Complexity in Power Grids: Surviving and Mitigating Large Failures in Power Grids

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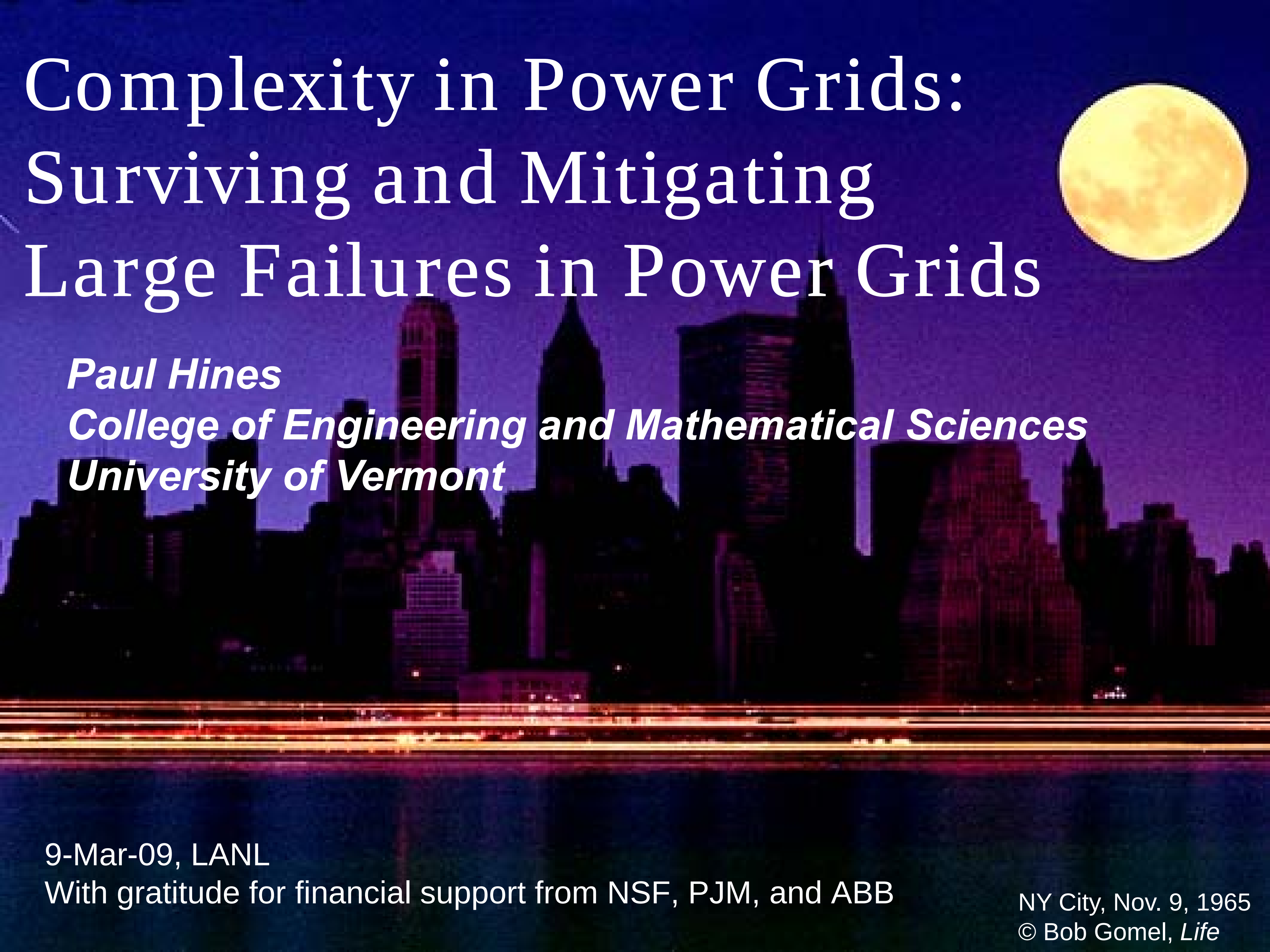
9-Mar-09, LANL

