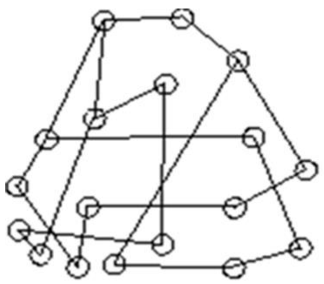
Network Science and Applications

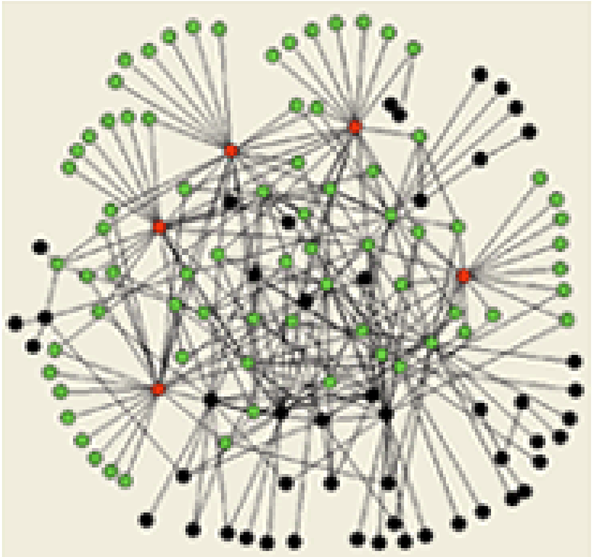
Epidemics, Parkinson, Fake News, Traffic, Climate, Physiology, Cascading failures etc.

Shlomo Havlin

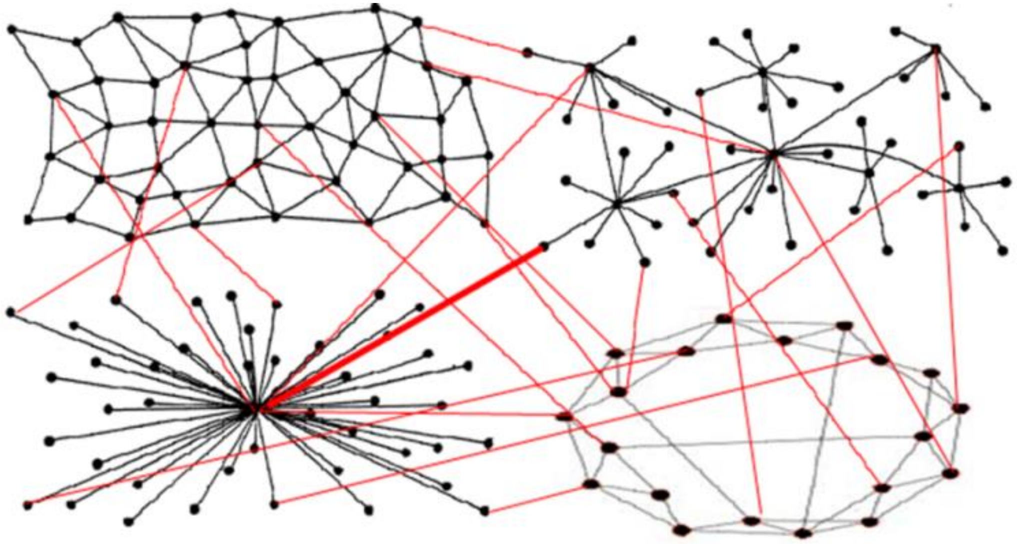
<2000
Poissonian



2000
Scale free – real networks $p(k) \sim k^{-\lambda}$



2010
Interacting networks: multilayer, multiplex …

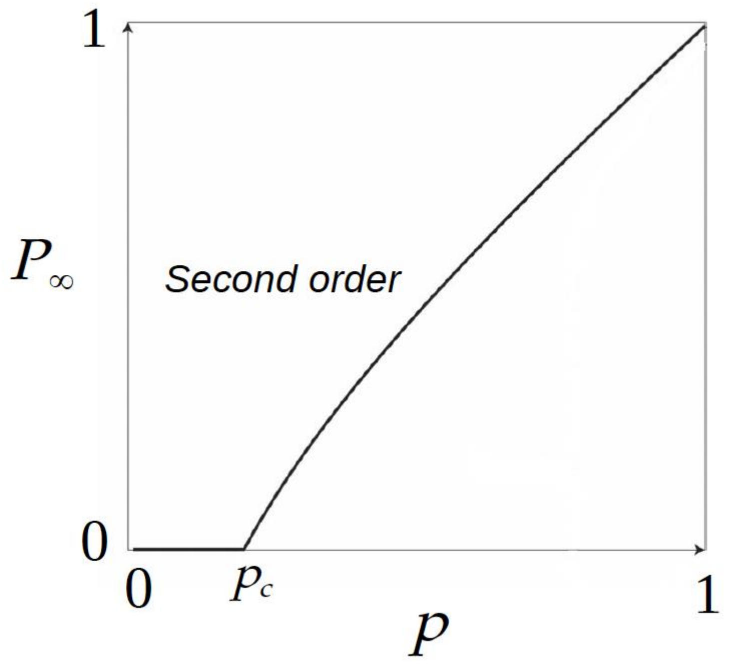


Electric grid,
Communication
Transportation
Services
Two types of links-novel phenomena

Covid-19: Bnaya Gross et al *EPL* (2020); Cohen et al PRL (2003); Yangyang Liu et al, National Science Review (2020);
Traffic: Daqing Li et al, PNAS 112, 669 (2015); G. Zeng et al, PNAS 116, 23 (2019); Shida et al Sci. Rep. 1, 10 (2020);
Parkinson: E. Asher, R. Bartsch et al, Nature Communications Biology, 4, 1 (2021);
Network Physiology: Bashan, Bartsch, Ivanov Nature Communications,, 3 702 (2012); Climate, Brain : Jurgen Kurths Lecture today
Interdependent Networks: Buldyrev et al Nature **464, 1025** (2010); Gao et al Nat. Phys. 8, 40 (2012), Danziger et al Nat. Phys. (2020)
Interdependent Superconducting Networks: I. Bonamassa et al, arXiv:2207.01669 (2022)

Percolation of Single networks

- Percolation theory
- Remove 1-p fraction of nodes
- Functioning – existence of giant component
- Network resilience



