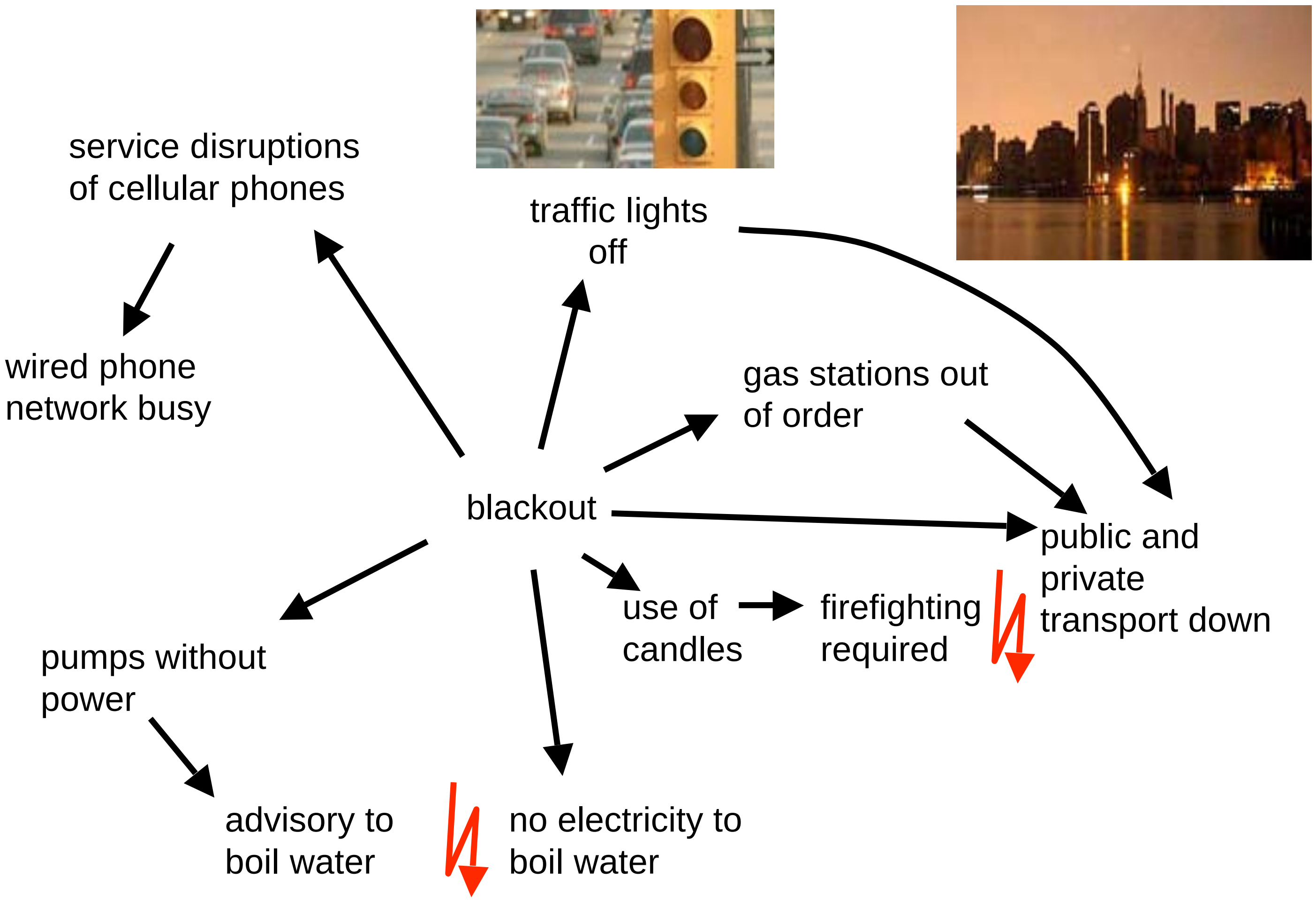
A power outage affects all fields of community.

Blackouts and Cascading Effects in Electricity Networks

New York, August 14, 2003

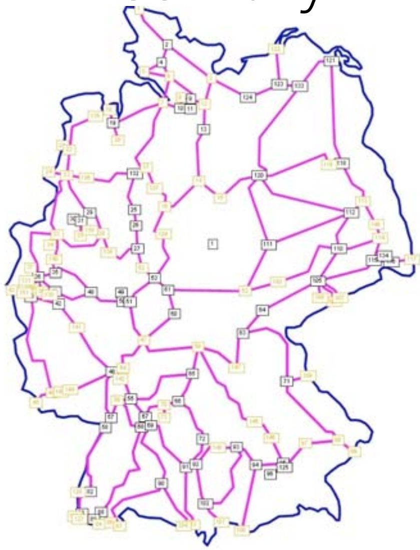
Rome, September 28, 2003

Causality Network for the Blackout in North America 2003 (Detail)

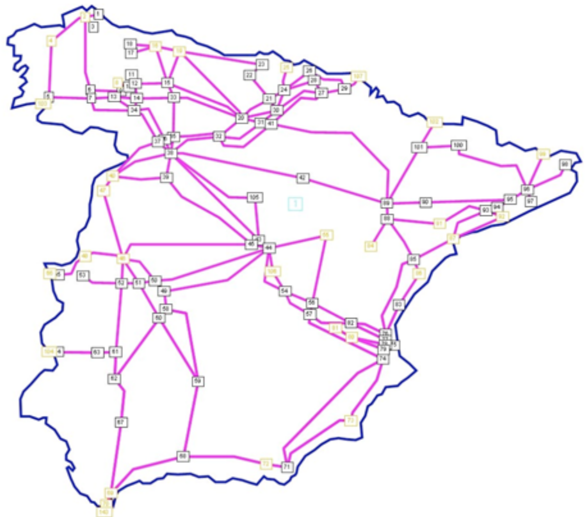


Networks

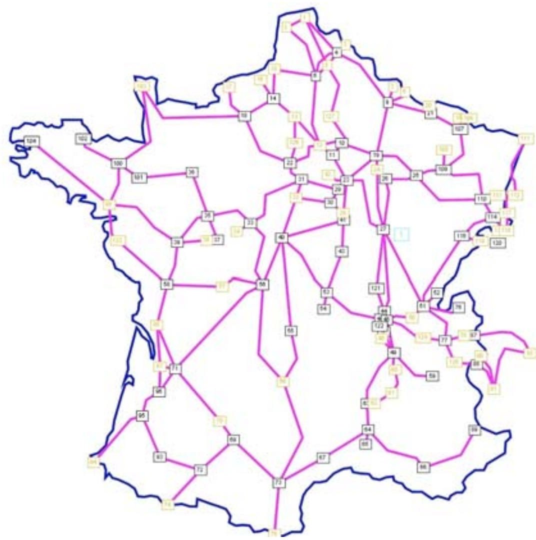
Germany



Spain



France



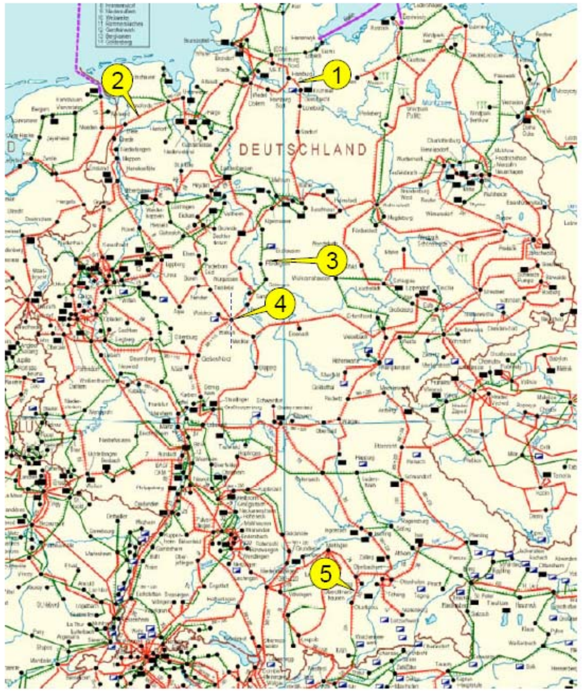
Generators	55	23	37
Loads	65	78	66
Border Nodes	22	7	15
Total production	62 629 MW	26 265 MW	60 399 MW
Total consumption	59 387 MW	25 035 MW	47 382 MW

Homogeneous setting of generators and loads

Susceptibility of wires proportional to the length

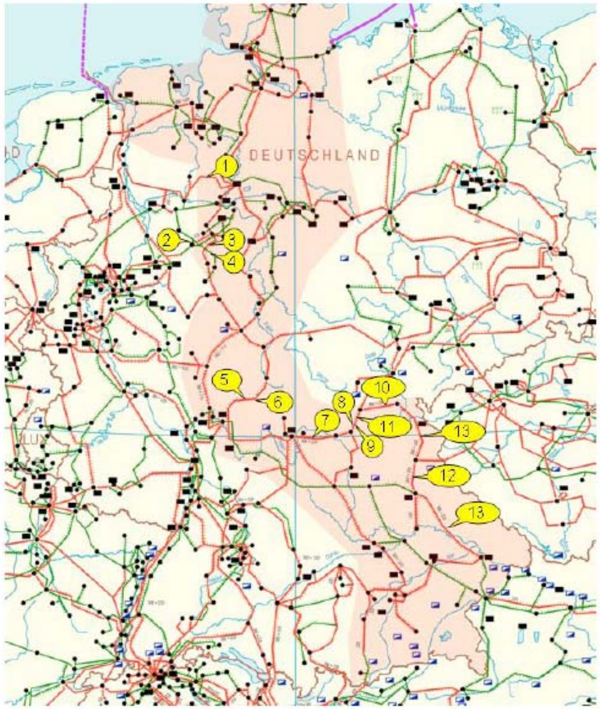
Blackouts and Cascading Effects in Electricity Networks

State of the power grid shortly before the incident



Sequence of events on November 4, 2006

Nr.	Zeit	kV	Leitung
1	22:10:13	380	Wehrendorf-Landesbergen
2	22:10:15	220	Bielefeld/Ost-Spexard
3	22:10:19	380	Bechterdissen-Elsen
4	22:10:22	220	Paderborn/Süd-Bechterdissen/Gütersloh
5	22:10:22	380	Dipperz-Großkrotzenburg 1
6	22:10:25	380	Großkrotzenburg-Dipperz 2
7	22:10:27	380	Oberhaid-Grafenrheinfeld
8	22:10:27	380	Redwitz-Raitersaich
9	22:10:27	380	Redwitz-Oberhaid
10	22:10:27	380	Redwitz-Etzenricht
11	22:10:27	220	Würgau-Redwitz
12	22:10:27	380	Etzenricht-Schwandorf
13	22:10:27	220	Mechlenreuth-Schwandorf
14	22:10:27	380	Schwandorf-Pleinting



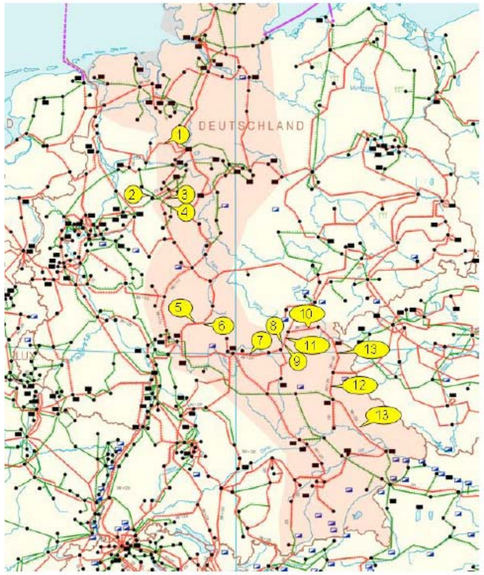
1,3,4,5 – lines switched off for construction work