With gratitude for financial support from NSF, PJM, and ABB



NY City, Nov. 9, 1965

Outline

- **Some properties of power grids**
  - continuous, discrete, and social dynamics,, power-laws, network structure
  - **Smart Grids?**
- **Reducing the impact of blackouts**
  - Reciprocal Altruism
  - Survivability

Complete ignorance
infinite intelligence

Properties of power grids

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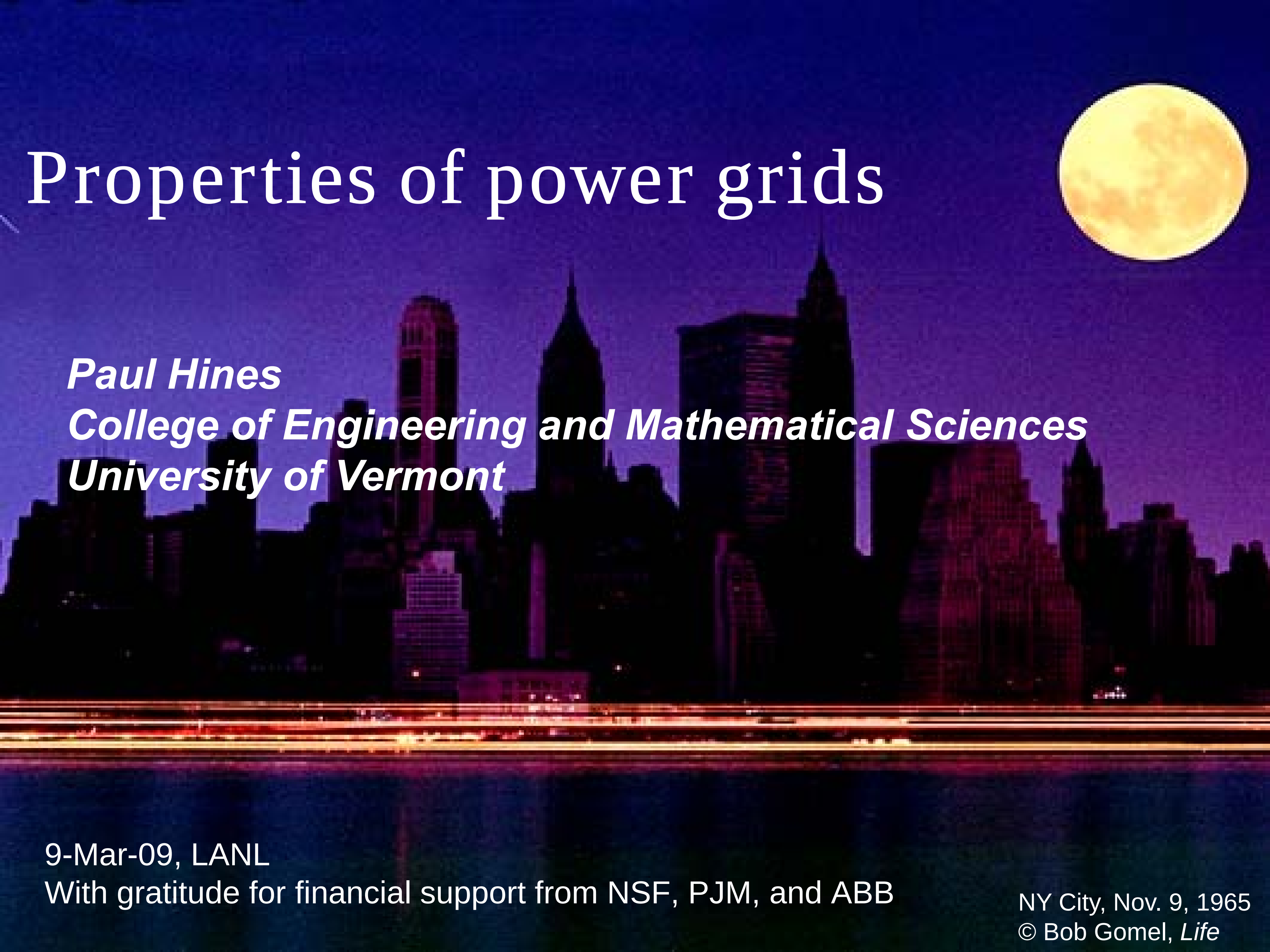