- Second order phase transition
- Critical behaviour
- Universality classes

<u>Scaling relations</u>

$n_s \sim s^{-\tau}$

$d\nu = 2\beta + \gamma$

$\delta - 1 = \gamma/\beta$

<u>Critical exponents</u>

$P_\infty \sim (p - p_c)^\beta$

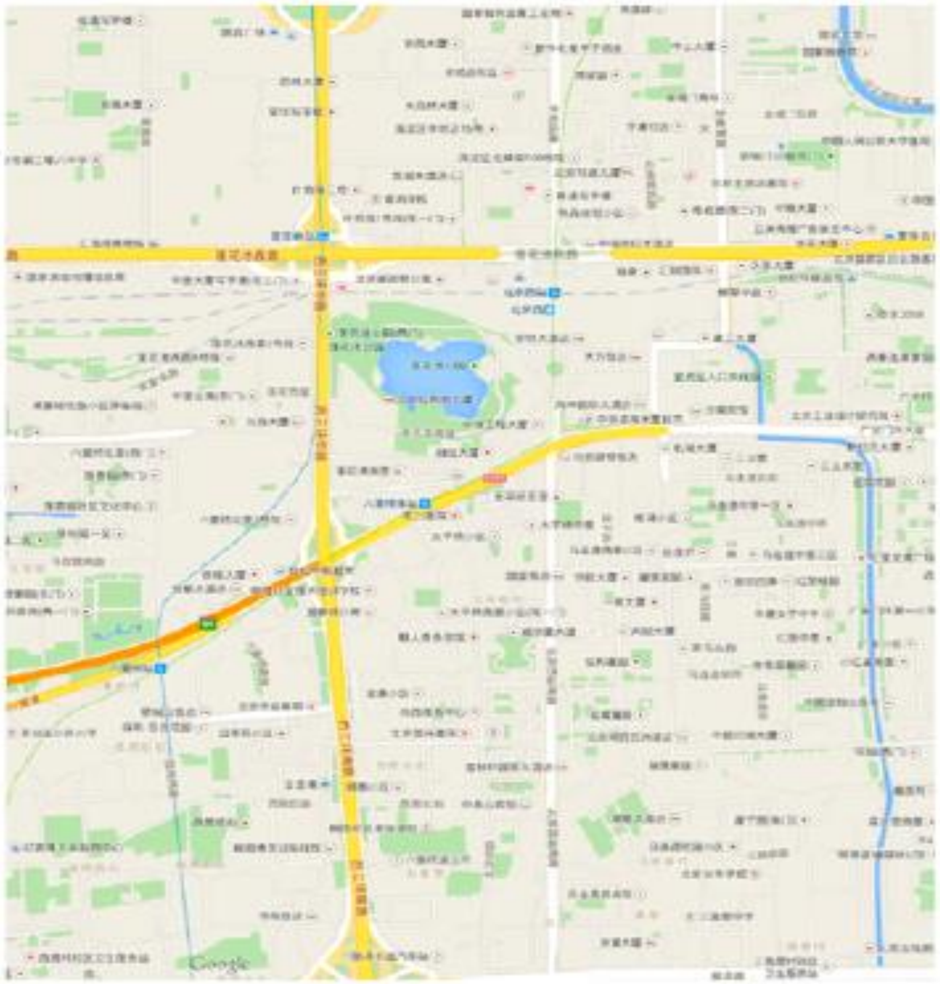
$\xi \sim |p - p_c|^{-\nu}$

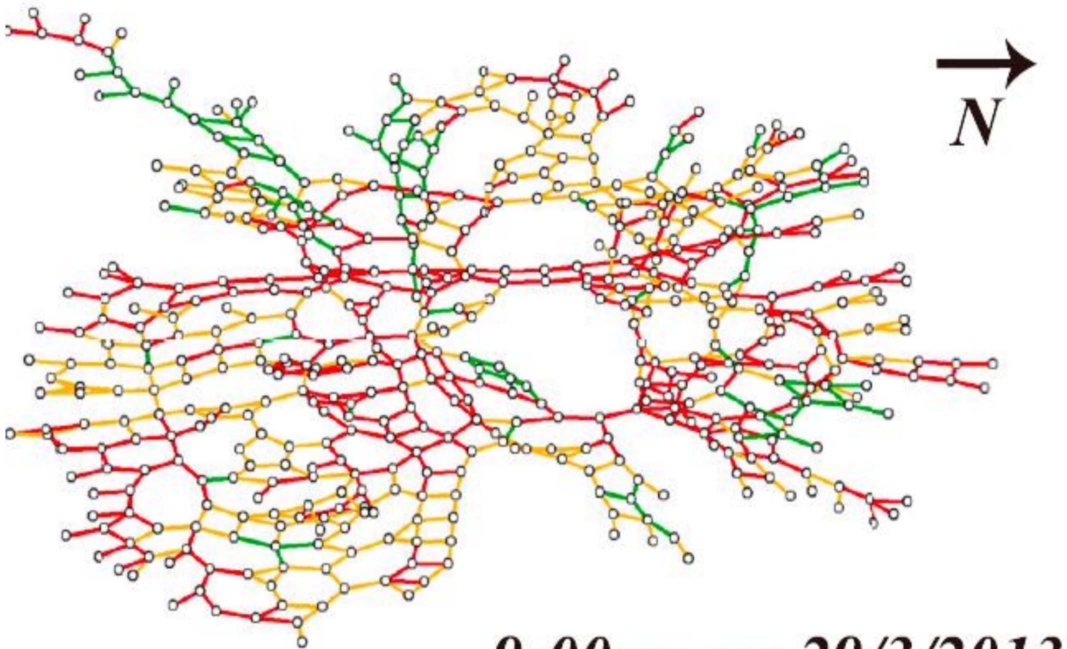
$\chi \sim |p - p_c|^{-\gamma}$

Traffic and Network Theory

1. Mapping traffic in Beijing as a dynamic network
2. Percolation theory identify bottlenecks

A



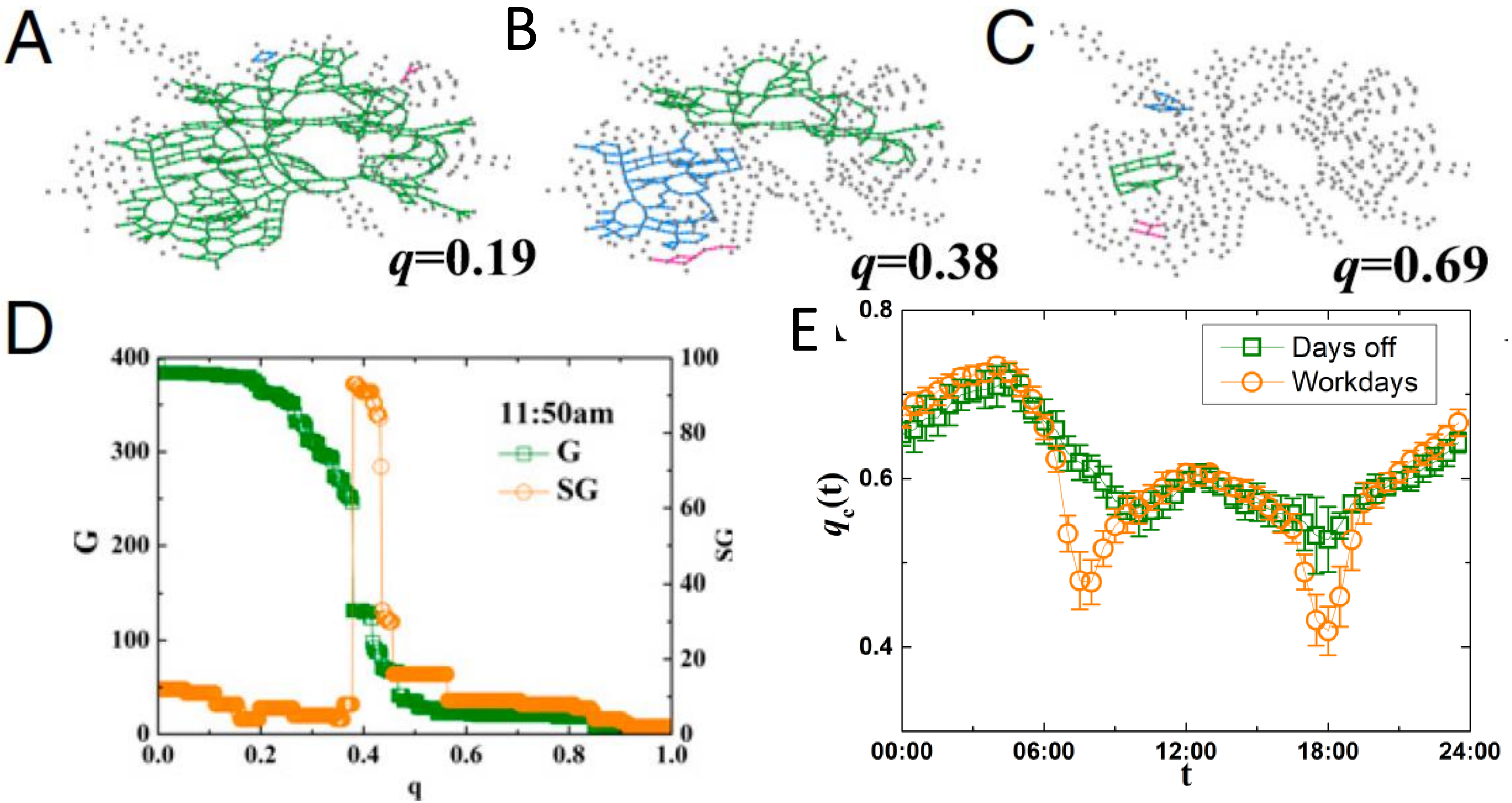


9:00am on 29/3/2013

Daqing Li et al, PNAS 112, 669 (2015)

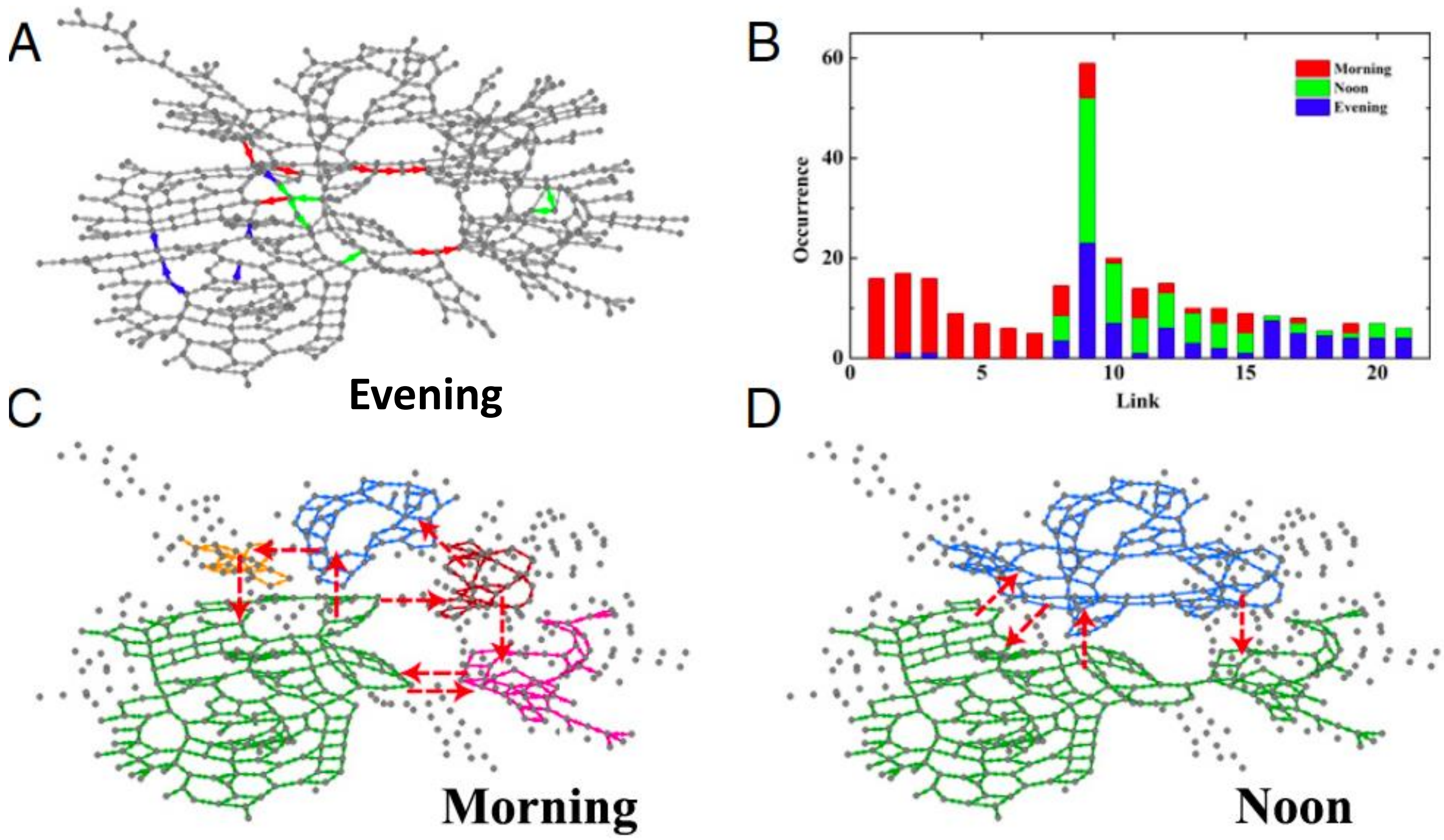
NETWORK, PERCOLATION AND TRAFFIC

q=1-p



Daqing Li et al PNAS, 112, 669 (2015)