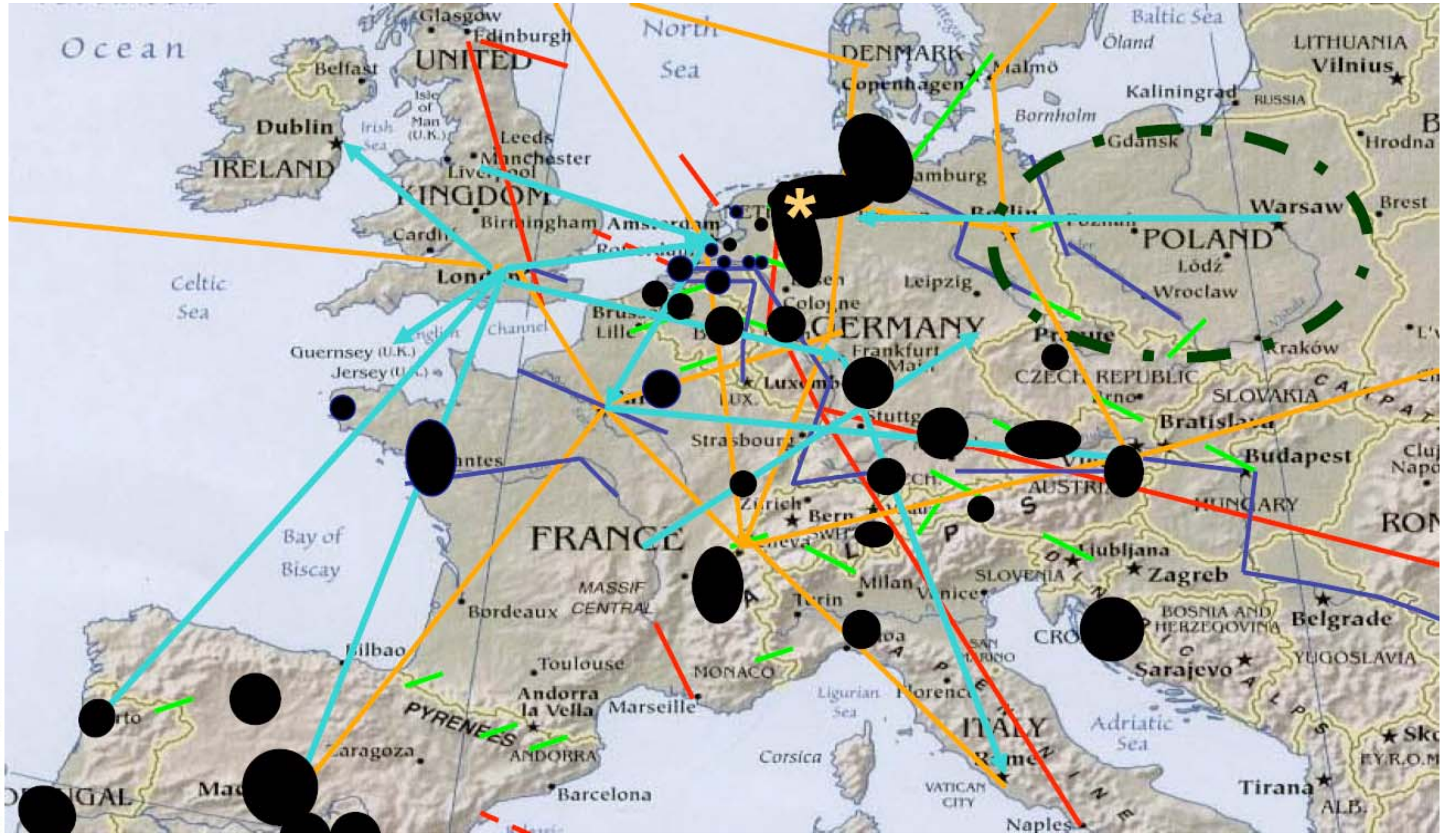
2 – line switched off for the transfer of a ship by Meyer -Werft

E.ON Netz's report on the system incident of November 4, 2006, E.ON Netz GmbH

Cascading Effects and Blackout in the European Electricity Networks

Failure in the continental European electricity grid on November 4, 2006

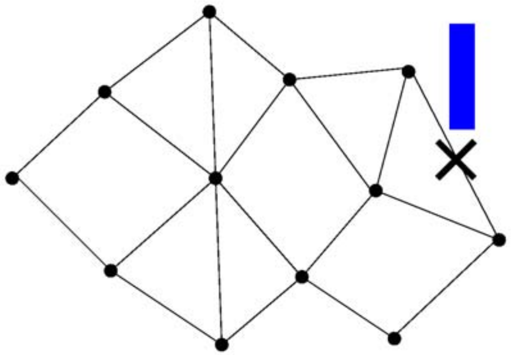




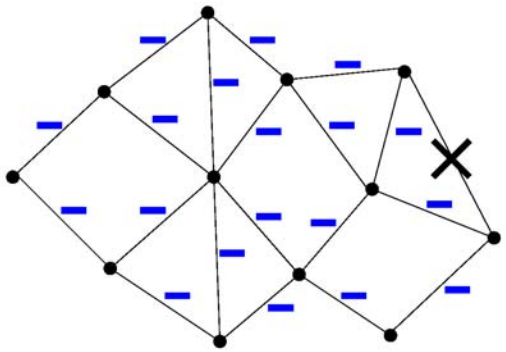
EU project IRRIIS: E. Liuf (2007) Critical Infrastructure protection, R&D view

Stationary and Dynamic Models for Cascading Failures

Initial failure

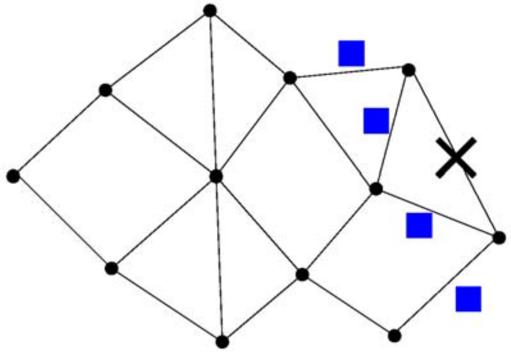


Stationary model

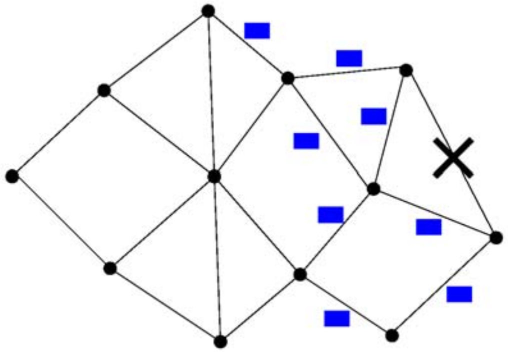


Dynamic model

t = 1

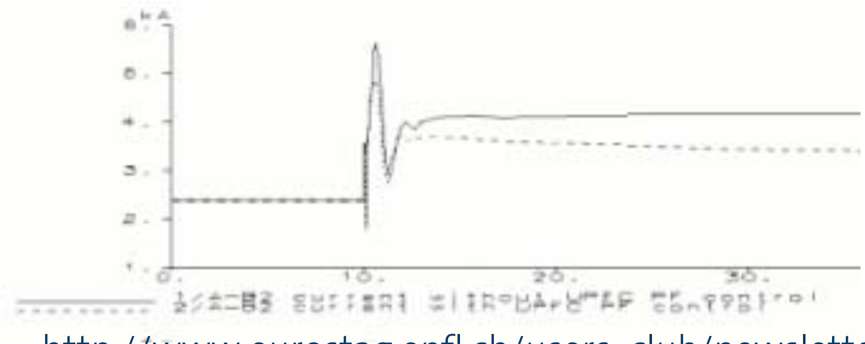


t = 2

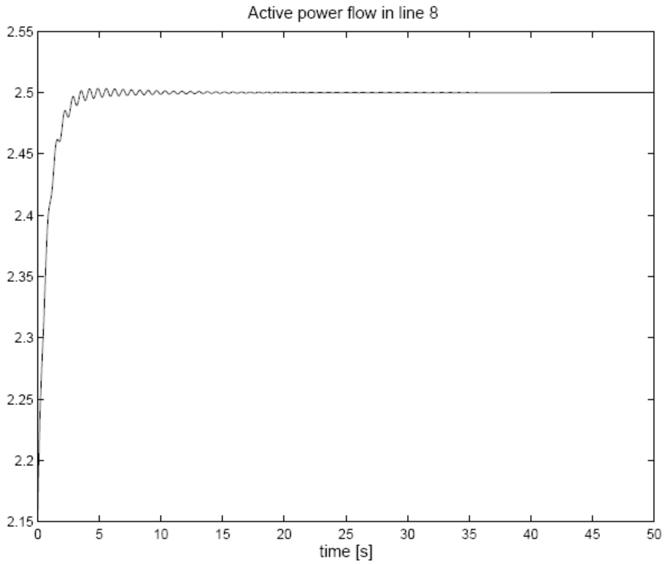


Model Dynamics

Power grid simulation model

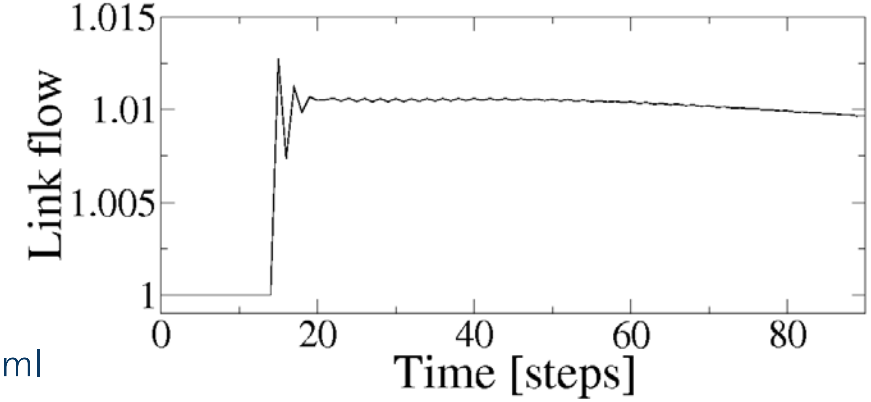


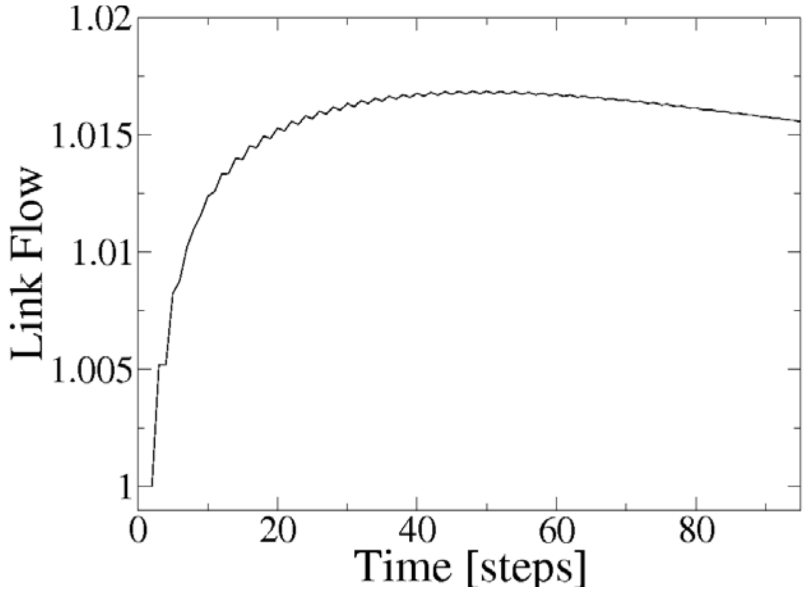
http://www.eurostag.epfl.ch/users club/newsletter/nl8.html



R. Sadikovic: Power flow control with UPFC, (internal report)

Our model





Model Dynamics

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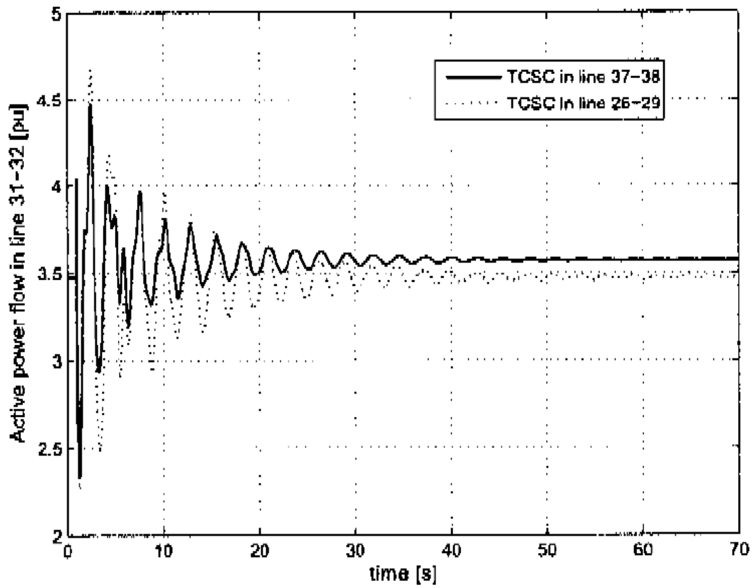