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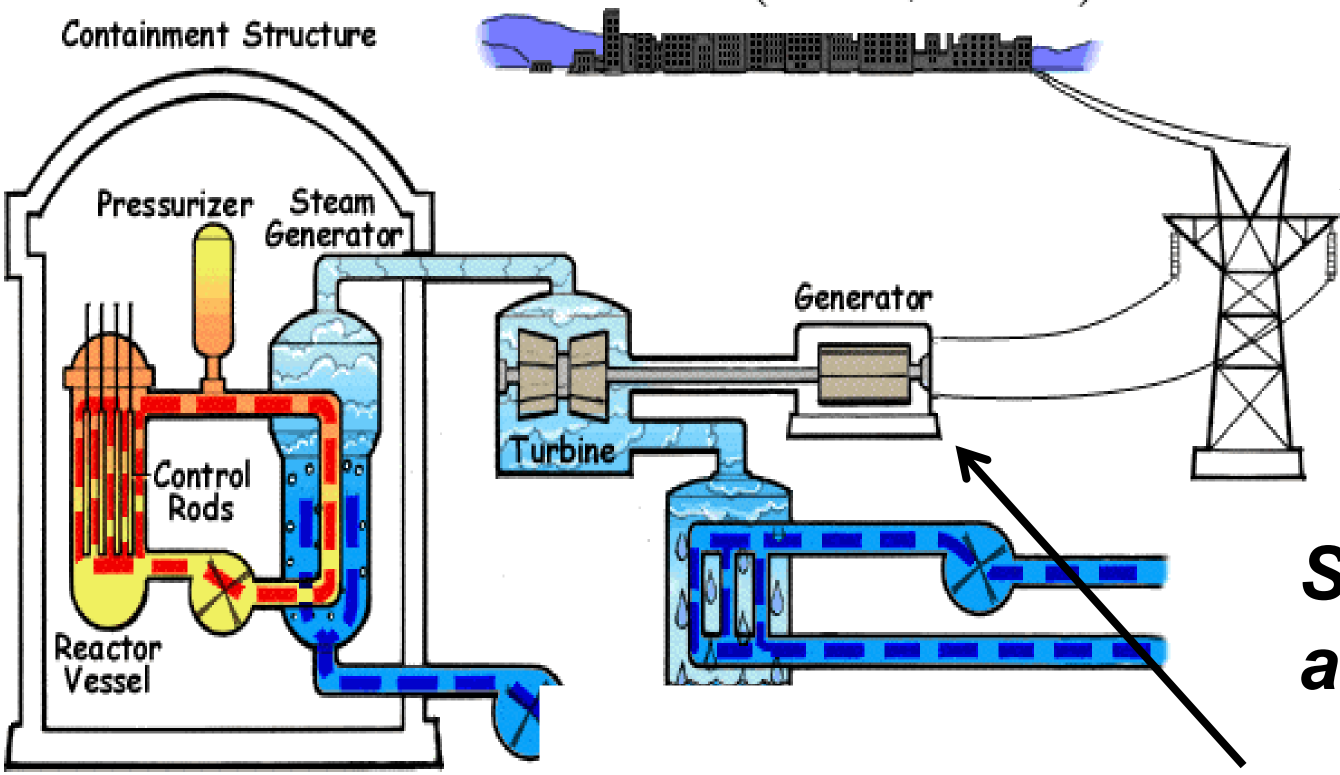
1. Non-linear continuous dynamics

$$\mathbf{S}(\mathbf{S}_G, \mathbf{S}_D) = \mathbf{V} \odot (\mathbf{Y}\mathbf{V})^*$$



Kirchoff's laws at nodes

Swing eq. at generator

$$P_m = P_g + K_D \omega + K_H \frac{d\omega}{dt}$$

2. Discrete dynamics

Selfish Relays?

3. Social Dynamics

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3. Social Dynamics

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MISO/Tim Johns: Midwest ISO, this is Tim.

Hoosier Energy/Bob: Yes, this is Bob at Hoosier.

MISO/Tim Johns: Hey Bob.

Hoosier Energy/Bob: What do you know, buddy?

MISO/Tim Johns: Same old stuff, man.