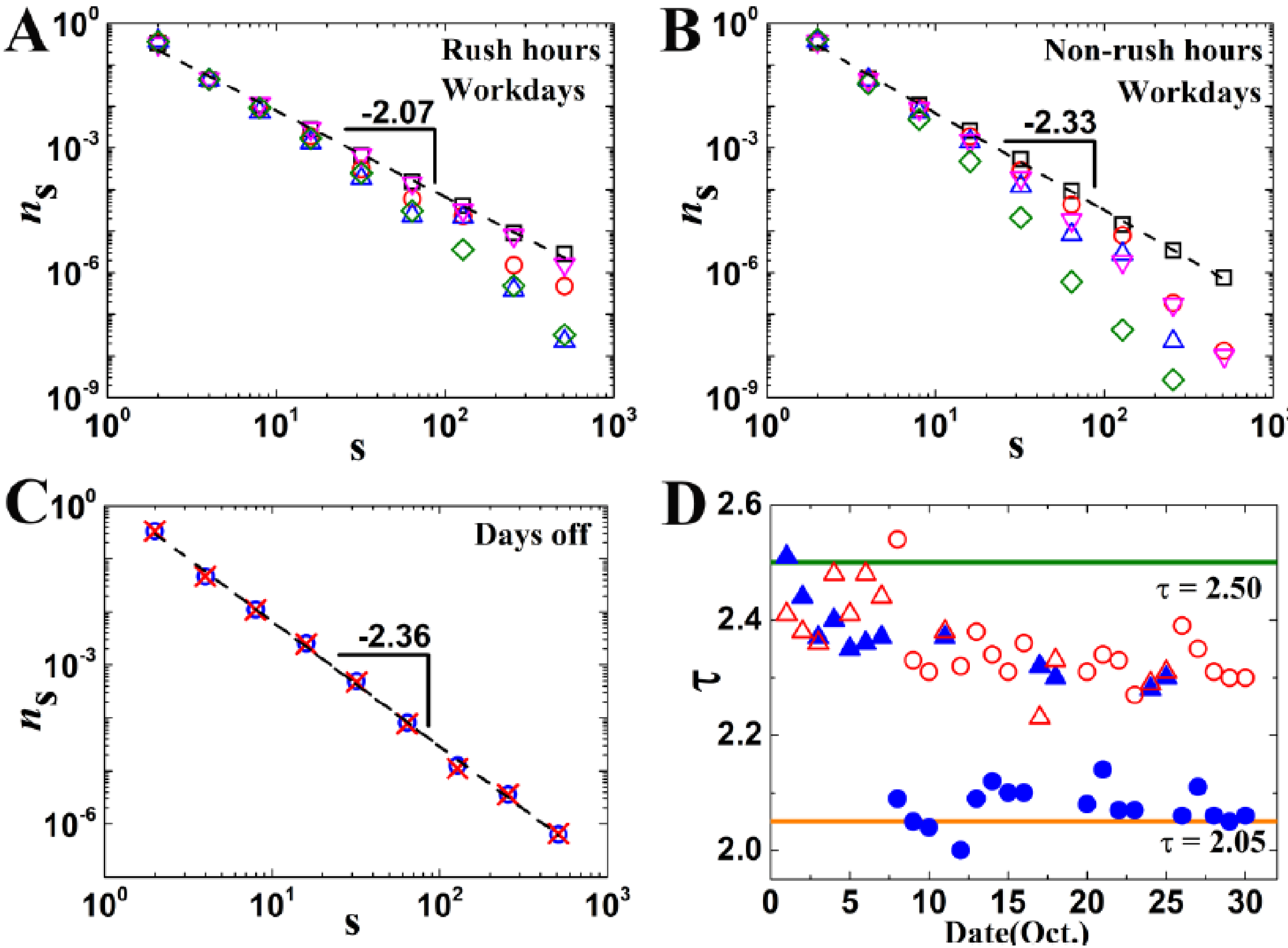
DIFFERENT HOURS DIFFERENT BOTTLENECKS



Daqing Li et al PNAS, 112, 669 (2015)

Percolation critical exponents

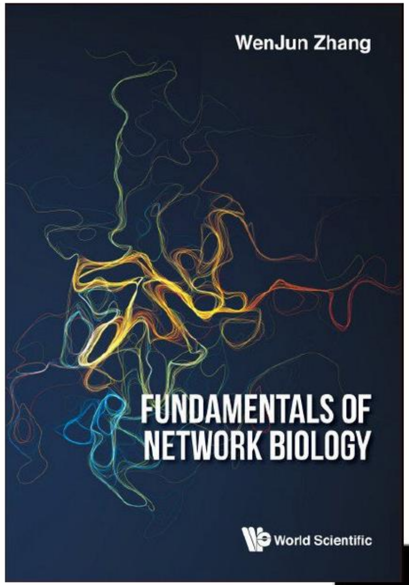
2015

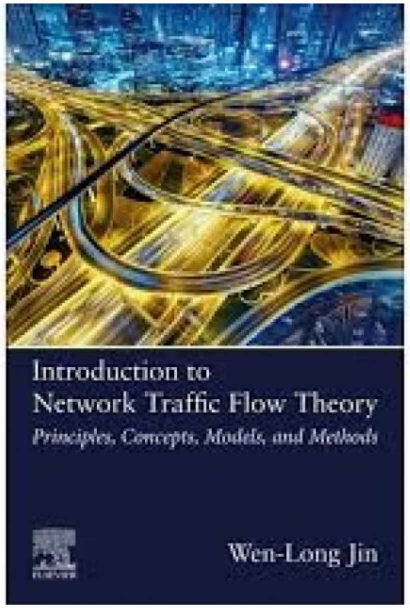


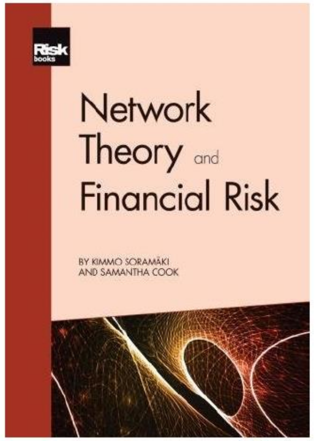
G. Zeng et al, PNAS 116, 23 (2019)

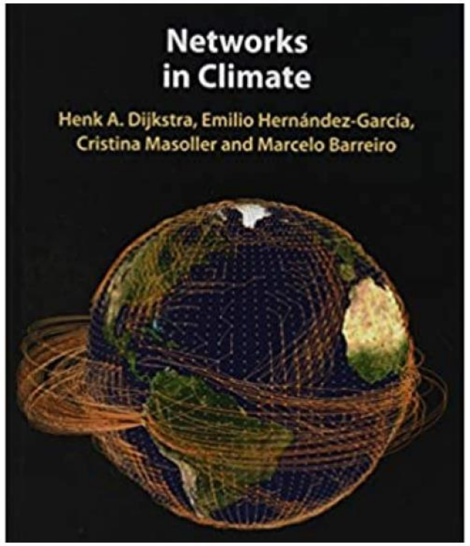
Multidisciplinary field

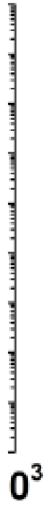
- Climate
- Earthquakes
- Traffic
- Biology
- Brain
- Finance
- Infrastructures

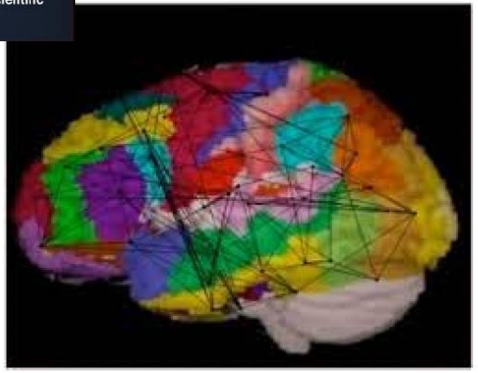


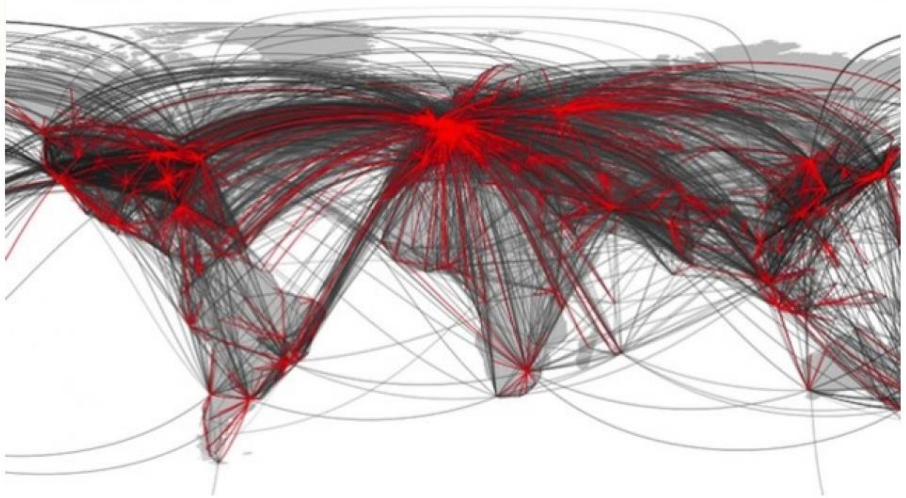












New concepts emerge!