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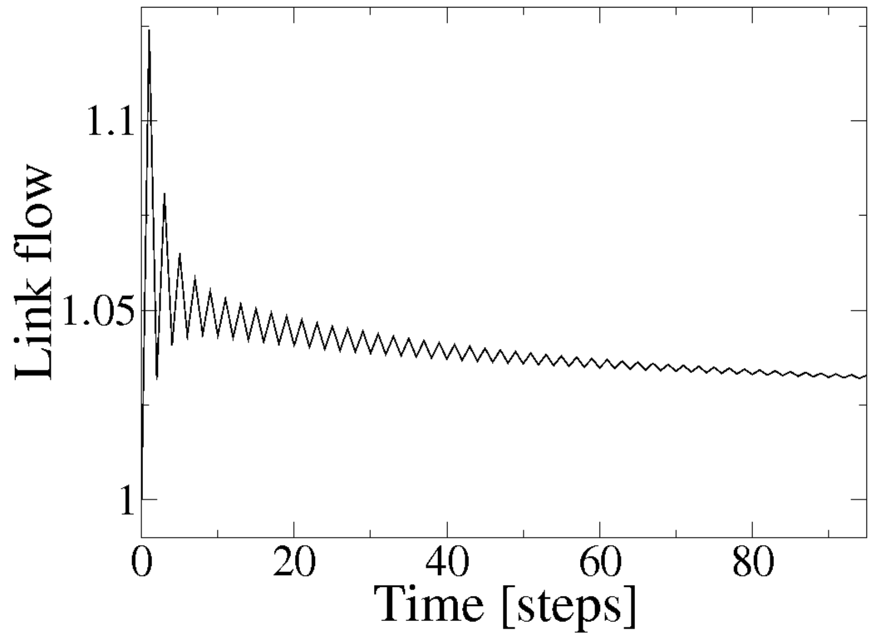
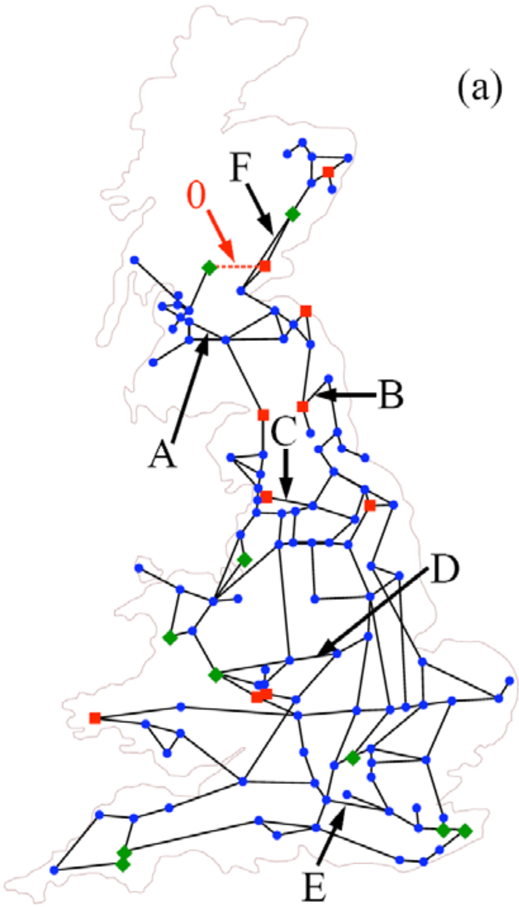
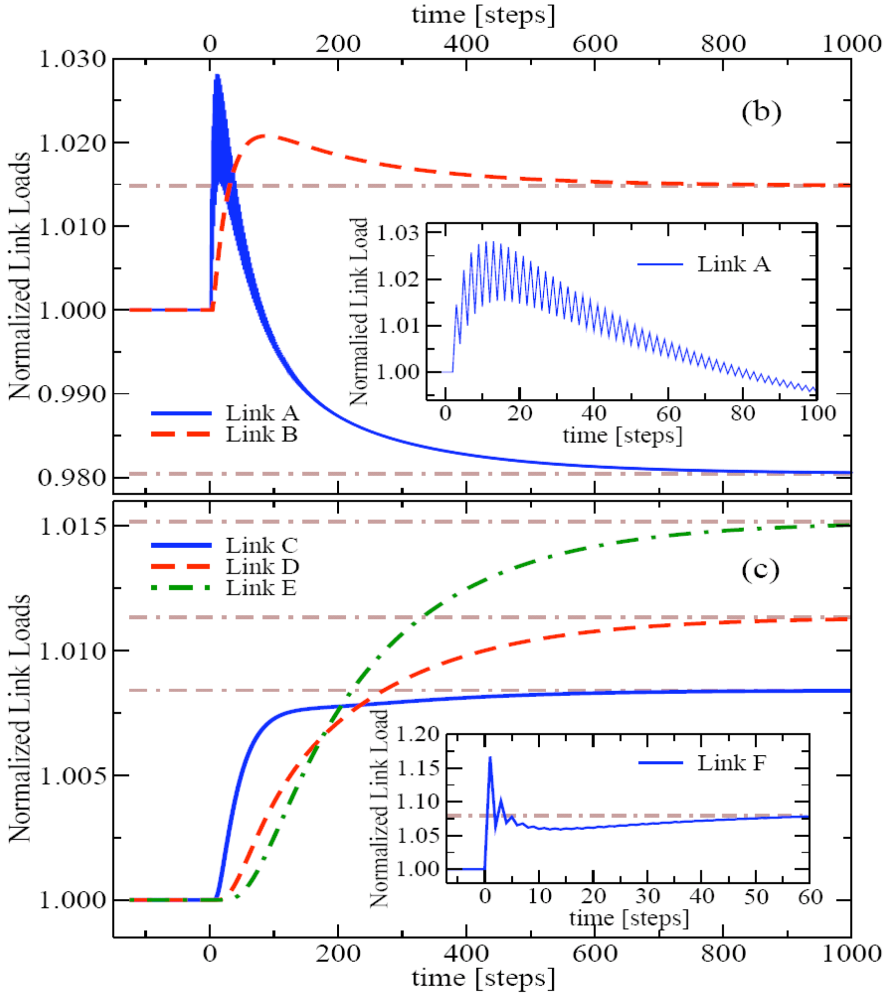


R. Sadikovic: Use of FACTS devices for power flow control and damping of oscillations in power systems, 2006, PhD thesis, ETH Zurich

Model Dynamics



UK high voltage power grid topology (300-400 kV)



Stationary Model vs. Dynamic Model

Link capacities:

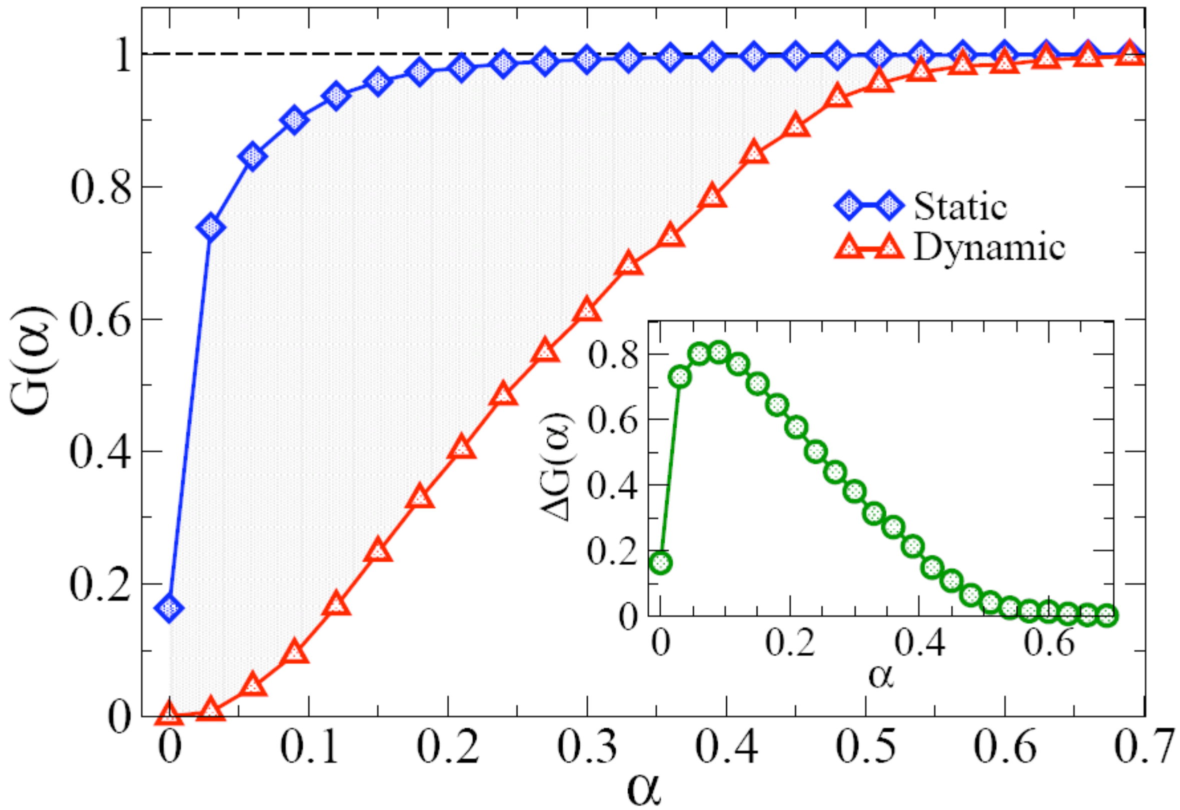
$$\mathcal{C}_{ij} = (1+\alpha)\, L_{ij},$$

$|\mathcal{N}|$ number of nodes

$|\mathcal{L}|$ number of links

$|\mathcal{N}_R|$ number of remaining nodes

$|\mathcal{L}_R|$ number of remaining links



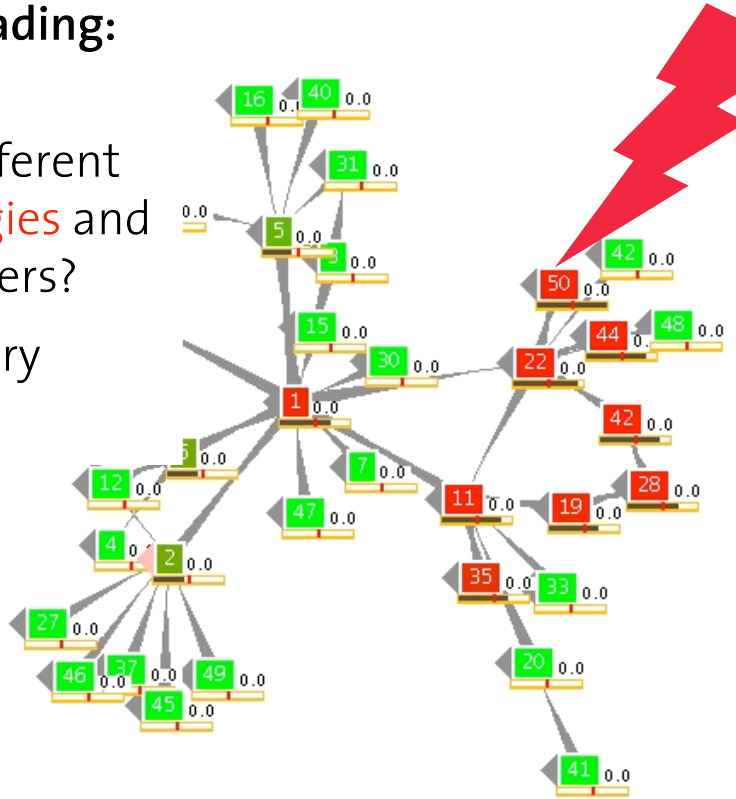
$$G_{\mathcal{L}}(\alpha) = \frac{|\mathcal{L}_R|}{|\mathcal{L}|} \approx G_{\mathcal{N}}(\alpha) = \frac{|\mathcal{N}_R|}{|\mathcal{N}|} = G(\alpha)$$

Modeling and Simulation of Disaster Spreading

Simulation of topology dependent spreading:

- What are the influences of different network topologies and system parameters?

- Optimal recovery strategies?



