TECHNISCHE UNIVERSITÄT DRESDEN

Physics of Risk
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Vilnius

Disaster spreading in complex networks

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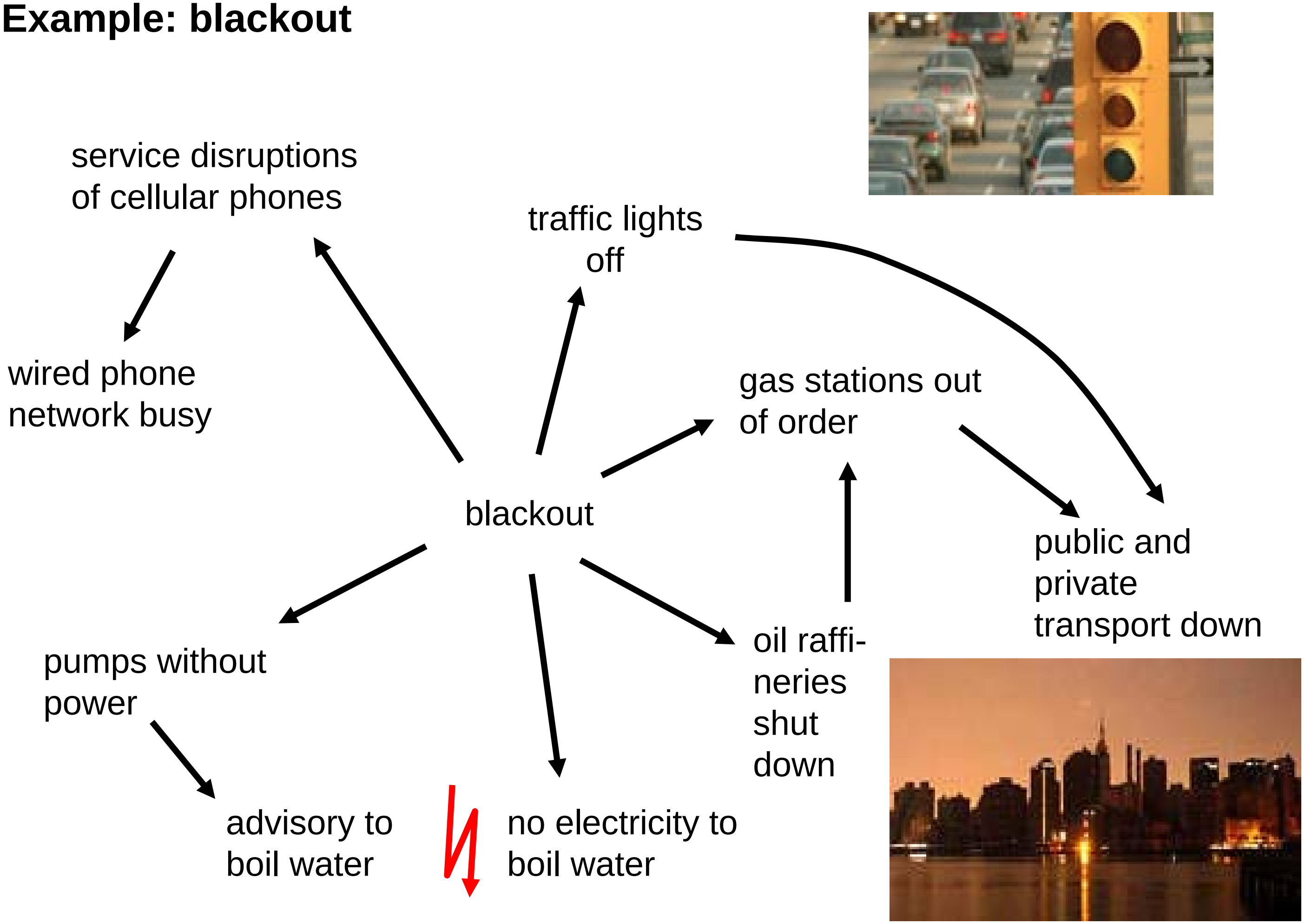
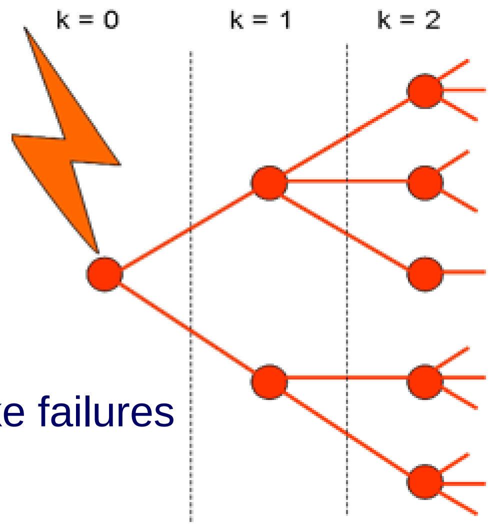
Identification of interaction networks