From network theory back to physics: interdependent physical networks

Single networks

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- Remove 1-p fraction of nodes
- Functioning – existence of giant component
- Network resilience

- Second order phase transition
- Critical behaviour
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<u>Scaling relations</u>

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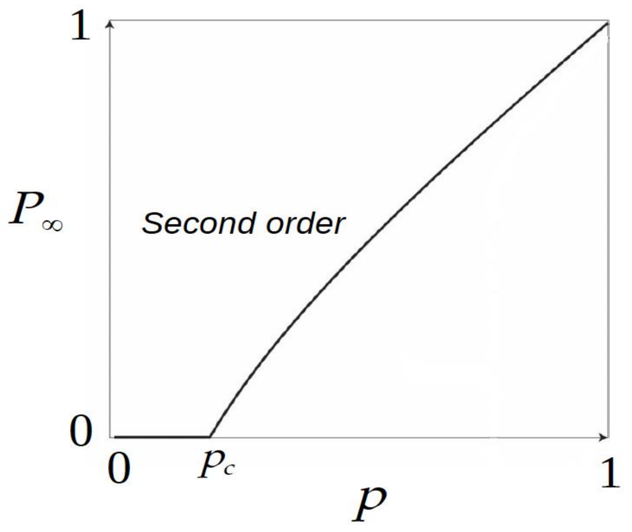


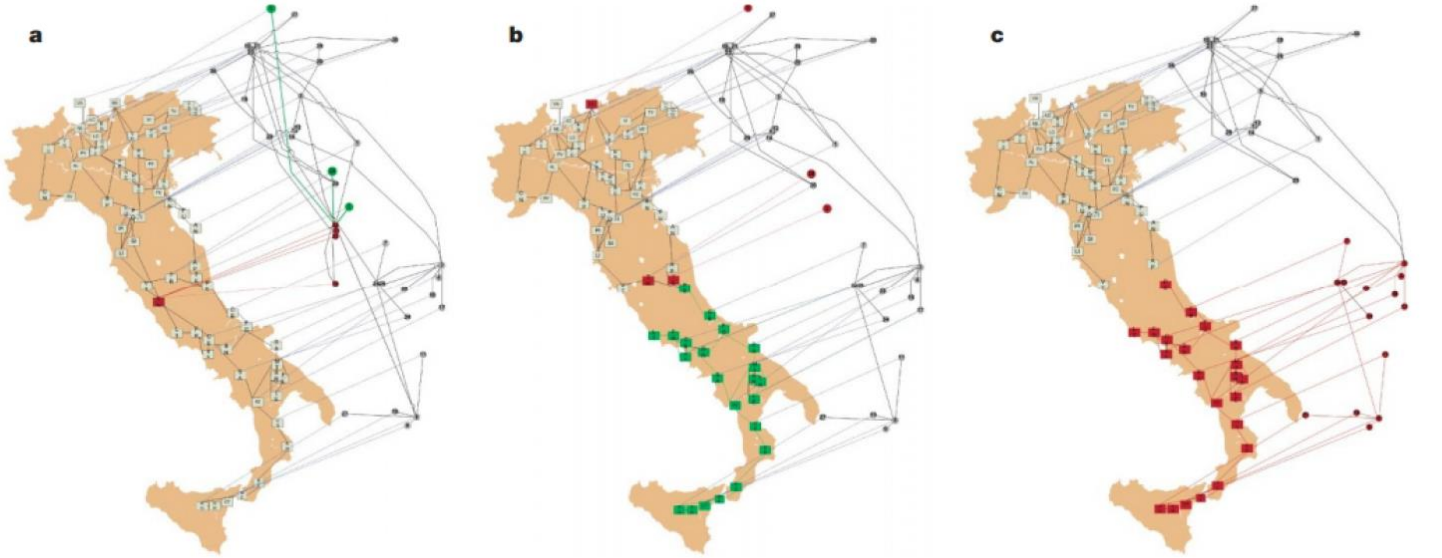
Blackout in Italy, September 2003

3:21 am: a tree too close to a power station recives the discharge of a line

Blackout in Italy, September 2003

<u>3:23 am:</u> the power outage extends to the whole country

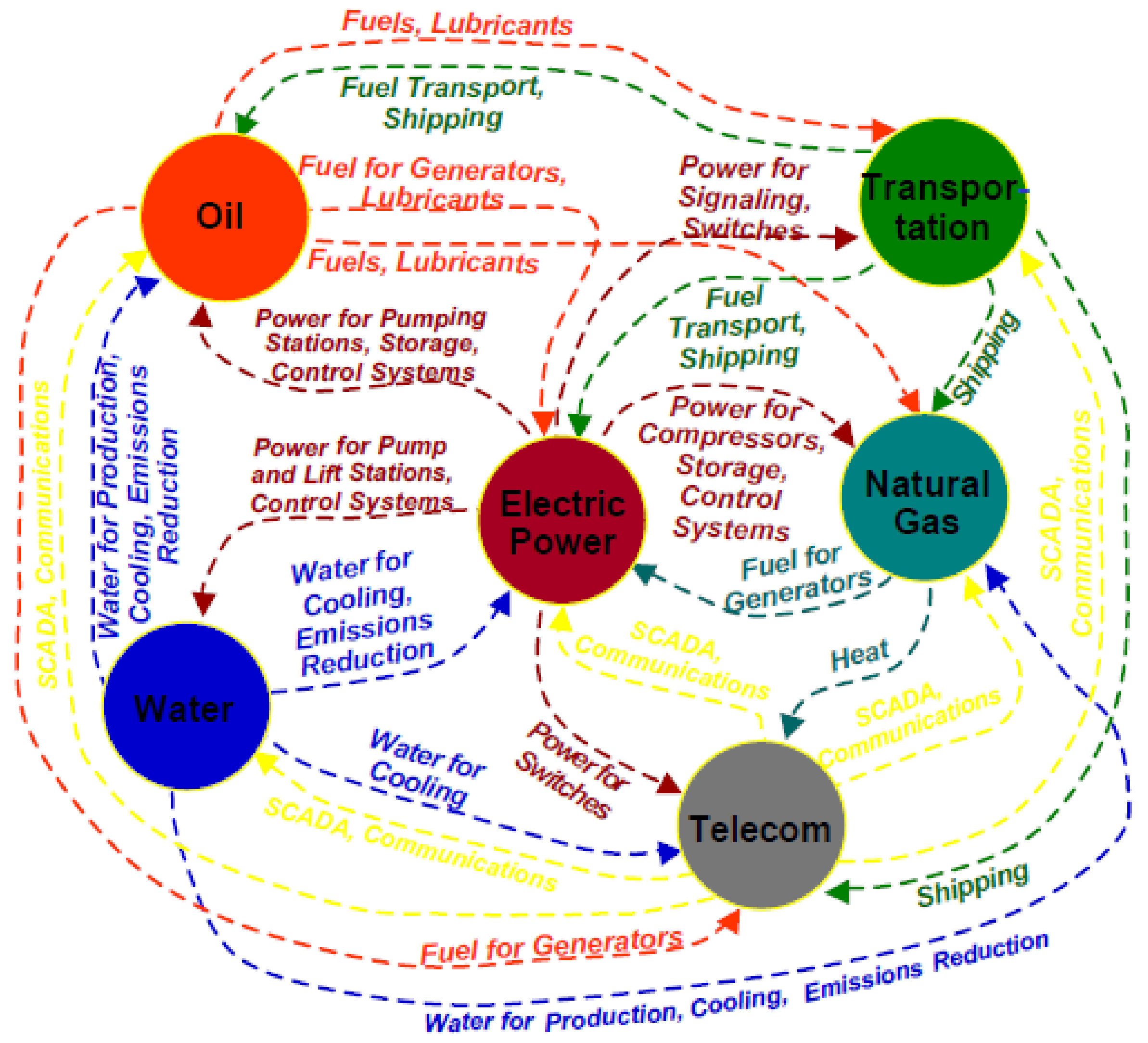
Interdependent networks



- Two networks: **Communication** network and **power-grid** network
- Two types of links: **Connectivity** within each network and **dependency** between the networks
- **<u>Dependency:</u>** If a node in one network fails, another node in the other network will fail as well