Buzna L., Peters K., Helbing D., Modelling the Dynamics of Disaster Spreading in Networks, Physica A, 2006

Spreading of disasters:

Causal dependencies (directed)

Initial event (internal, external)

Redistribution of loads

Delays in propagation

Capacities of nodes (robustness)

Cascade of failures

Scope of research:

Spreading conditions (network topologies, system parameters)

Optimal recovery strategies

Mathematical Model of Disaster Spreading

Node dynamics:

$$\frac{dx_i}{dt} = -\frac{x_i}{\tau} + \Theta\left(\sum_{j\neq i} \frac{M_{ij}x_j(t-t_{ij})}{f(O_i)} \mathrm{e}^{-\beta t_{ij}/\tau}\right) + \xi_i(t)$$

x_i state of the node

$x_i = 0$ usual situation

$x_i > \theta_i$ node is destroyed

$$\Theta(x) = \frac{1-\exp(-\alpha x)}{1+\exp[-\alpha(x-\theta_i)]}$$

$$f(O_i) = \frac{aO_i}{1+bO_i}$$

θ_i node threshold

t_{ij} time delay

M_{ij} link strength

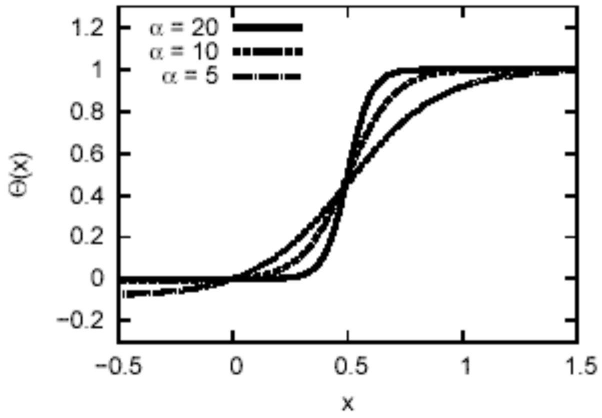
a, b, α, β fit parameters

$1/\tau$ healing rate

$\xi_i(t)$ internal noise

O_i node out-degree

Threshold function:



$$\Theta(x) = \frac{1-\exp(-\alpha x)}{1+\exp[-\alpha(x-\theta_i)]}$$

Node degree:

$$f(O_i) = \frac{aO_i}{1+bO_i}$$

➡ **We use a directed network, dynamical, bistable node models and delayed interactions along links.**

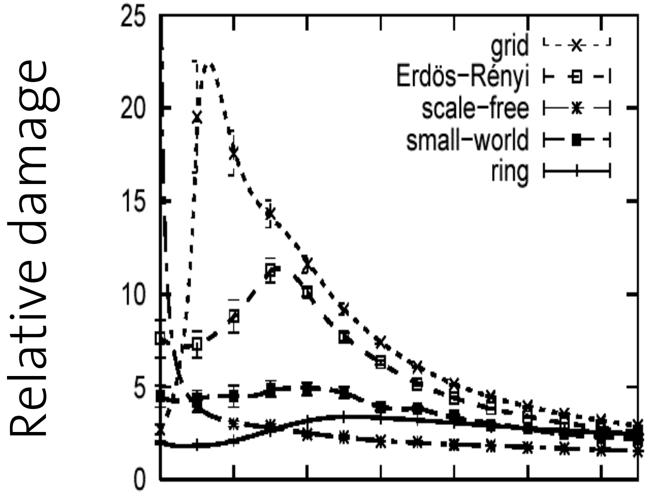
Failures Triggered by Internal Fluctuations

Coinciding, distributed, random failures:

$$\frac{dx_i}{dt} = -\frac{x_i}{\tau} + \Theta\left(\sum_{j\neq i} \frac{M_{ij}x_j(t-t_{ij})}{f(O_i)} \mathrm{e}^{-\beta t_{ij}/\tau}\right) + \xi_i(t)$$

Damage compared to an "unconnected network":

Homogeneous networks



Level of internal noise ($\xi_i(t)$)

L. Buzna, K. Peters, D. Helbing: Modeling the dynamics of disaster spreading in networks, *Physica A* **363**, 132-140 (2006)

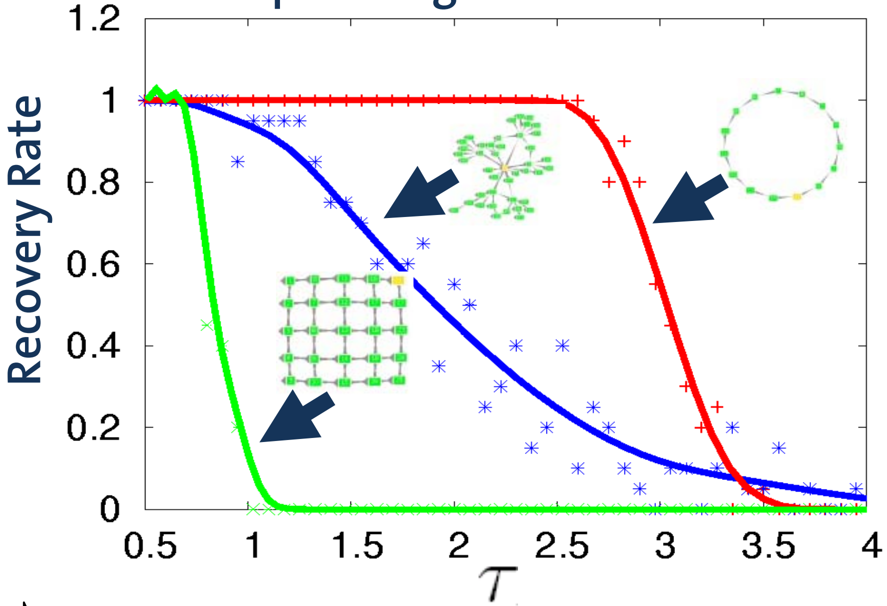
Connectivity is an important factor (in a certain region).

Phase Transition in Disaster Spreading

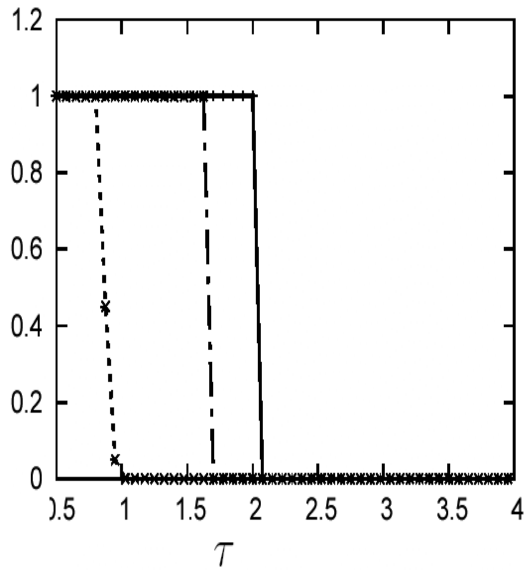
Node robustness vs. failure propagation:

$$\frac{dx_i}{dt} = -\frac{x_i}{\tau} + \Theta\left(\sum_{j\neq i}\frac{M_{ij}x_j(t-t_{ij})}{f(O_i)}\mathrm{e}^{-\beta t_{ij}/\tau}\right) + \xi_i(t)$$

Spreading Threshold



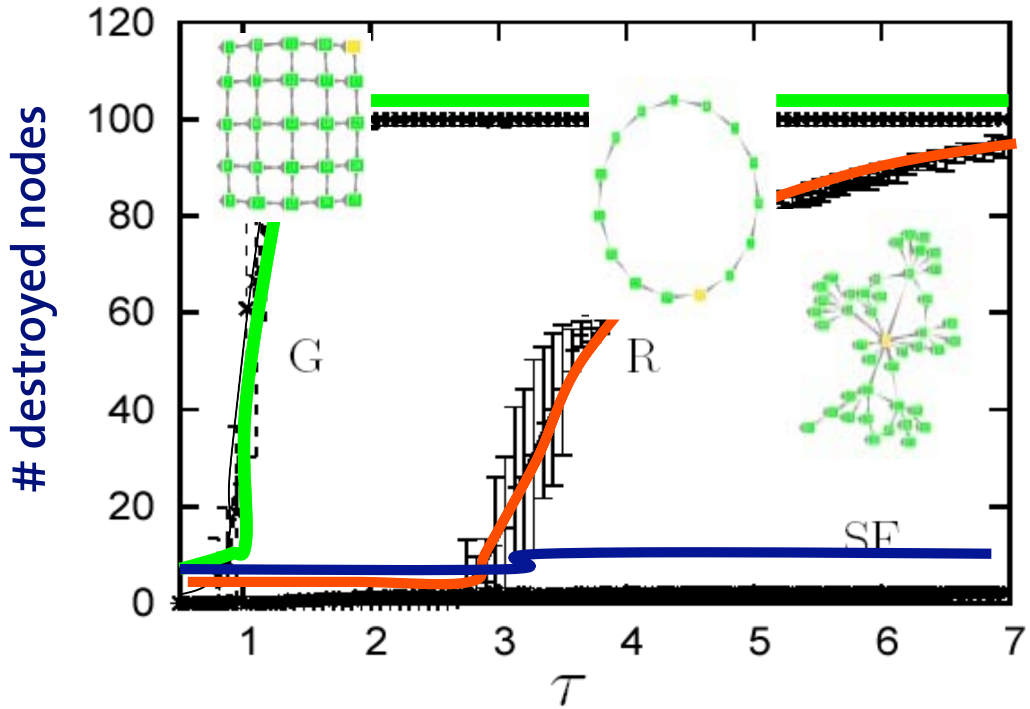
Homogeneous networks



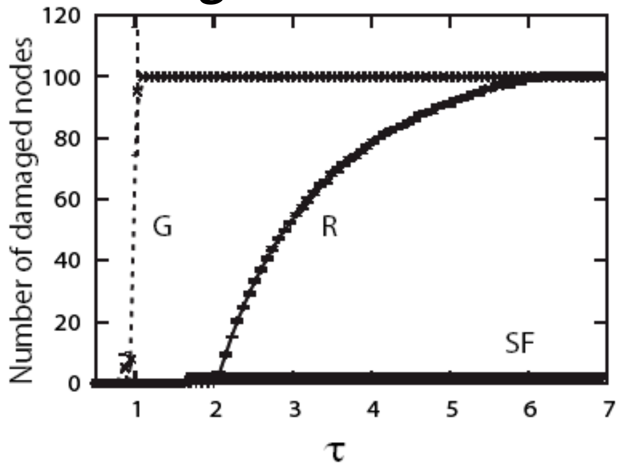
We found a critical threshold for the spreading of disasters in networks.
Topology and parameters are crucial.

Topology and Spreading Dynamics

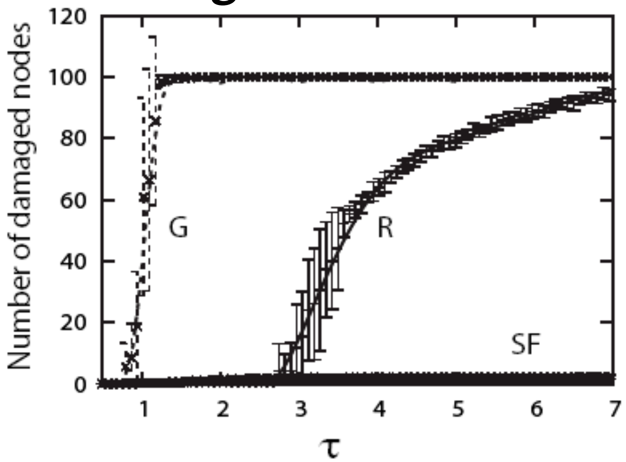
Example: 100 nodes, average state after t=300



Homogeneous network



Heterogeneous network



➡ We found a topology dependent „velocity" of failure propagation.
Spreading in scale-free networks is slow.

K. Peters, L. Buzna, D. Helbing: Modelling of cascading effects and efficient response to disaster spreading in complex networks, International Journal of Critical Infrastructures, in print (2007).