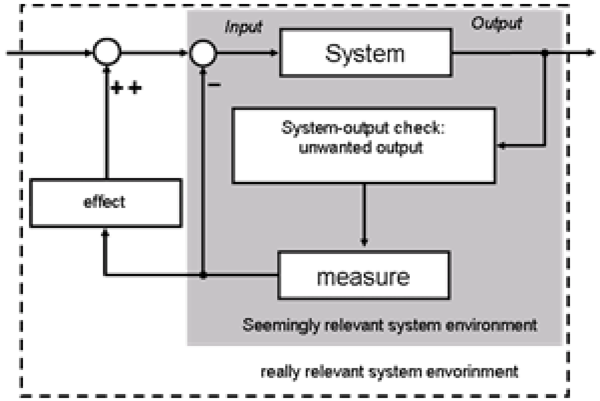
Example: blackout



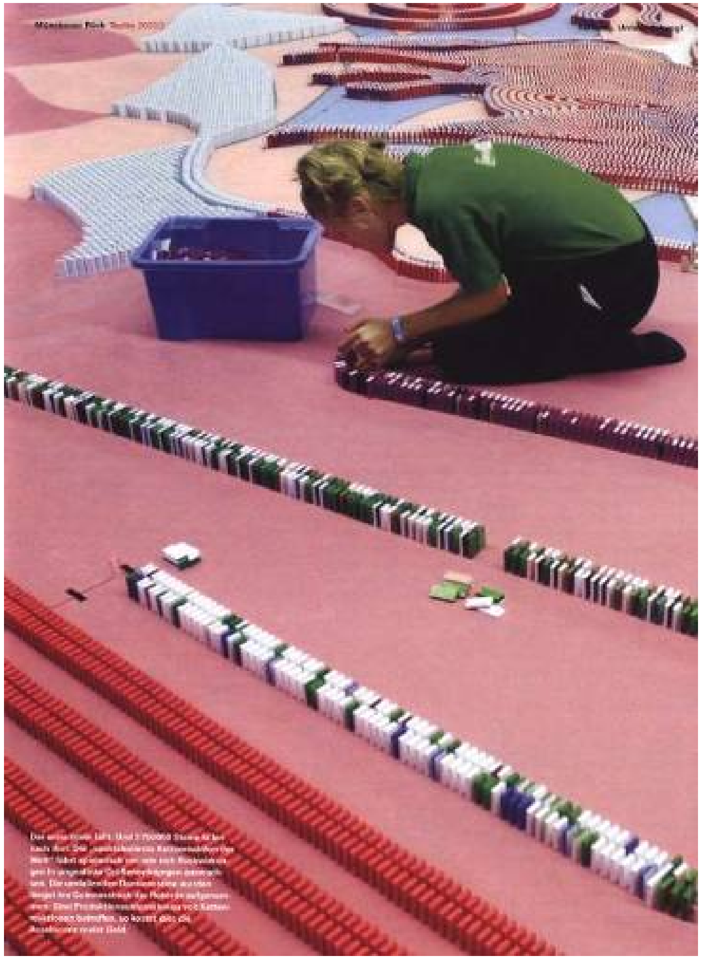
Disaster dynamics: What are we interested in.