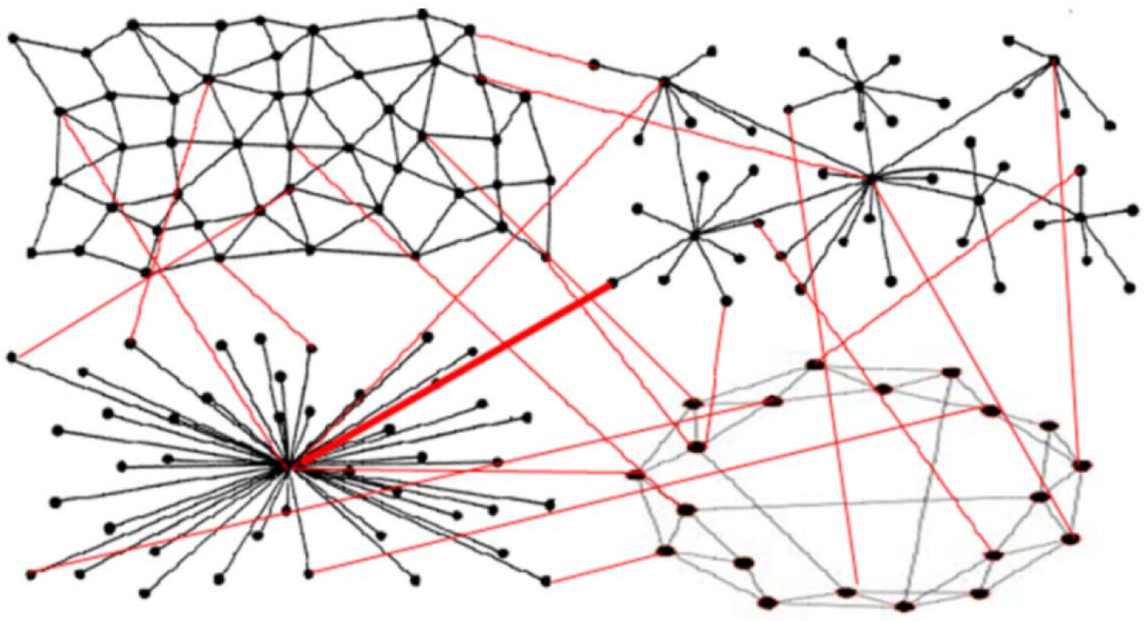
Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. Nature, 464(7291), 1025-1028.

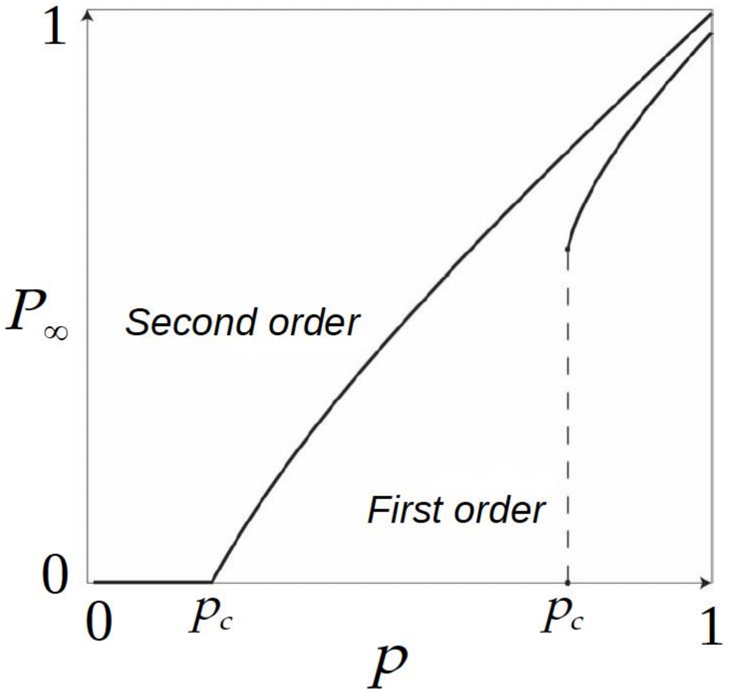
How interdependent are infrastructures?



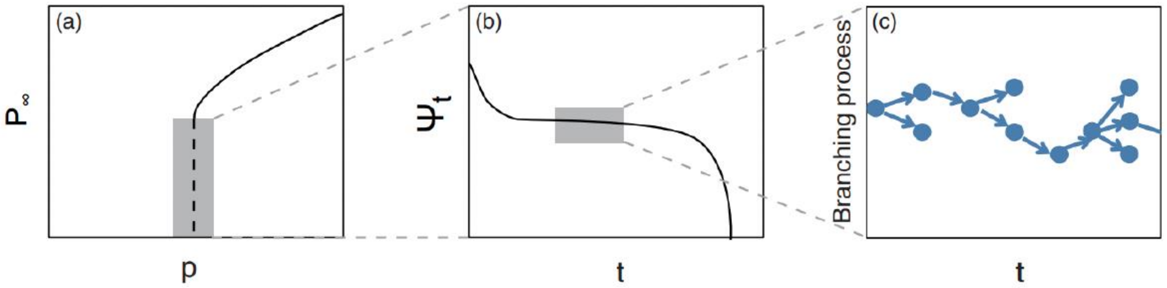
Peerenboom, Fisher, and Whitfield, 2001

Interdependent networks





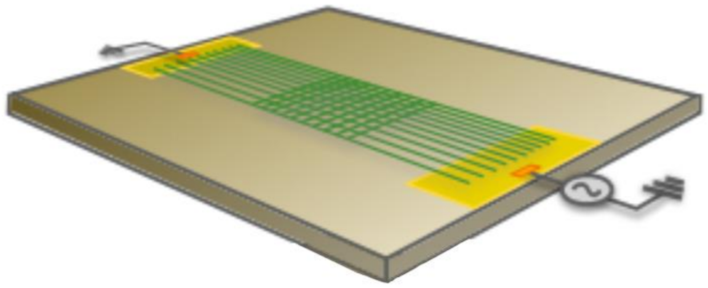
- Cascading failures
- Local failure leads to total collapse

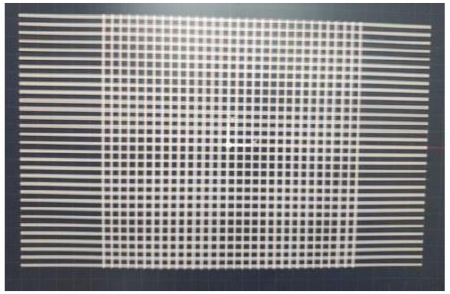


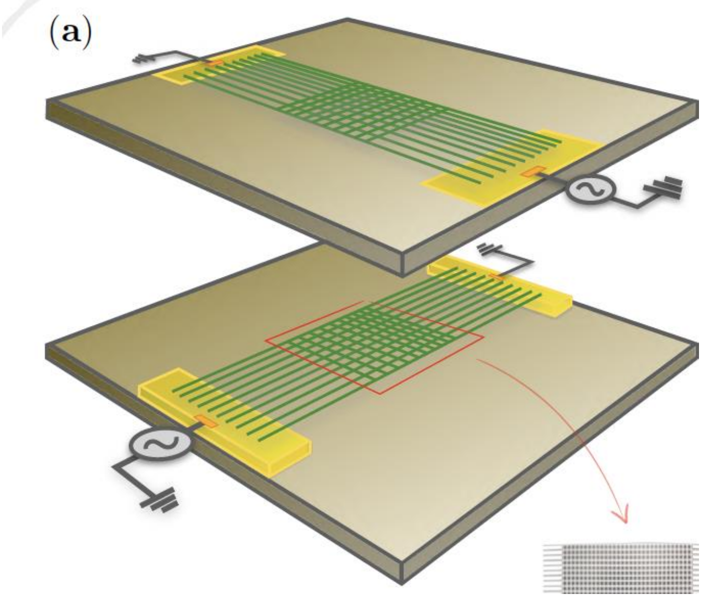
Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. Nature, 464(7291), 1025-1028.

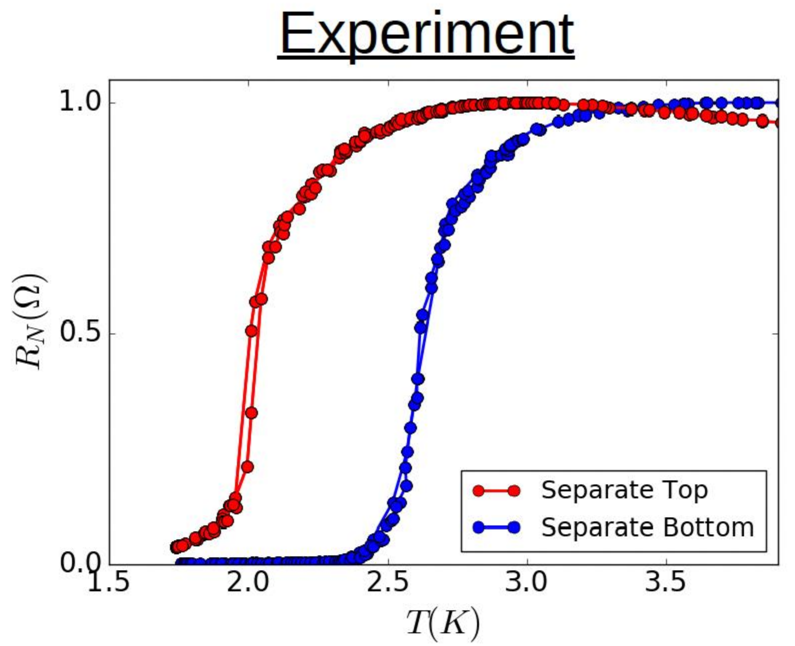
Can we apply the concept of interdependent networks in physical systems?