Modelling the Recovery of Networks

1. Mobilization of external resources:

$$r(t) = a_1 t^{b_1} e^{-c_1 t}$$

2. Formulation of recovery strategies as a function of

- the network topology
- the level of damage

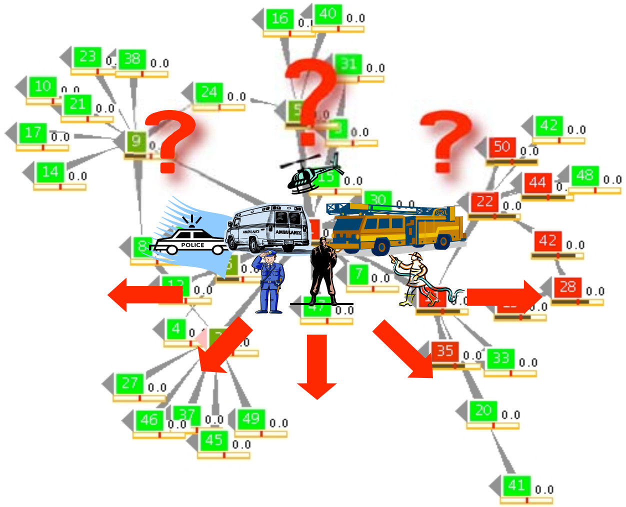
$$\frac{1}{\tau_i(t)} = \frac{1}{(\tau_{start} - \beta_2)e^{-\alpha_2 R_i(t)} + \beta_2}$$

3. Application of resources in nodes

Parameters:

t_D time delay in response

R disposition of resources



$R_i(t)$ cumulative number of resources deployed at node *i*

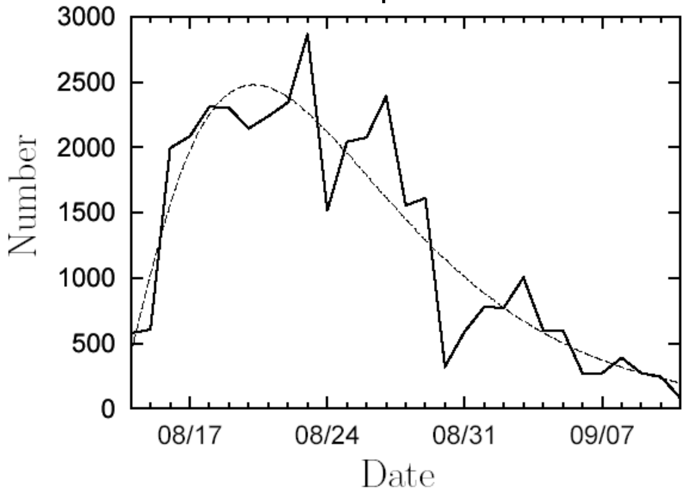
τ_{start} initial intensity of recovery process

α_2 β_2 fit parameters

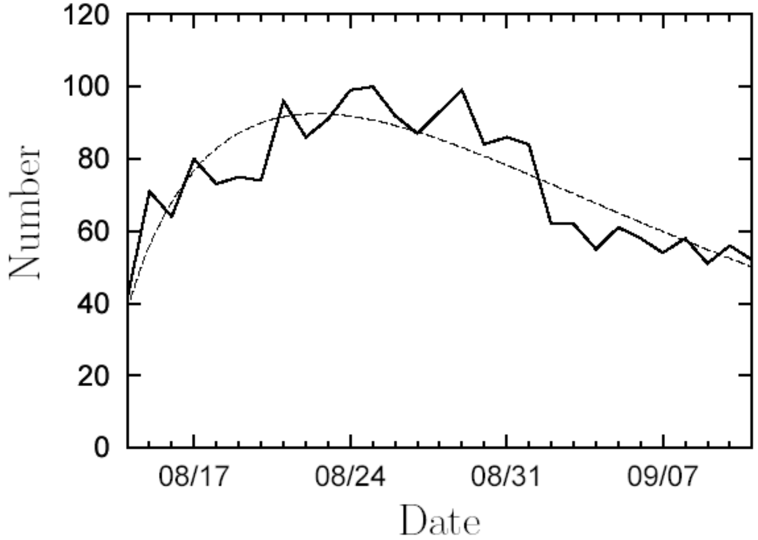
Mobilization of Resources

Example: Mobilization during the Elbe flood 2002:

Manpower



Vehicles



Mobilization of resources (time dependent)

External resources become available after a certain response time delay T_D

During mobilization the number of resources increases

Later a phase of demobilization occurs

Number of available resources *r(t)*:

$$R(t) = a_1 t^{b_1} e^{-c_1 t}$$

a_1, b_1, c_1 are fit parameters

How to Distribute Available Resources ?

Formulation of recovery strategies, based on information :

S_0 no recovery

Topology information only:

S_1 uniform deployment

S_2 out degree based dissemination

Damage information:

S_3 uniform reinforcement of challenged nodes (x_i>0)

S_4 uniform reinforcement of destroyed nodes (x_i> θ_i)

Damage & topology information:

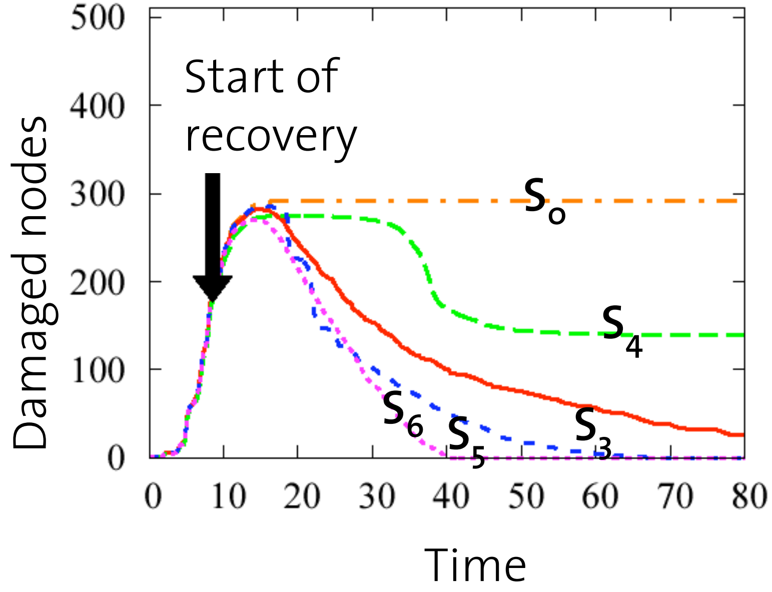
S_5 targeted reinforcement of highly connected nodes

1st priority: fraction q to hub nodes

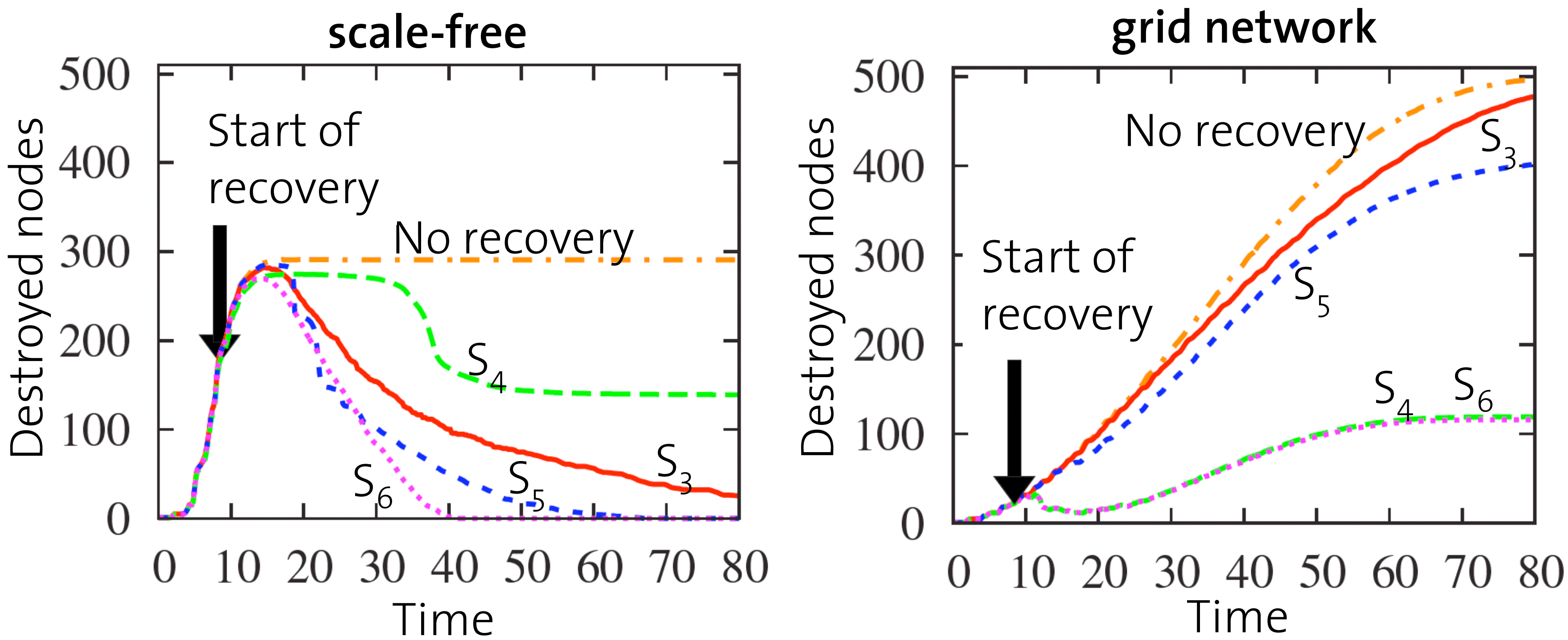
2nd priority: fraction 1-q according to S_4

S_6 out-degree based targeted reinforcment of destroyed nodes

Application of resources to a scale-free network



Recovery of Networks



Parameters: Network topology

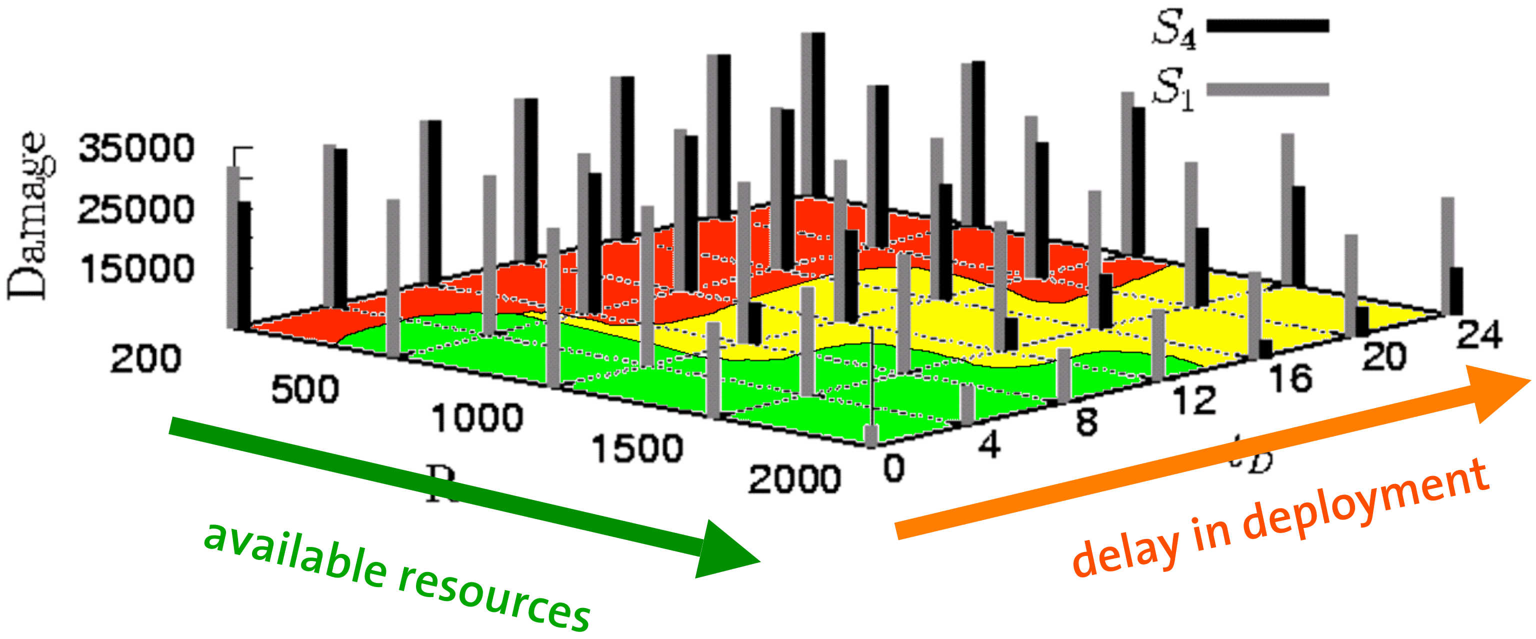
time delay in response $t_D = 8$

disposition of resources $R = 1000$

L. Buzna, K. Peters, H. Ammoser, Ch. Kuehnert and D. Helbing: Efficient response to cascading disaster spreading, *Physical Review E* **75**, 056107 (2007)

Recovery of Networks: When Does Strategy Matter?

Comparison of efficient and inefficient strategies:

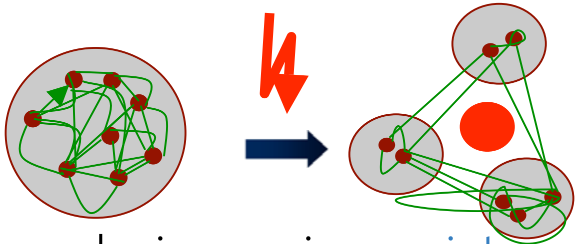


- The delay of recovery activities is crucial.
- Optimization of recovery strategies is promising in certain parameter regions.