Cascade-like failures



Vicious cycles



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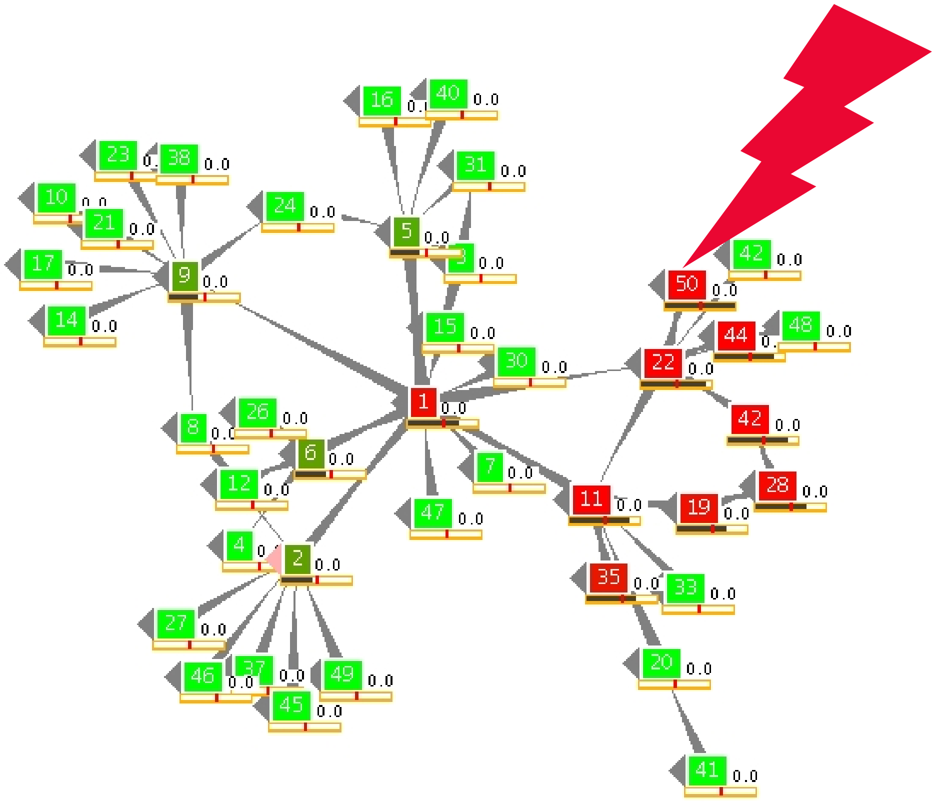
Modeling and simulation of disaster spreading



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

Simulation of topology dependent spreading:

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

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Node model

Node dynamics:

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

x_i - state of the node

$x_i = 0$ state: usual situation

$x_i > \theta_i$ state: node is destroyed

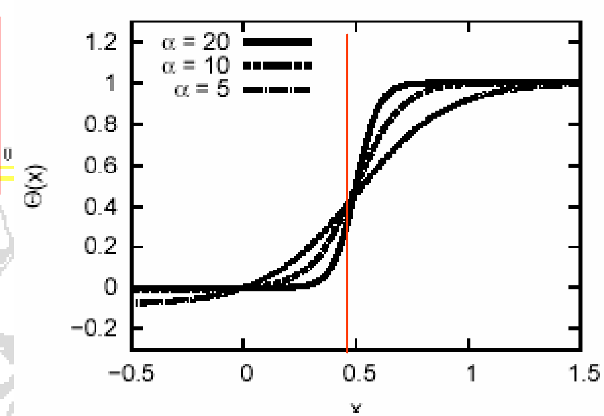
θ_i - node threshold $1/\tau$ - robustness (rate)

t_{ij} - time delay $\xi_i(t)$ - internal noise

M_{ij} - link strength O_i - node out-degree

a, b, α, β - fit parameters

Threshold function:



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

Node degree:

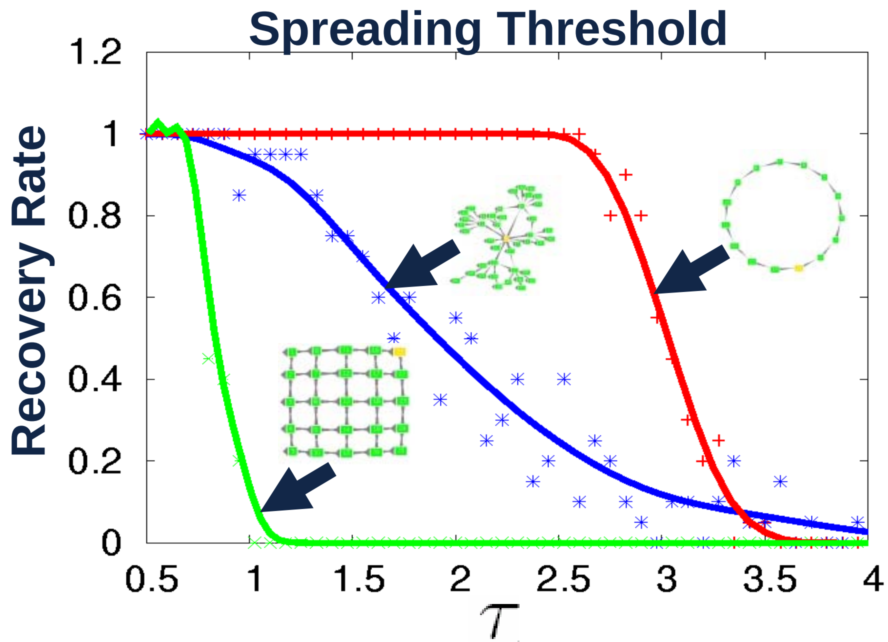
$$f(O_i) = \frac{aO_i}{1+bO_i}$$

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

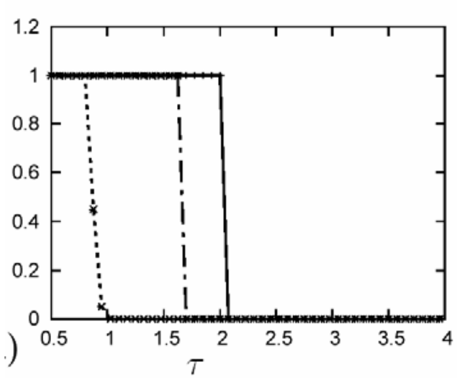
Phase transition in disaster spreading

Node robustness vs. failure propagation:

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