Single Superconducting networks

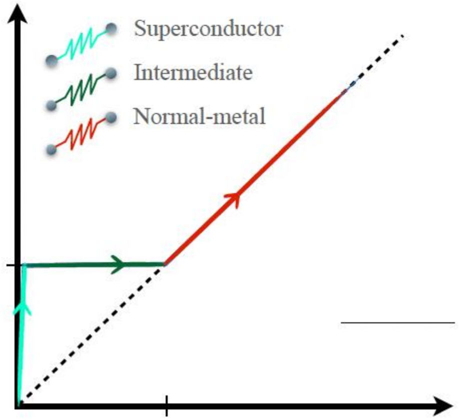






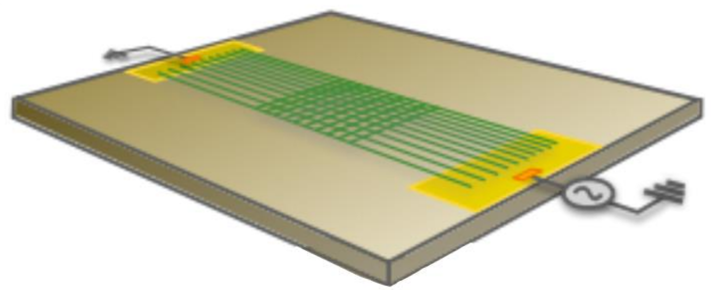


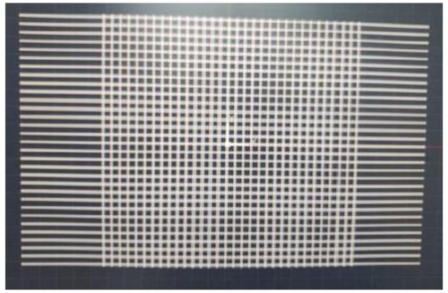
Josephson junction characteristics

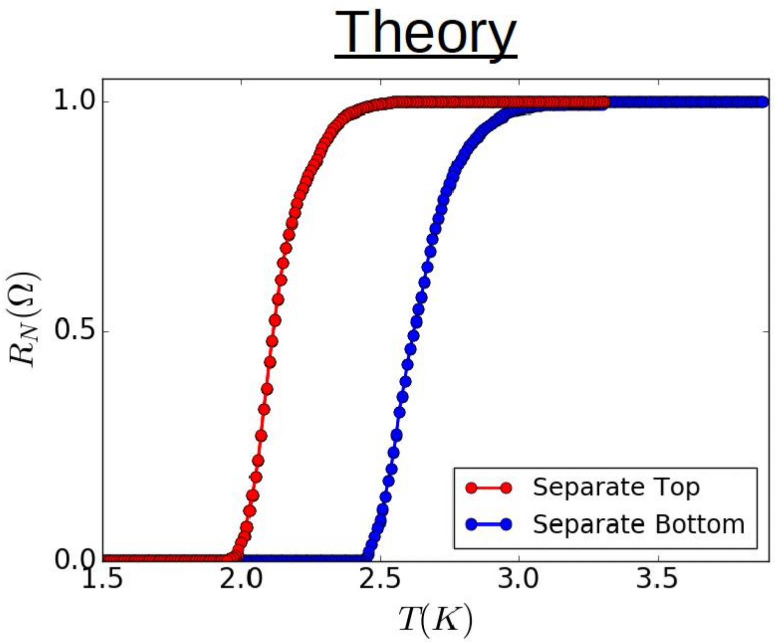


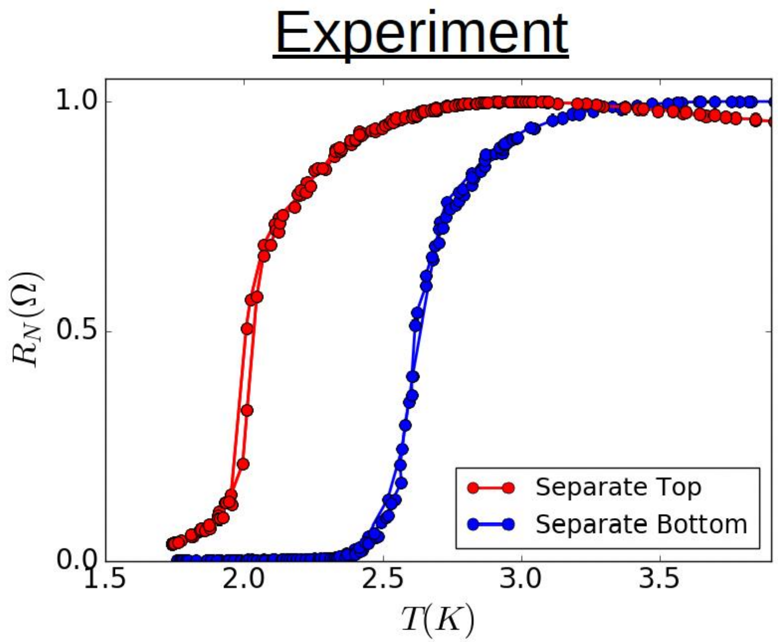
- Second order phase transition
- Superconductor-normal transition