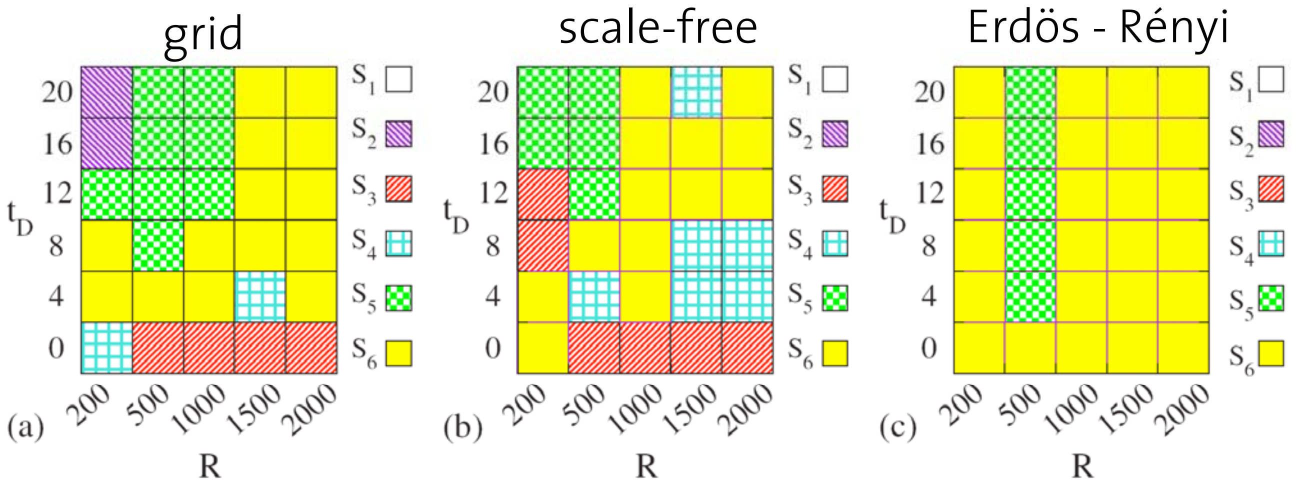
Most Efficient Strategies Are Highly Non-Trivial

Network vulnerability can be reduced

- by improving the network structure
  - by introducting redundancy
  - by limiting size & interconnectedness



  - by increasing variety in the system
- by immediate response to perturbations
- Example: Internet, disaster management



There is no unique optimal response strategy:

Strategies based on the network structure has been proved as a most suitable for scale-free structures.

Strategies based on the damage information are more appropriate for regular networks.

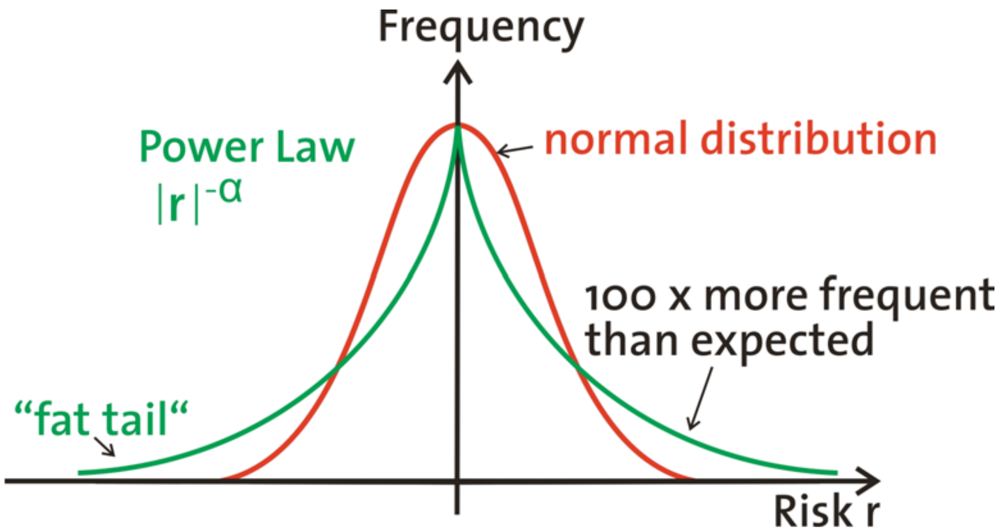
The situation in Erdős-Rényi and small-world networks depends on t_D

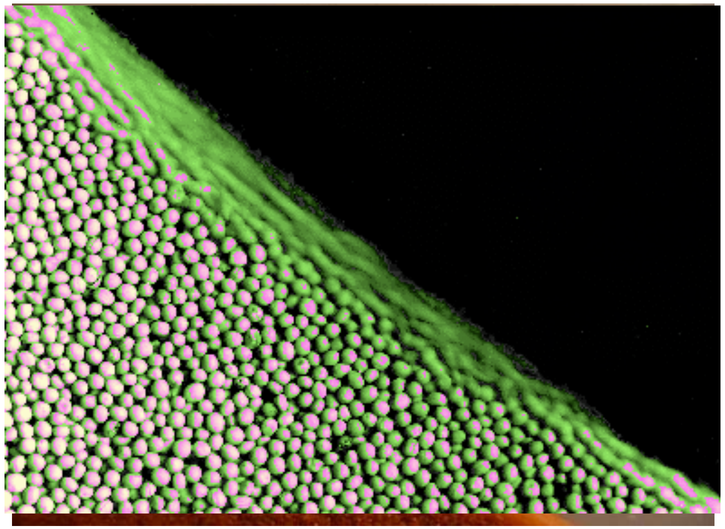
(short t_D => damage-based strategies)

(large t_D => network-structure-based strategies)

Power Laws and Self-Organized Criticality

- Power laws: Extreme events occur more frequently than expected (compared with the common normal distribution)

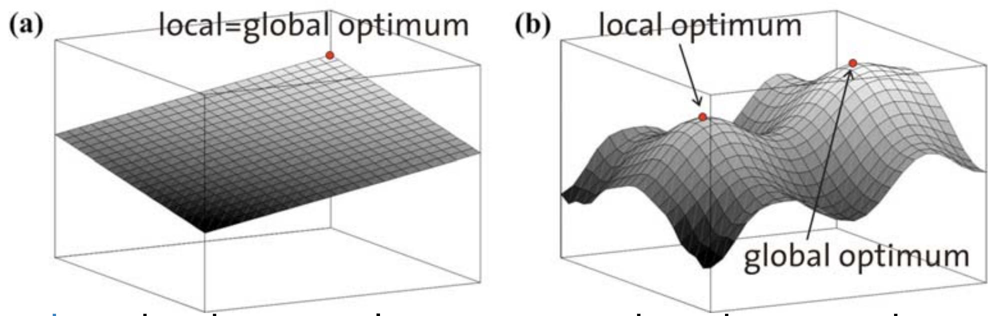




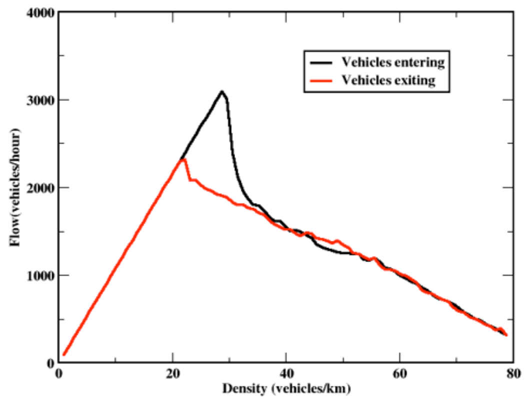
- Examples: Frequency of floods, storms, earth quakes, wars
- Important for insurance business, pricing of financial derivatives
- Self-organized criticality: The system may drive itself to a critical state, thereby causing power laws
- Example: Avalanche sizes in growing sand heaps; probably also: economic bankruptcy cascades

Weaknesses of Classical Optimization

- One can only optimize for one goal at a time, but usually, one needs to meet several objectives
- Optization routine may get stuck in a local optimum

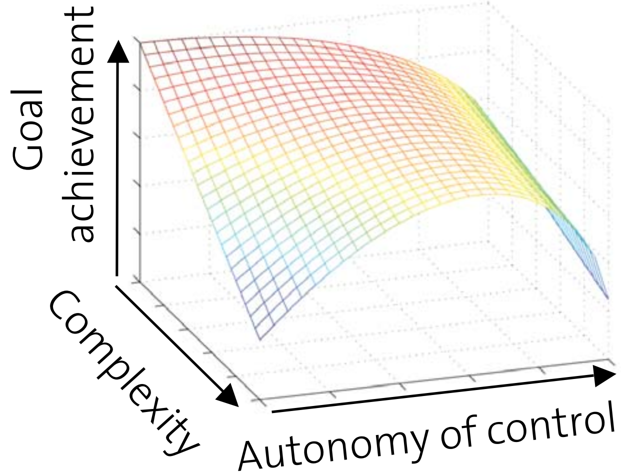


- Evolutionary dead ends: The best solution may be the combination of two bad solutions (i.e. gradual optimization may not work)
- Optimization tends to drive the system closer to instabilities
- Example: Utilization of maximum road capacity will eventually cause capacity drops



Weaknesses of Classical Optimization II

- NP-hardness: Complexity of optimization problem often prevents exact online optimization
- Optimization based on average or past data optimizes for a non-existent situation, i.e. it the applied solution is NOT optimal in reality
- Example: Today's traffic light control
- Often, there is a lack of data to determine model parameters accurately
- Example: Portefolio optimization
- I. Kondor: „The complexity of financial systems exceeds what is knowable"
- Other problems: Information delays or overloads, and inconsistent information
- Problem: What ARE the relevant indicators or control variables?



(Windt, Böse, Philipp, 2006)

Is It a Lost Battle?

- In a strongly varying world, strict stability and control is not possible anymore or excessively expensive
- Example: Public spending deficits

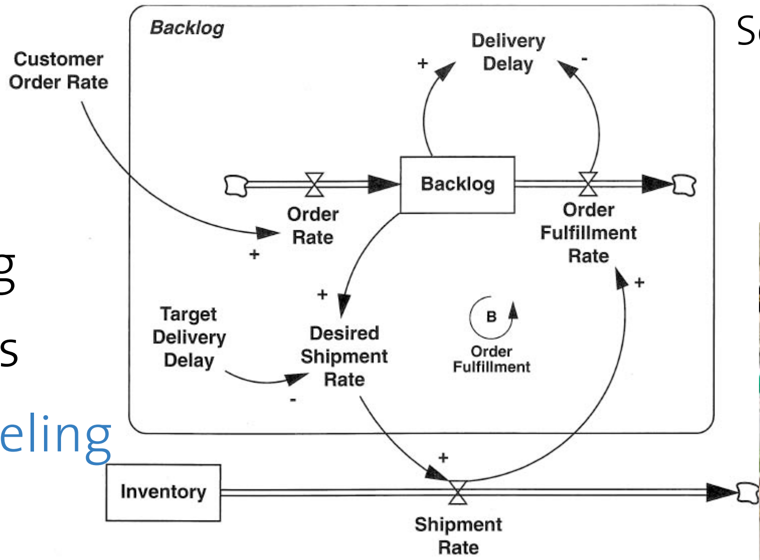
- Hierarchically organized structures have a critical size, beyond which they become unstable
- Examples: Decay of Soviet Union; many failed mergers in the last decade (Daimler-Chrysler, BMW-Rover, Allianz-Dresdner Bank, ...)
- A paradigm shift towards flexible, agile, adaptive systems is needed, possible - and overdue!