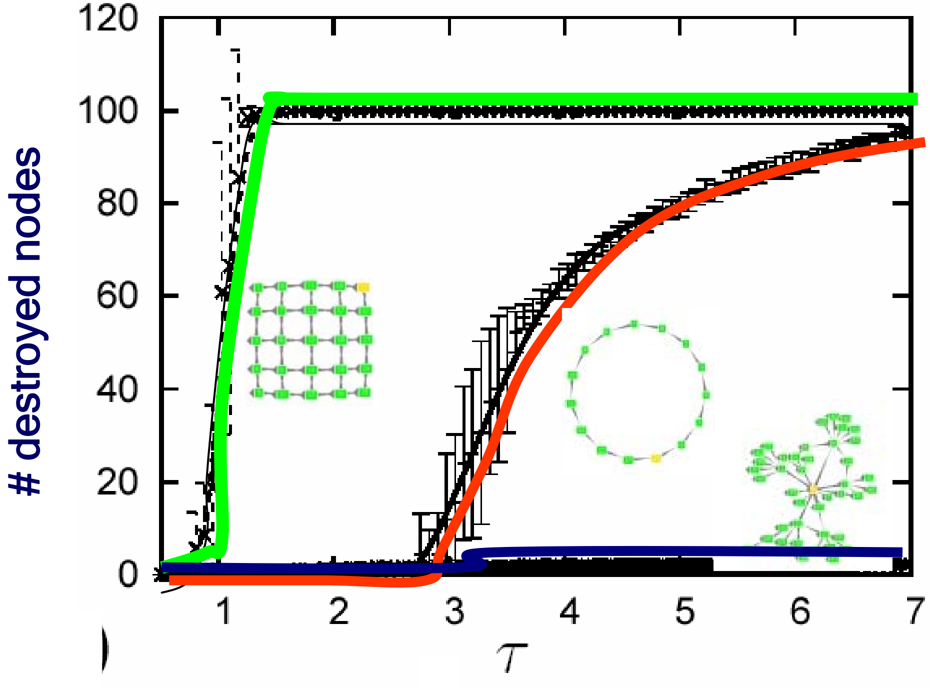
homogeneous networks:



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



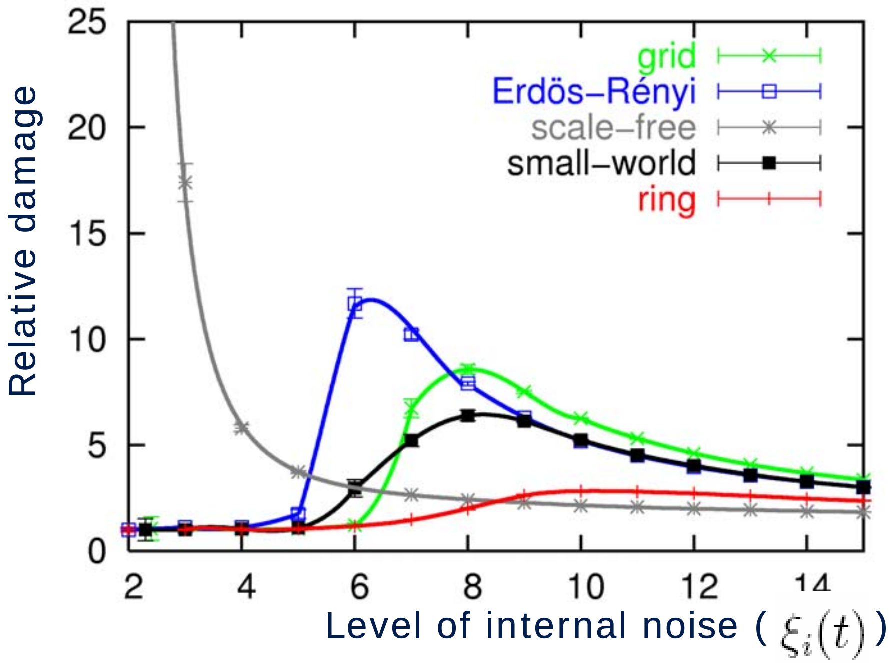
We found a topology dependent „velocity“ of failure propagation. Spreading in scale-free networks is slow.