Hoosier Energy/Bob: Having just a quiet night, kicking back, watching TV. Is that what's going on up there?

MISO/Tim Johns: What, watching TV? Sure. Yes.

Hoosier Energy/Bob: I understand. Busy, man. This is kind of a strange thing, man.

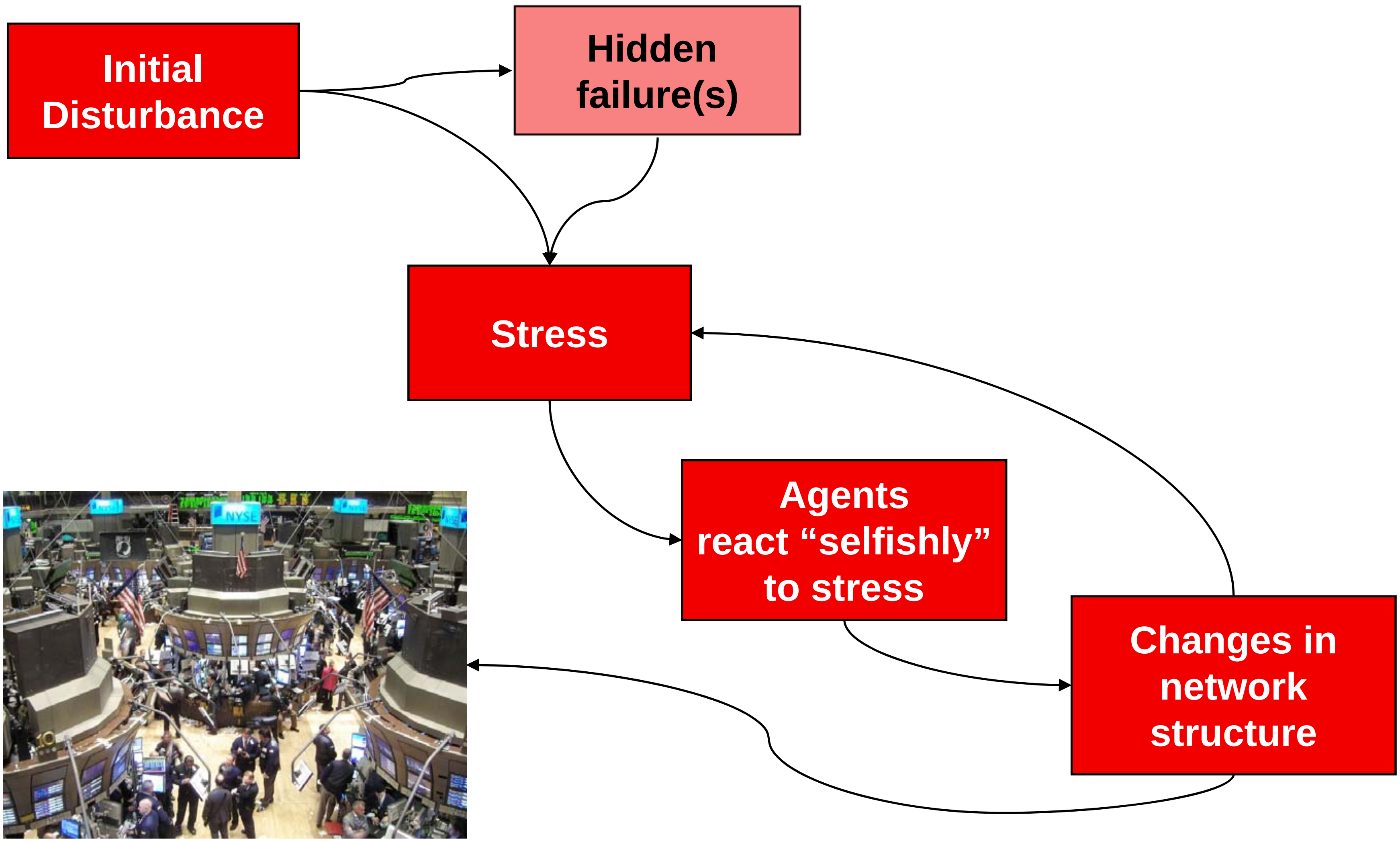
MISO/Tim Johns: Pretty much.