Boeing 747: Constructed for stable flight

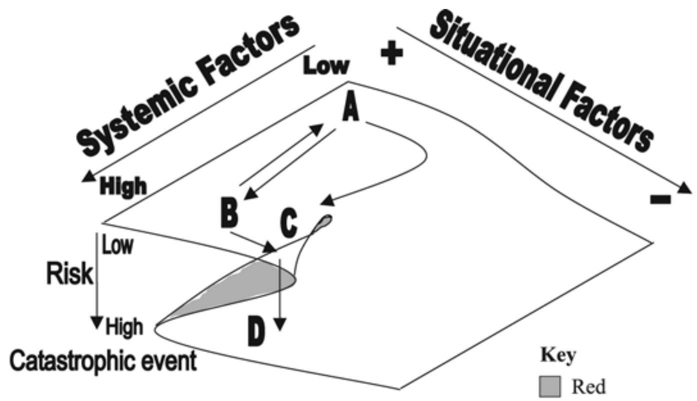

Su-47: Utilizes dynamic instability

Techniques Used in Complexity Science

- Data mining
- Network analysis
- System dynamics
- Scenario modeling
- Sensitivity analysis
- Agent-based modeling
- Statistical physics
- Non-linear dyamics and chaos theory
- Systems theory and cybernetics
- Catastrophe theory
- Statistics of extreme events
- Theory of critical phenomena

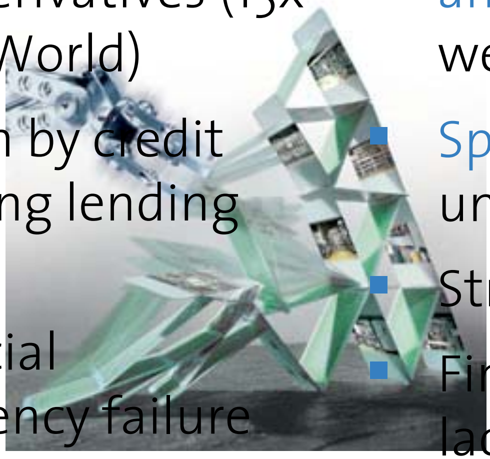


Source: J. D. Sterman



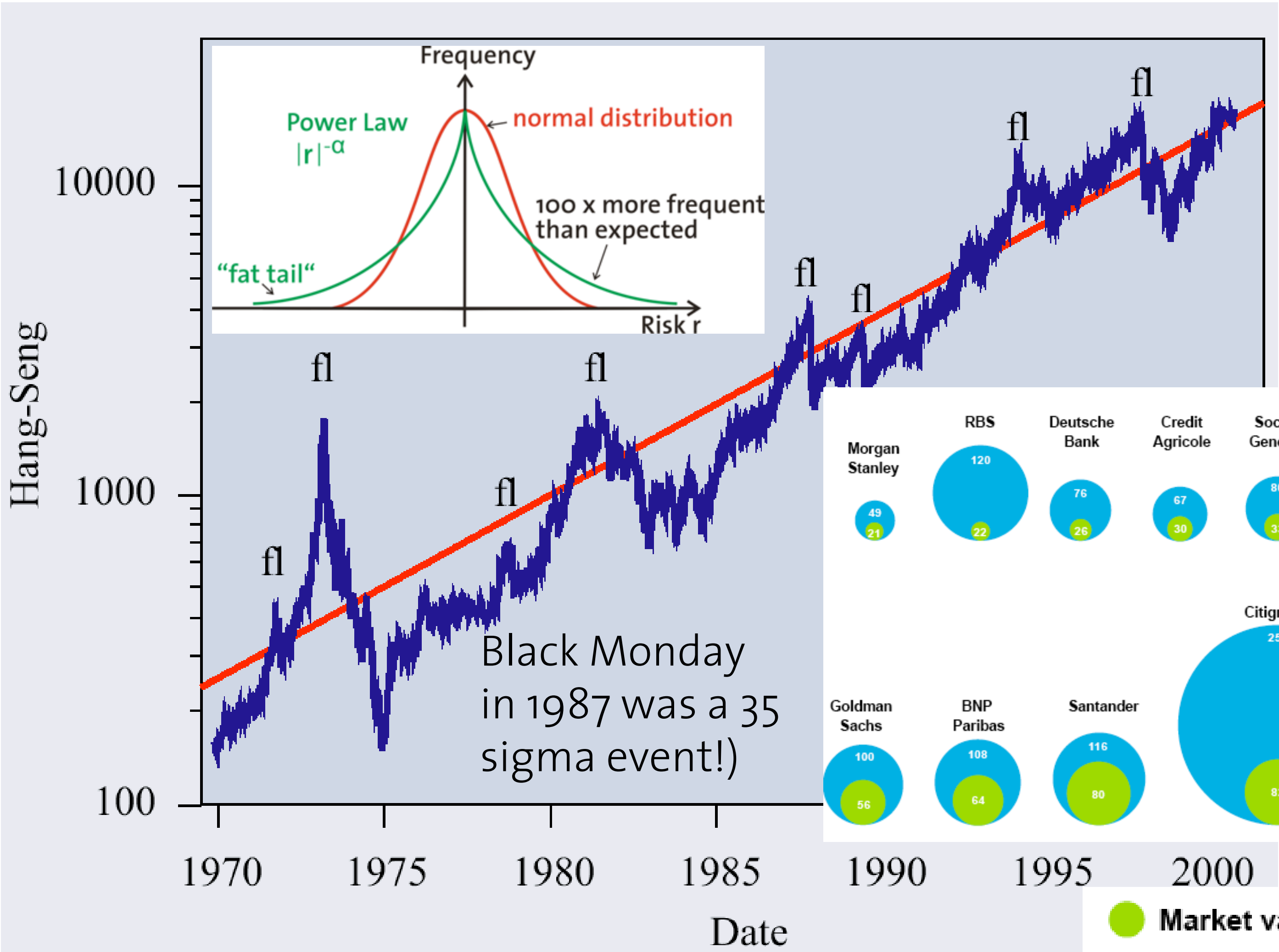
The Financial Crises Has Many Explanations

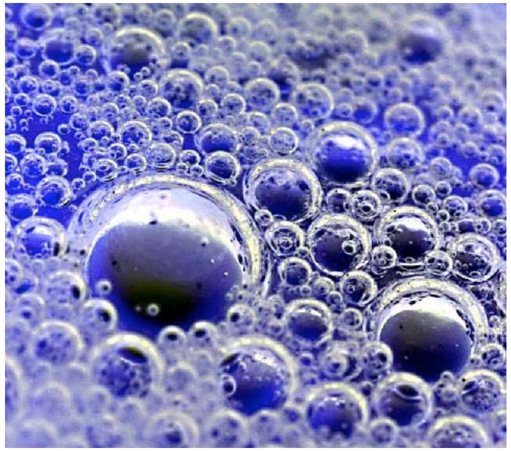
- Deregulation
- Explosive spread of derivatives (15x Gross Product of the World)
- „Riskless“ securization by credit default swaps, lowering lending standards
- Opaqueness of financial derivatives, rating agency failure
- Off-balance „shadow“ banking
- Bad risk models (Basel II)
- Insufficient net assets of banks
- Growth of over-capacities
- Low interest rates to fight previous crises (Greenspan strategy)
- Wrong incentives, managers‘ greed

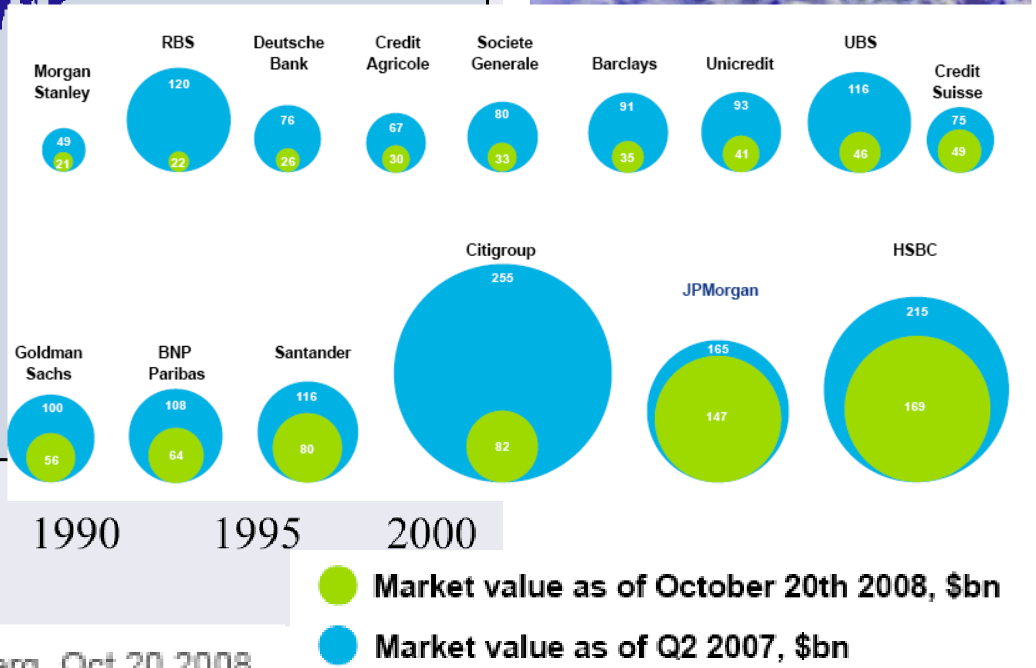


- Complexity of financial architecture and dynamics: Financial products were constructed like a house of cards
- Spreading of risk all over the system, underestimation of systemic risks
- Strong interactions and correlations
- Finance system as „global village“, lack of firewalls
- Self-organized criticality, too little variety
- Price formation mechanism combines material values and psychology
- Network of trust has broken down
- A theory of what constitutes „value“ is missing (--> fitness, particle mass)