Failures triggered by internal fluctuations

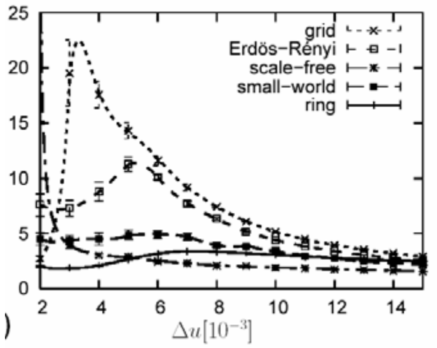
Coinciding, distributed, random failures.

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

Damage compared to an unconnected "network":



homogeneous networks:



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

Modelling the recovery

1. **Mobilization of external resources:**

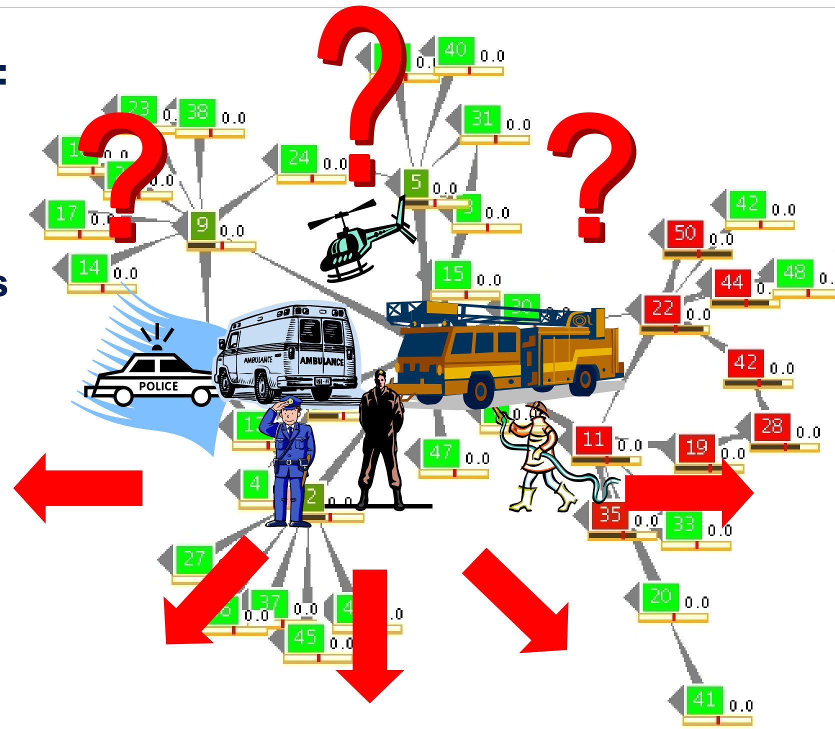
$$r(t) = a_1 t^{b_1} e^{-c_1 t}$$

2. **Formulation of recovery strategies**

- Network topology
- Level of damage

3. **Application of resources** in nodes

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



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

τ_{start} - initial intensity of recovery process

α_2 β_2 - fit parameters

Parameters

Network topology

t_D time delay in response

R disposition of resources

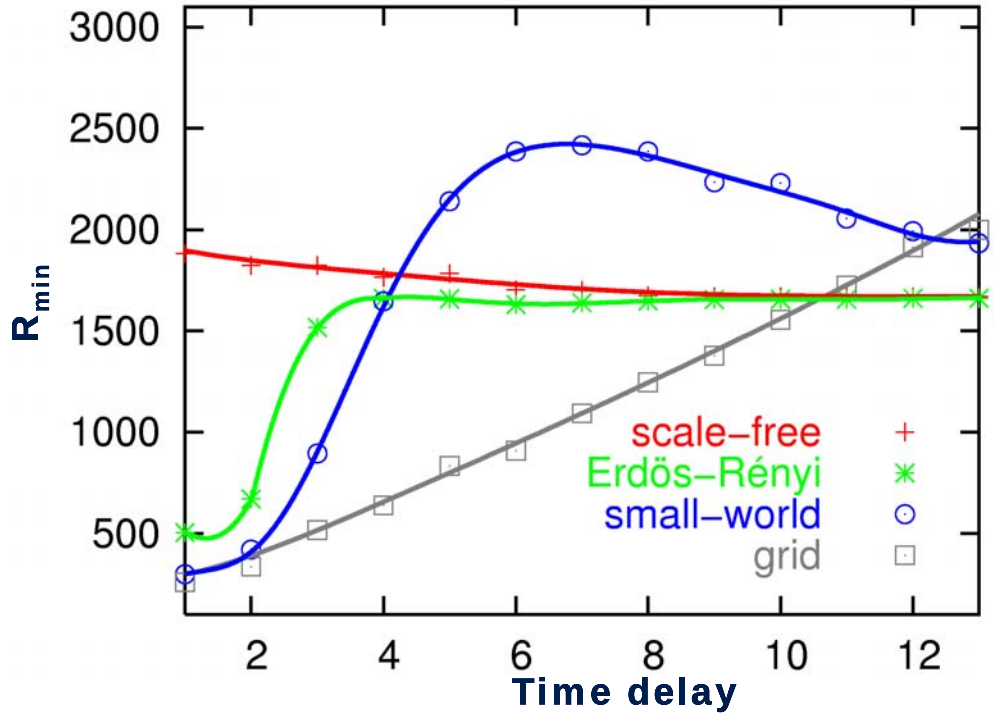
Recovery of networks

Given: amount of resources, mobilized with certain delay.

Worst – case scenario

Is the network able to recover?

Recovery strategy: uniform protection of all damaged nodes $(x_i > 0)$



Recovery (in reasonable time) is not always possible.

Recovery of networks

Formulation of recovery strategies:

Network topology

Level of damage

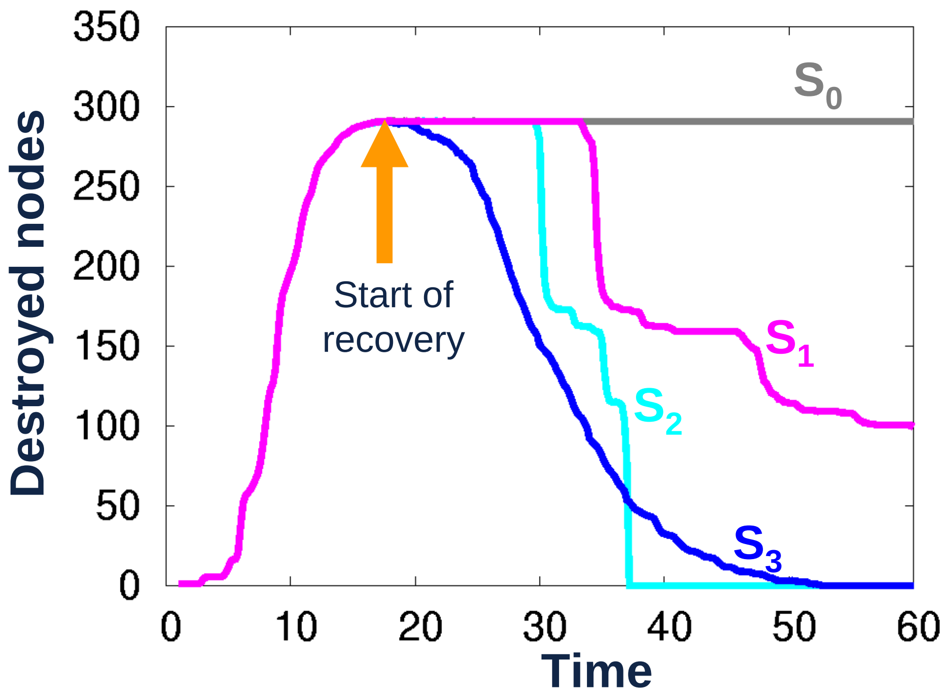
S_0 – no recovery

S_1 – uniform deployment

S_2 – priority1: destroyed nodes
priority2: damaged nodes

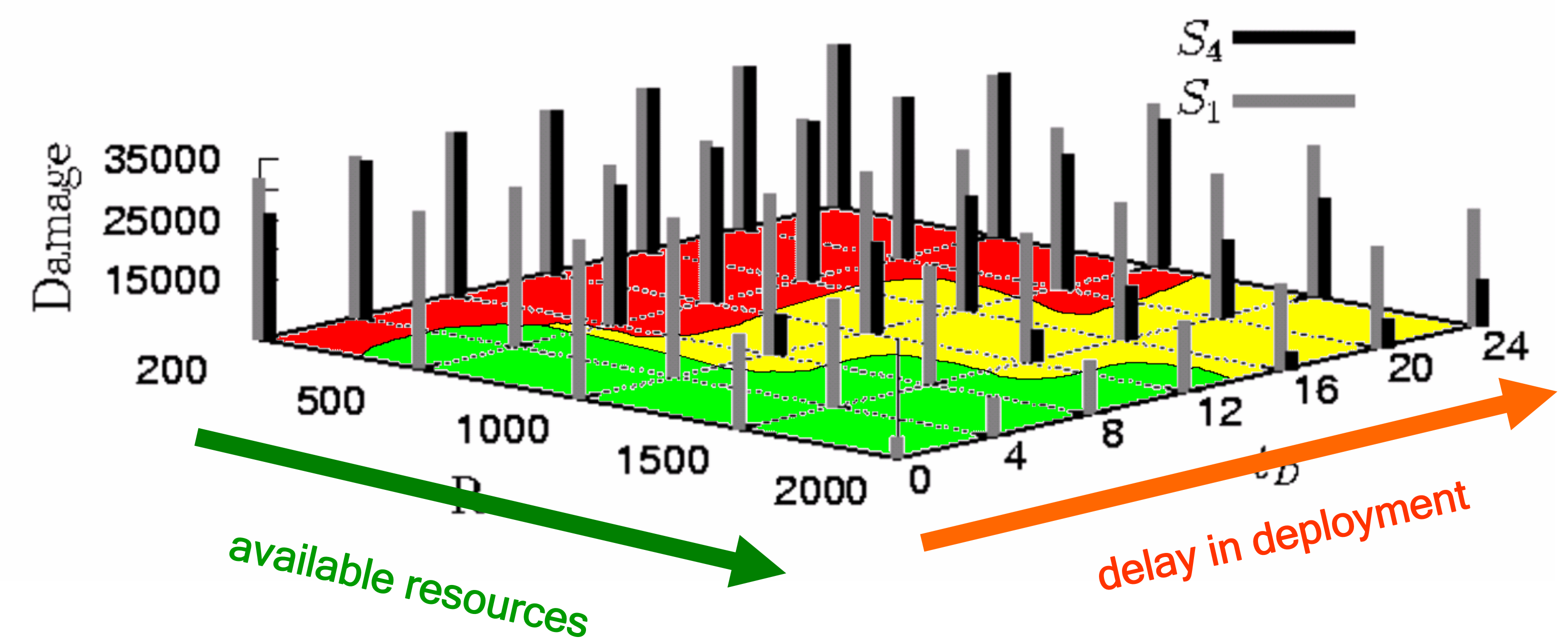
S_3 – out-degree based deployment

Application of resources on a scale-free network



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.**

Recovery of networks

Average behaviour of strategies

- Strategies based on the network structure are important for scale-free structures.
- Strategies based on damage information are more appropriate for regular networks.
- The optimal strategy is time dependent!
  (short t_D => damage)
  (large t_D => network structure)

Conclusions

- We proposed a generic model for the spreading of failures in dynamic networked systems.
- The model facilitates an assessment of the stability and robustness of interaction networks and infrastructures.
- It assists the evaluation of disaster response management strategies.

Topology aspects:

- Pase transition in dynamic behaviour
- Different spreading conditions
- Robustness under distributed random failures

There is no unique robust and reliable architecture !
e.g.: redundancy, hubs, feedback loops

Recovery aspects:

- Effectivness of damage oriented or connectivity dependent response strategies
- Minimum of resources to stop an evolving disaster
- Optimization of disaster response

There is no unique optimal response startegy!
e.g.: delay, available forces, topology

Thank you for your attention.