Single Superconducting networks

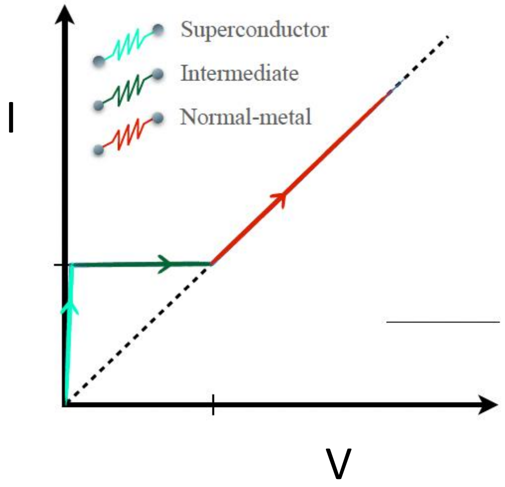








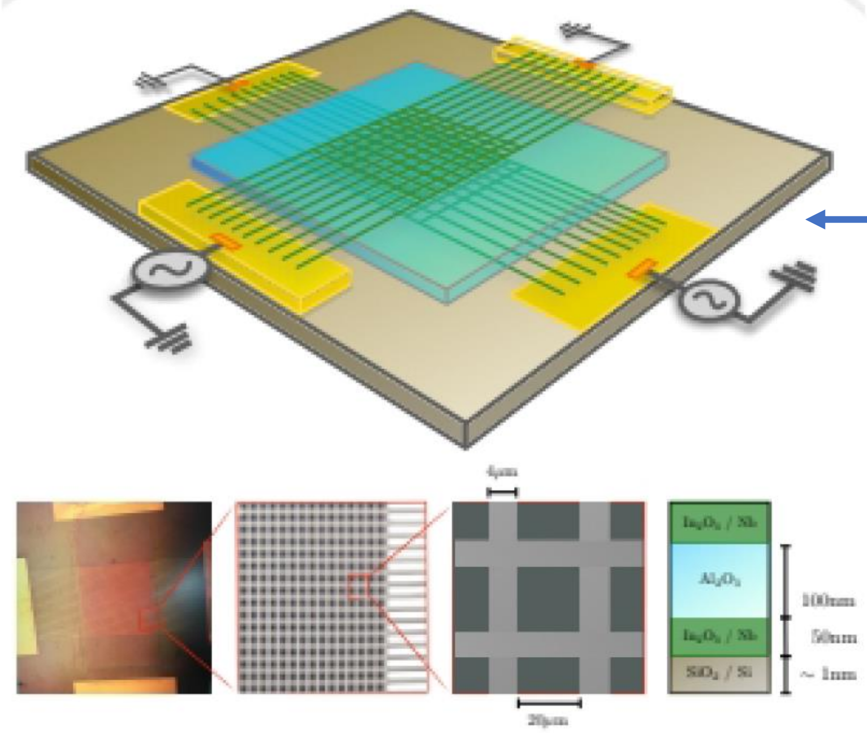
Josephson junction characteristics

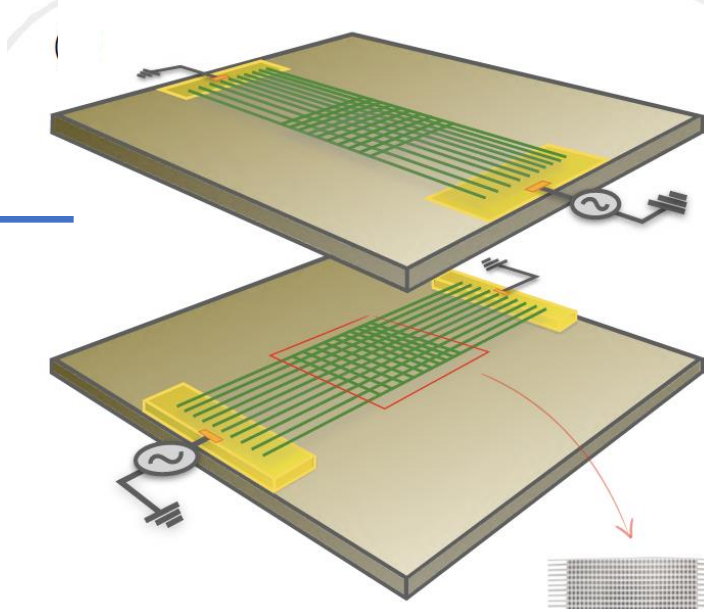


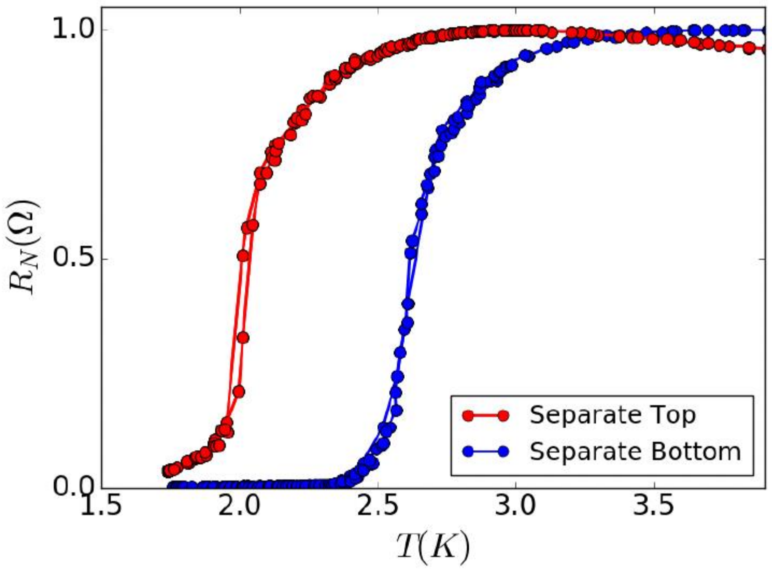
- Second order phase transition
- Superconductor-normal transition