Superexponential Bubbles or Crashes Instead of Stable Growth

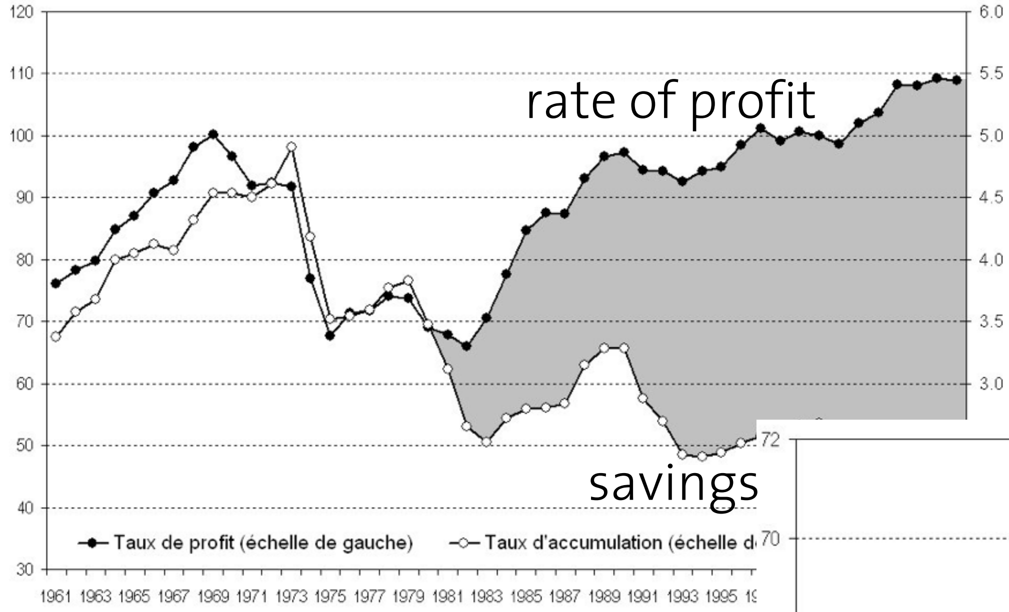




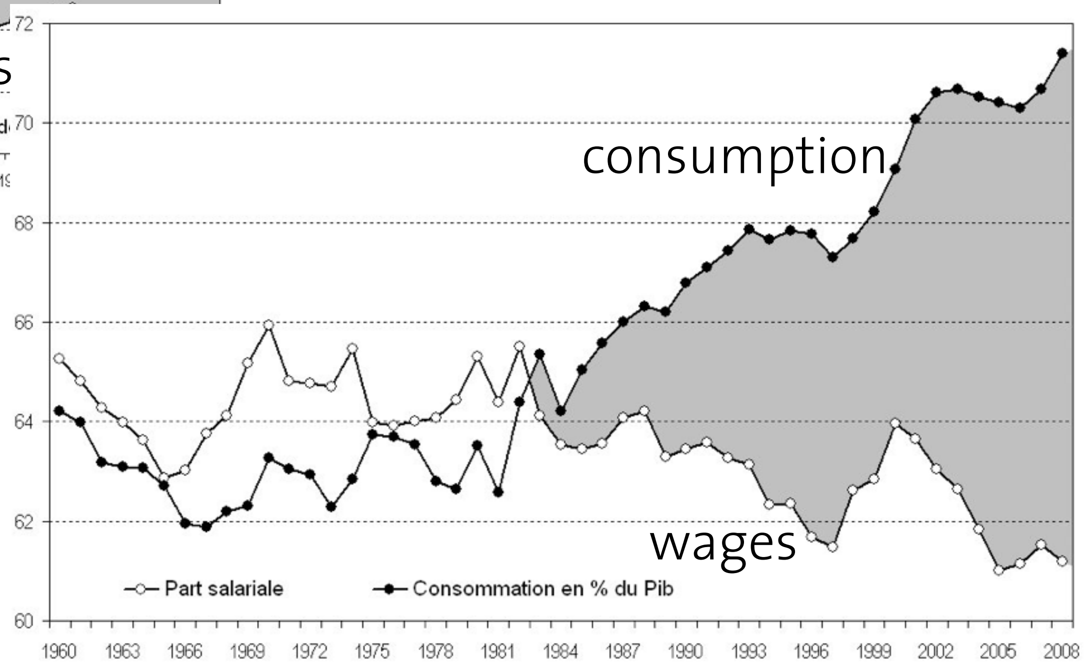


Source: J.P. Morgan, Bloomberg, Oct 20 2008

Finance Allows Increasing Dept and Virtual Wealth Growth

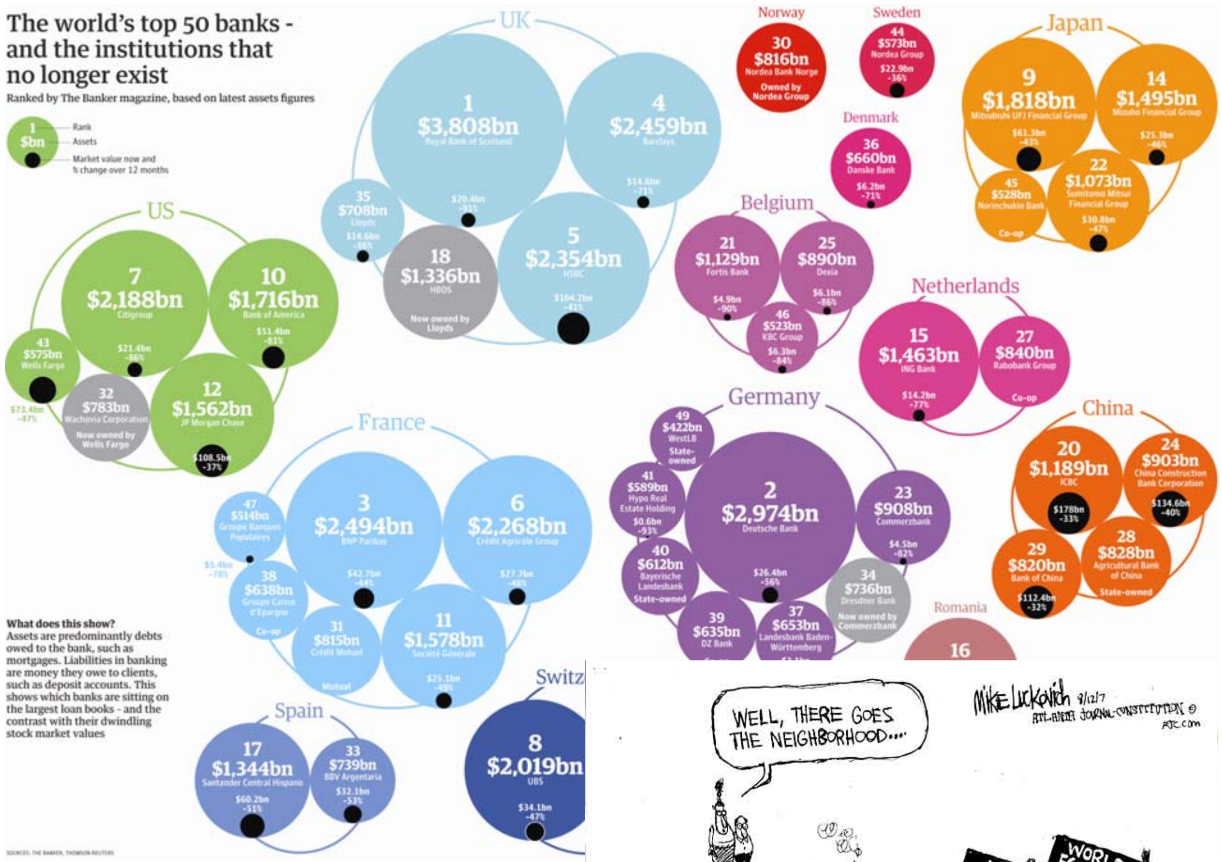


Rate of profit and rate of accumulation: The United States + European Union + Japan
Rate of accumulation = rate of growth rate of the net volume of capital
Rate of profit = profit/capital
(base: 100 in 2000)
Sources and data of the graphs:
http://hussonet.free.fr/toxicap.xls



United States Share of wages and of private consumption in Gross Domestic Product (GDP)
Source of data and graphics: http://hussonet.free.fr/toxicap.xls

Systemic Risks: Debts vs. Market Values of Largest Banks



Risk of domino effects: See impact of the bankruptcy of Lehmann Brothers

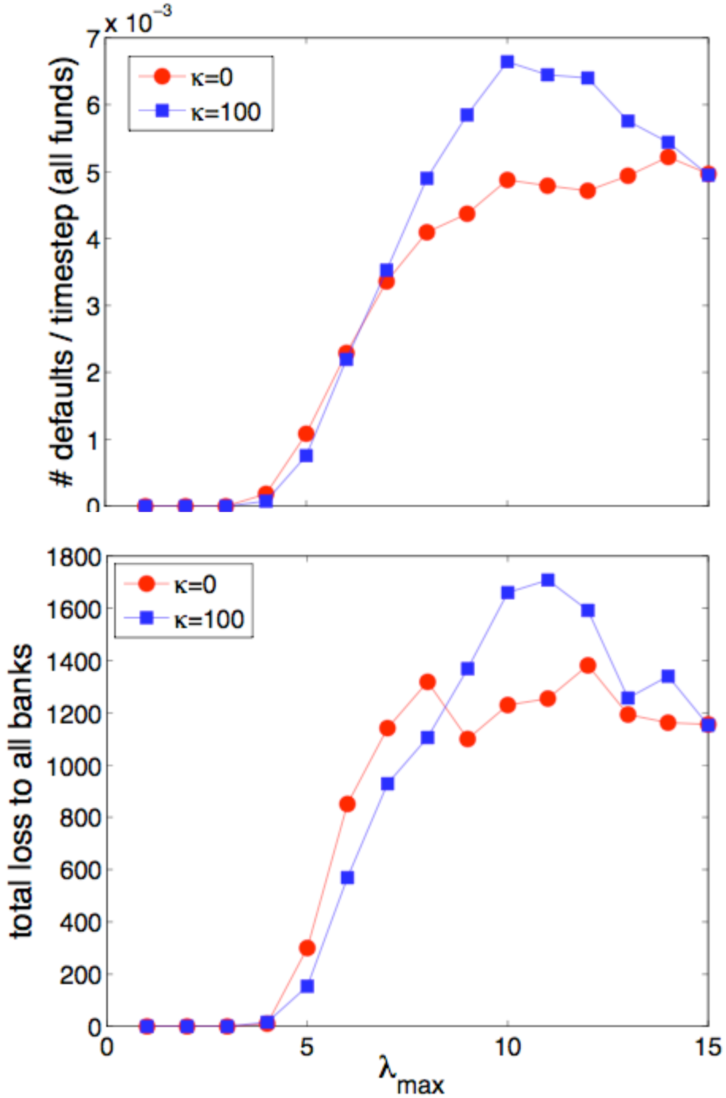
Country	GDP (Mio. USD)
World	**60,689,812**
European Union	18,394,115
United States	14,264,600
Japan	4,923,761
China (PRC)	4,401,614
Germany	3,667,513
France	2,865,737
United Kingdom	2,674,085
Italy	2,313,893
Russia	1,676,586
Spain	1,611,767
Brazil	1,572,839
Canada	1,510,957
India	1,209,686
Mexico	1,088,128
Australia	1,010,699

Source: IMF 2008

Hedge Fonds: Self-Organized Criticality and Problems of Regulation

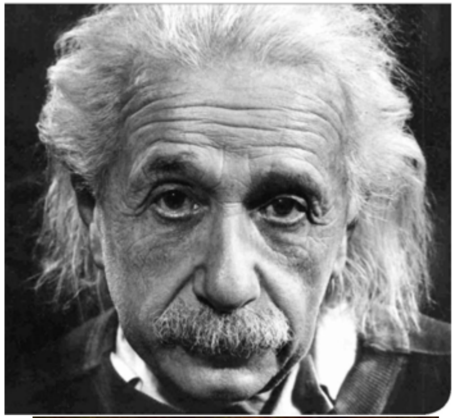
Dilemma: Large volatility due to high leverage or defaults and huge price jumps

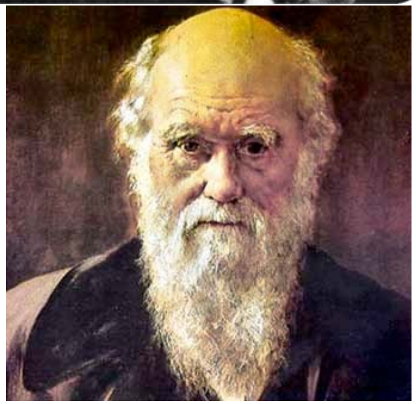
- Price returns depend on leverage in the system
- Evolutionary pressure for higher leverage
- Large system-wide leverage levels are pre-requisites of collapses
- Crises emerge out of practically 'nothing'
- But wrong regulation can have adverse effects: More defaults
- Volatility damping:
  - regulation, but not the currently practiced
  - adaptive restrictions of maximum leverage which are non pro-cyclical
  - enforcement of slow debt re-payment

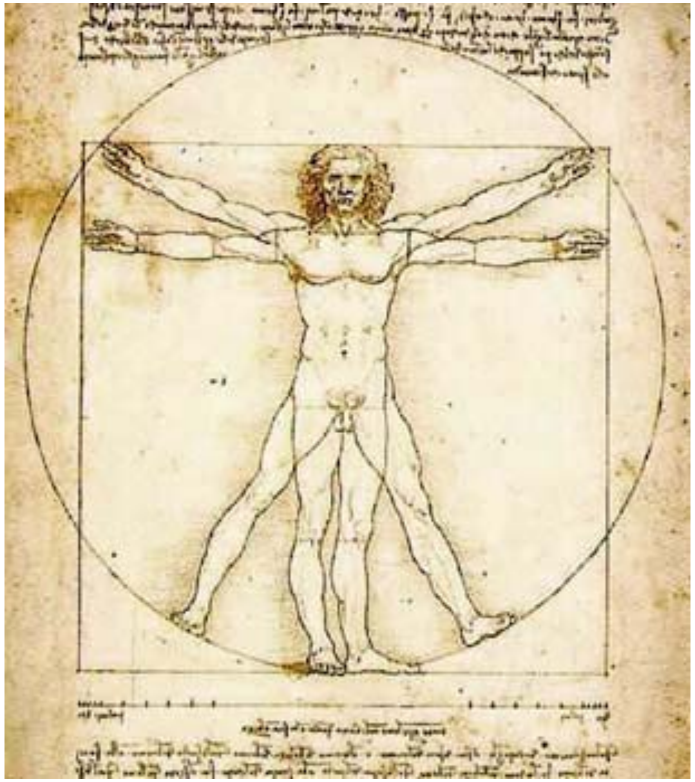


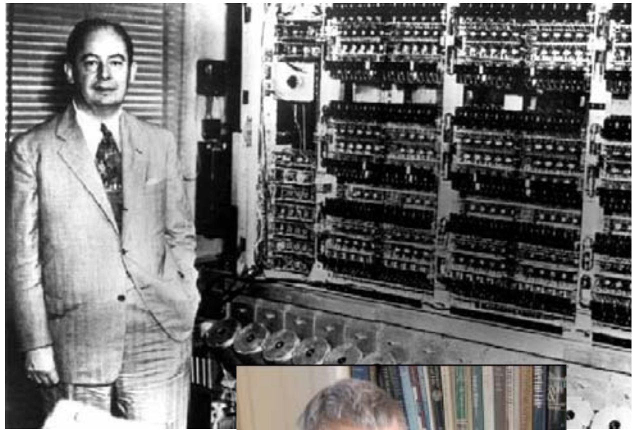
From: Stefan Thurner

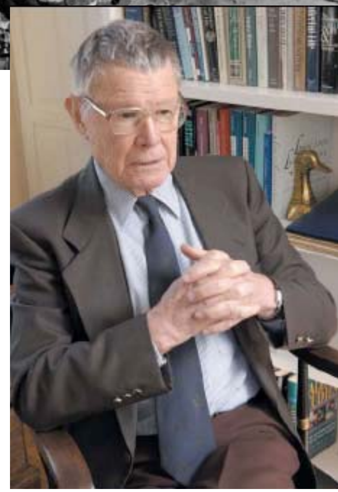
The Need of Integrative Systems Design + Complex Systems Science











We envision to create a socio-economic knowledge accelerator - a multi-disciplinary Apollo project for the social sciences, involving natural scientists and engineers

ETH Zurich's Competence Center

Coping with Crises in Complex Socio-Economic Systems

Kay Axhausen, Lars-Erik Cederman,

Dirk Helbing, Hans Herrmann,

Frank Schweitzer, Didier Sornette

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COPING WITH CRISES
IN COMPLEX SOCIO-ECONOMIC SYSTEMS
A Competence Center of ETH Zurich