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Interaction networks

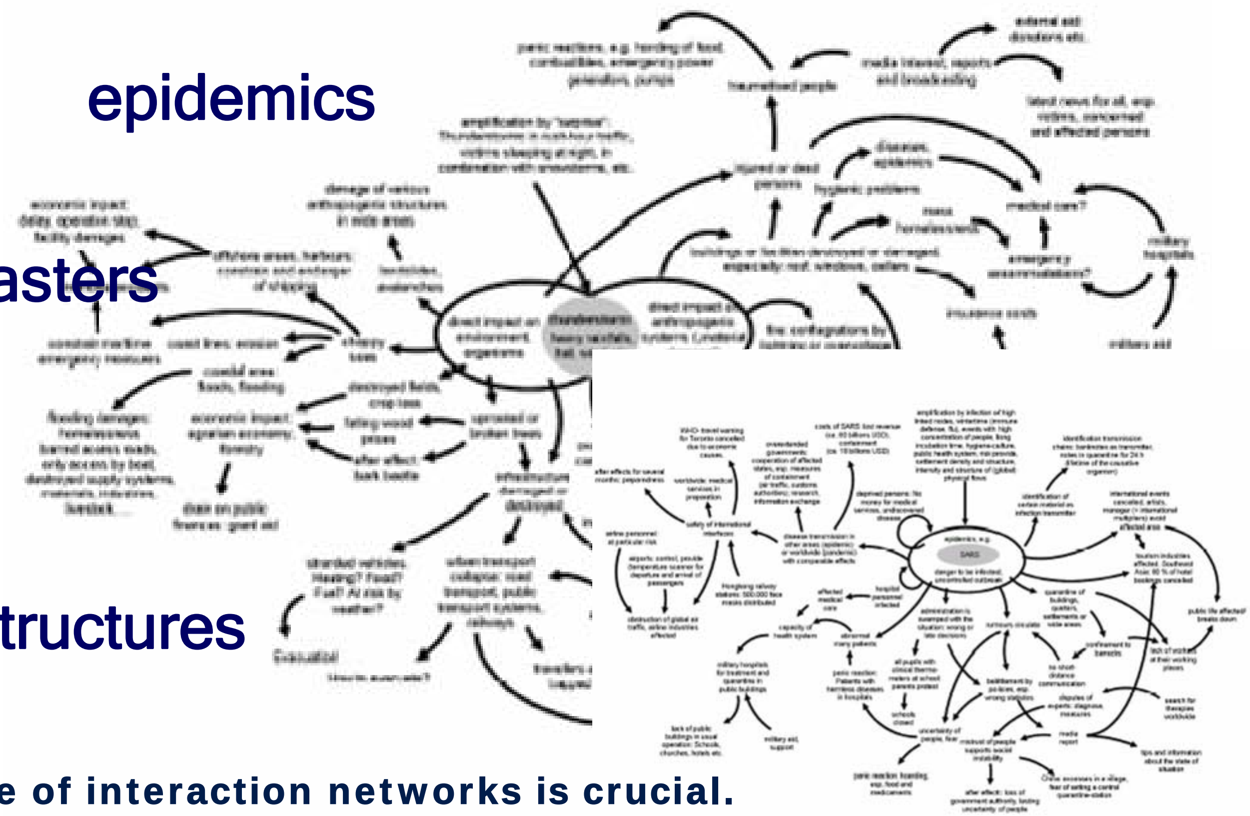
blackouts

epidemics

natural disasters

- Sanstorms
- Hurricanes
- Floods
- earthquakes

infrastructures

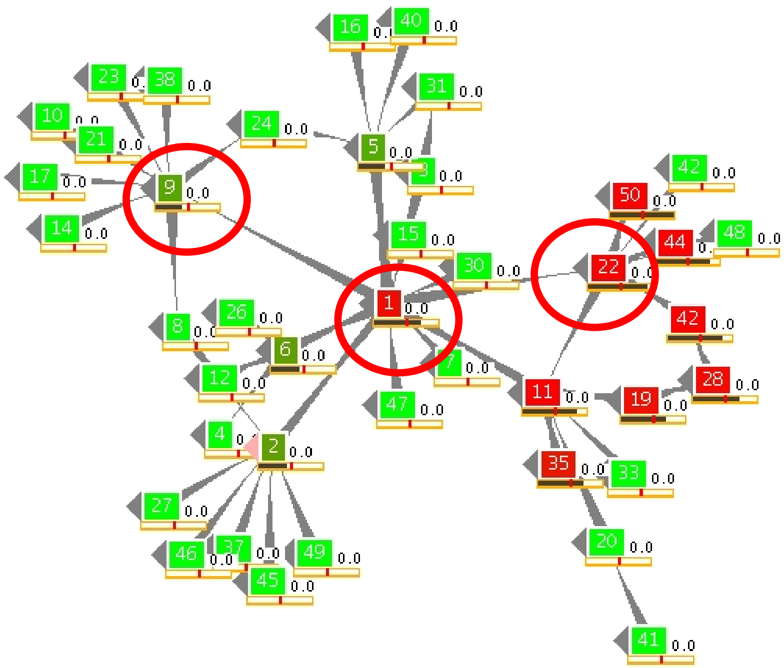


The structure of interaction networks is crucial. Feedback loops are particularly important.

D. Helbing, H. Ammoser, C. Kühnert: Disasters as extreme events and the importance of networks for disaster response management ,Springer (Berlin 2006) (in print)

Importance of hubs in networks ?

- Inhomogeneities can have considerable damping effects on spreading failures
- Hubs reduce the robustness against (small) disturbances and attacks.
- Scale-free networks are among the safest structures in case of large and distributed failures.



Hubs play a quite ambigiuous role !