Kirchhoff equations: $G \cdot W = I_{inj}$

Interdependent superconducting networks

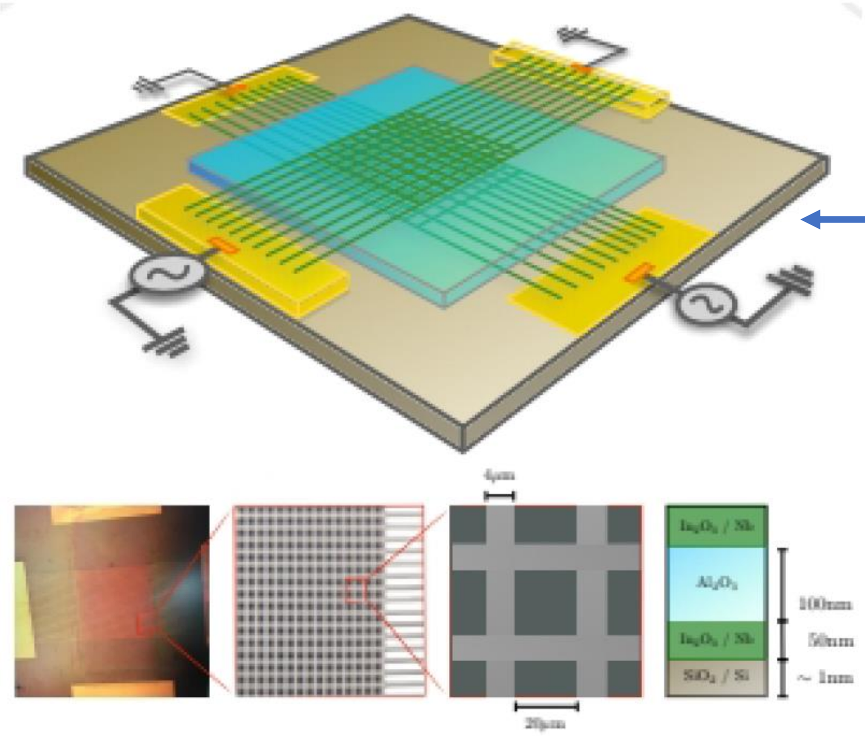


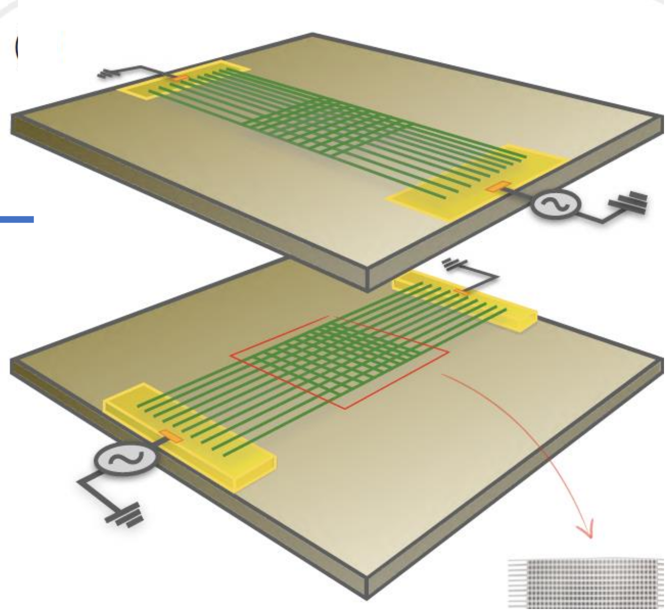


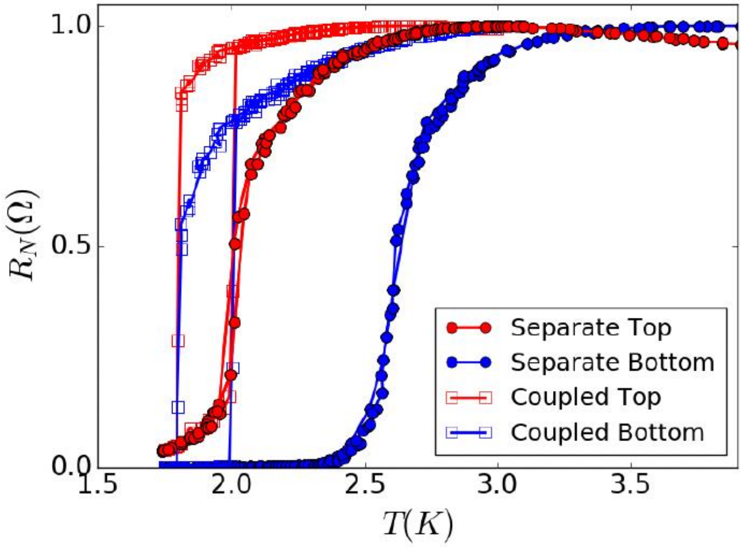


In between thermal conductance—electric insulator

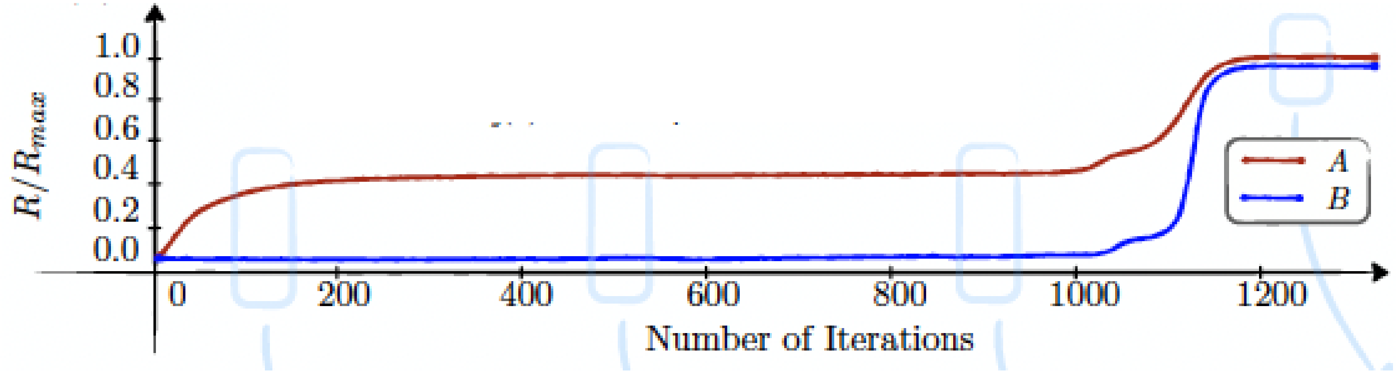
Interdependent superconducting networks



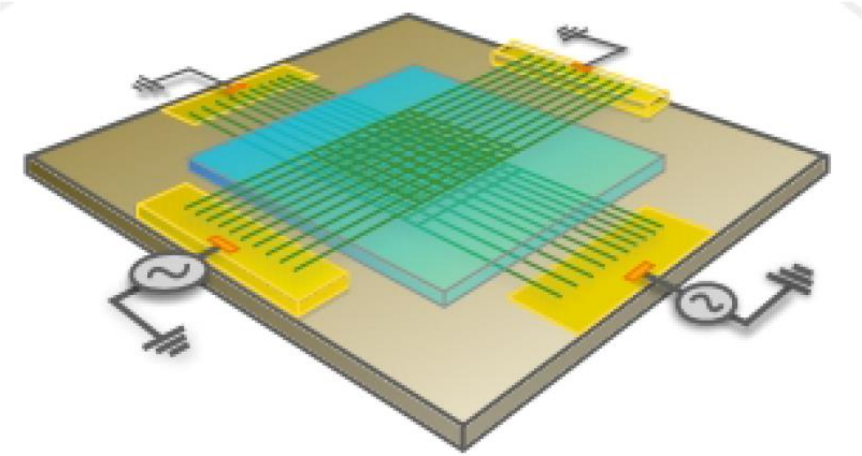


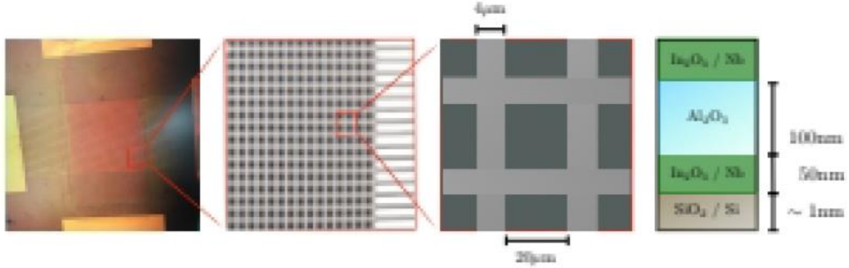


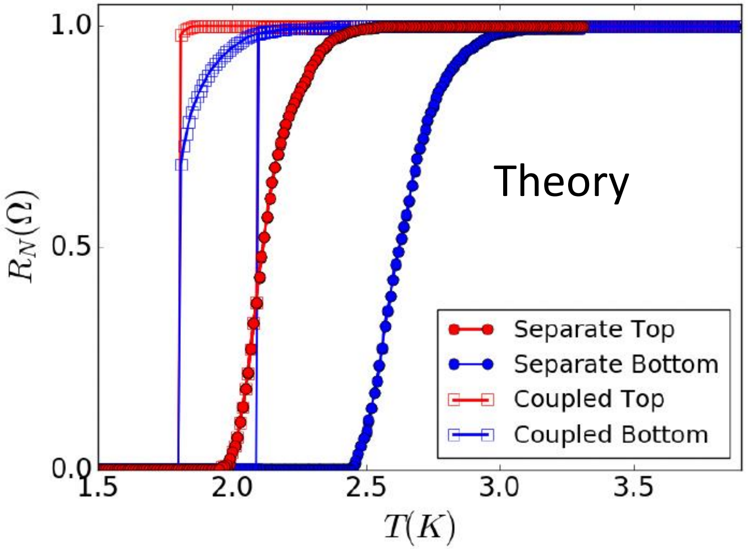
In between thermal conductance—electric insulator

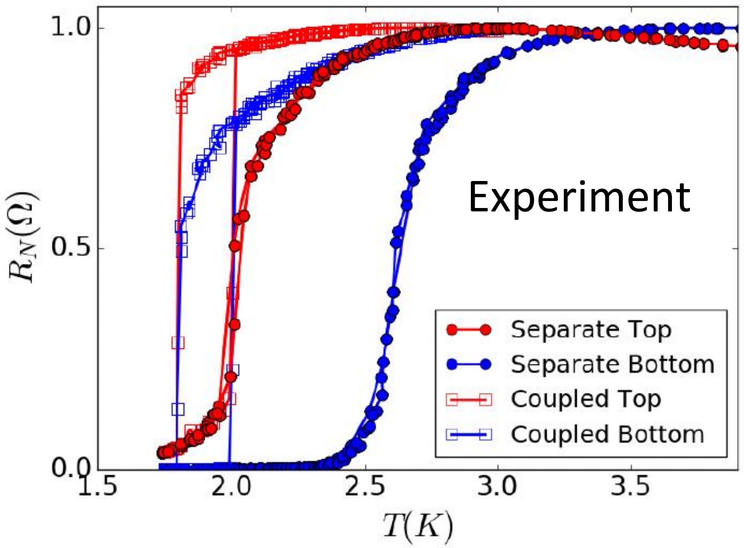


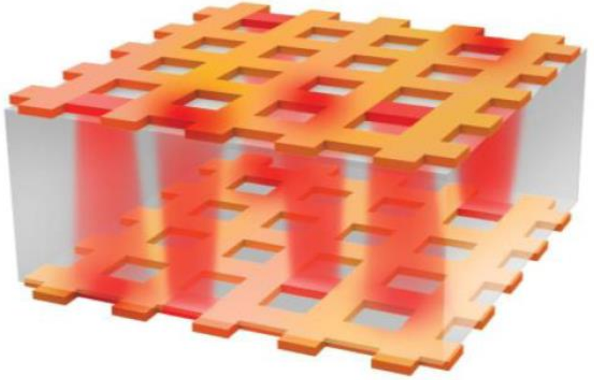
Interdependent superconducting networks











- Dependency – **<u>heat dissipation!</u>**
- Cascade of heat!

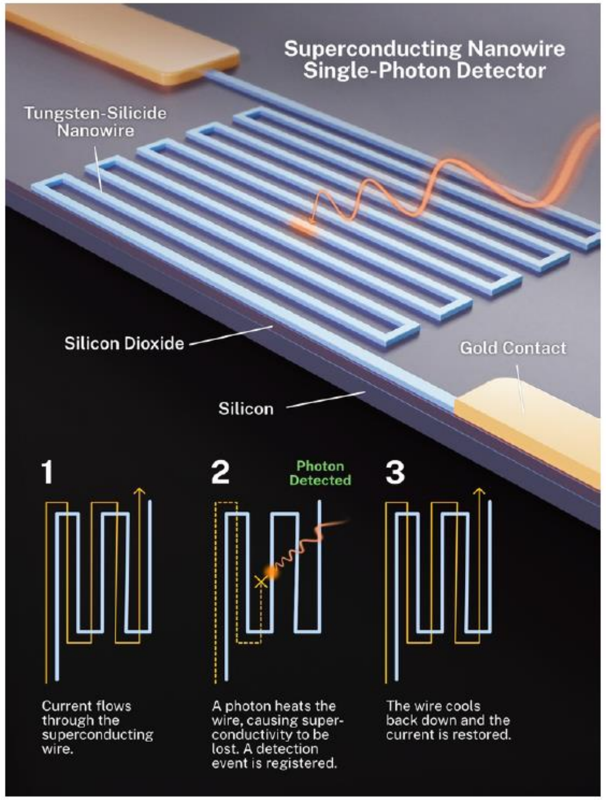
$$G_1 \cdot W_1 = I_{inj,1} \qquad G_2 \cdot W_2 = I_{inj,2}$$

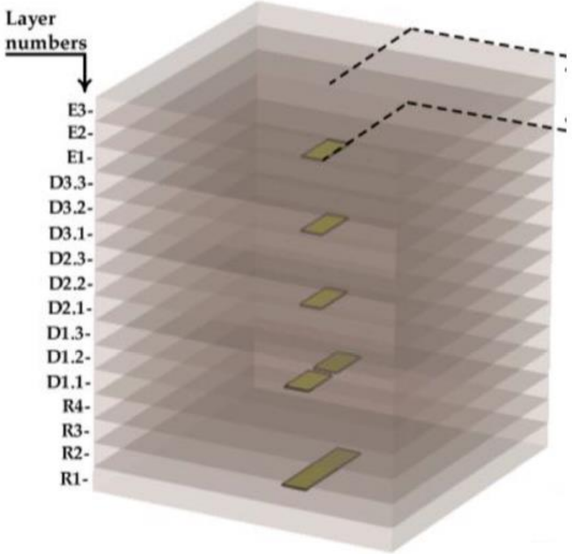
$$\begin{pmatrix} T^1_{eff} \\ T^2_{eff} \end{pmatrix} = T + \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix} \begin{pmatrix} R_1 I^2_{b,1} \\ R_2 I^2_{b,2} \end{pmatrix}$$

Ivan Bonamassa et al arXiv:2207.01669 (2022)

Applications

- Single photon detector
- Multilayer materials
- Biological/Chemicals sensors?





Summary

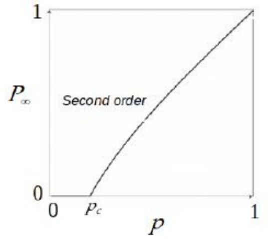
Physics

Physics and networks

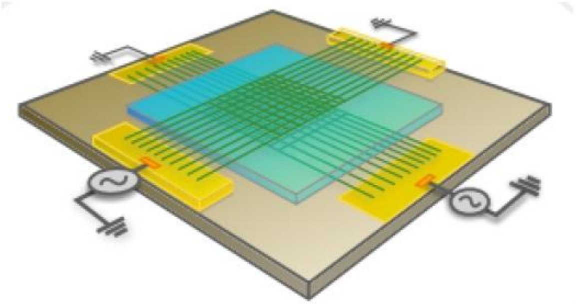
$P_\infty \sim (p - p_c)^\beta$

$\xi \sim |p - p_c|^{-\nu}$

$\chi \sim |p - p_c|^{-\gamma}$



Interdependent physical networks



Network theory

Multidisciplinary field

Climate

Brain

Finance

Traffic

Network theory

Biology

Infrastructures

Earthquakes

Interdependent networks