Hoosier Energy/Bob: Yes, it is. No, Tim, I just came in a little bit, you know. Just ciphering things up.

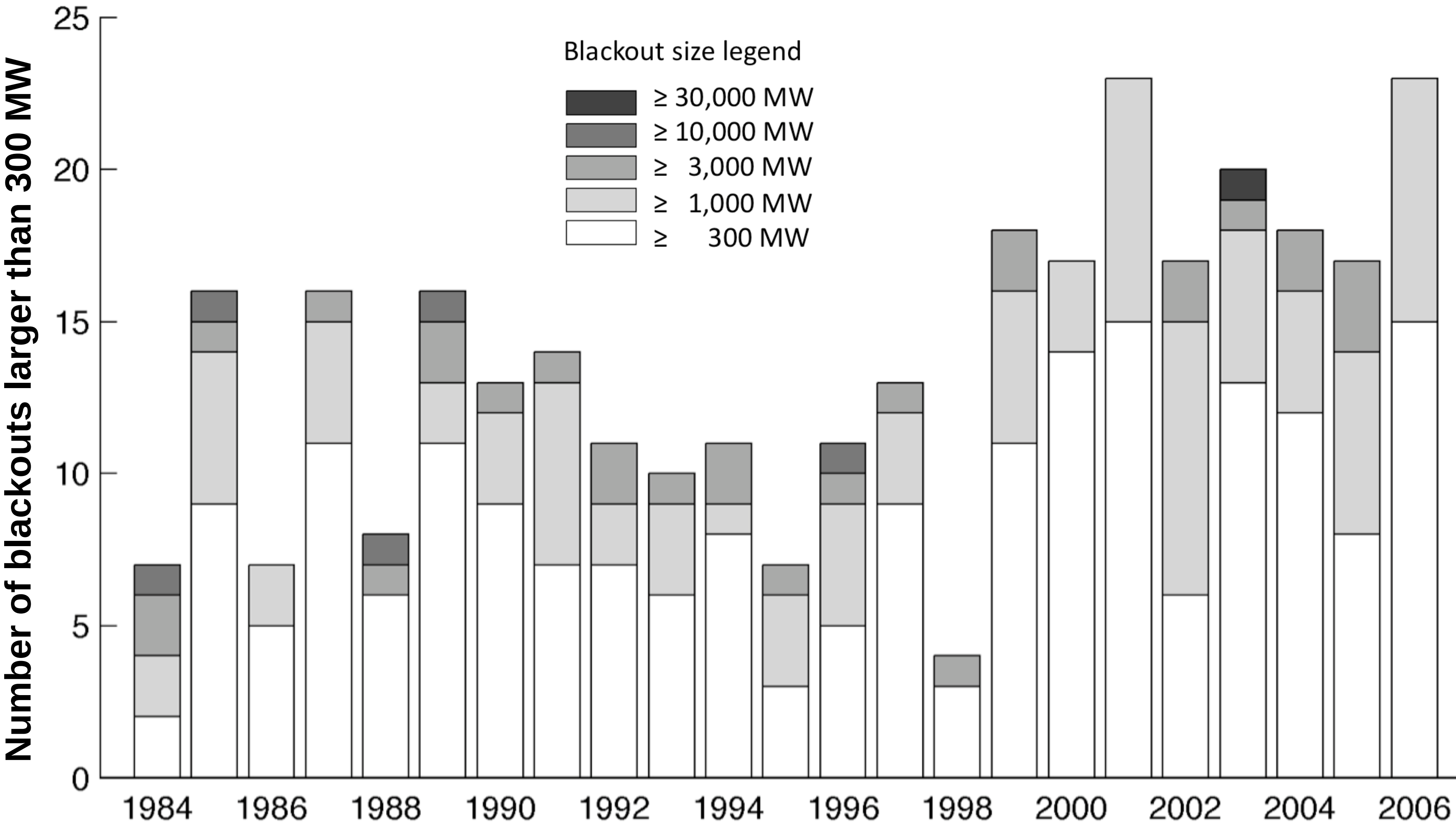
MISO/Tim Johns: We're still ciphering up here.

Hoosier Energy/Bob: Do you have any kind of a -- kind of a mock diagram of that region that's affected

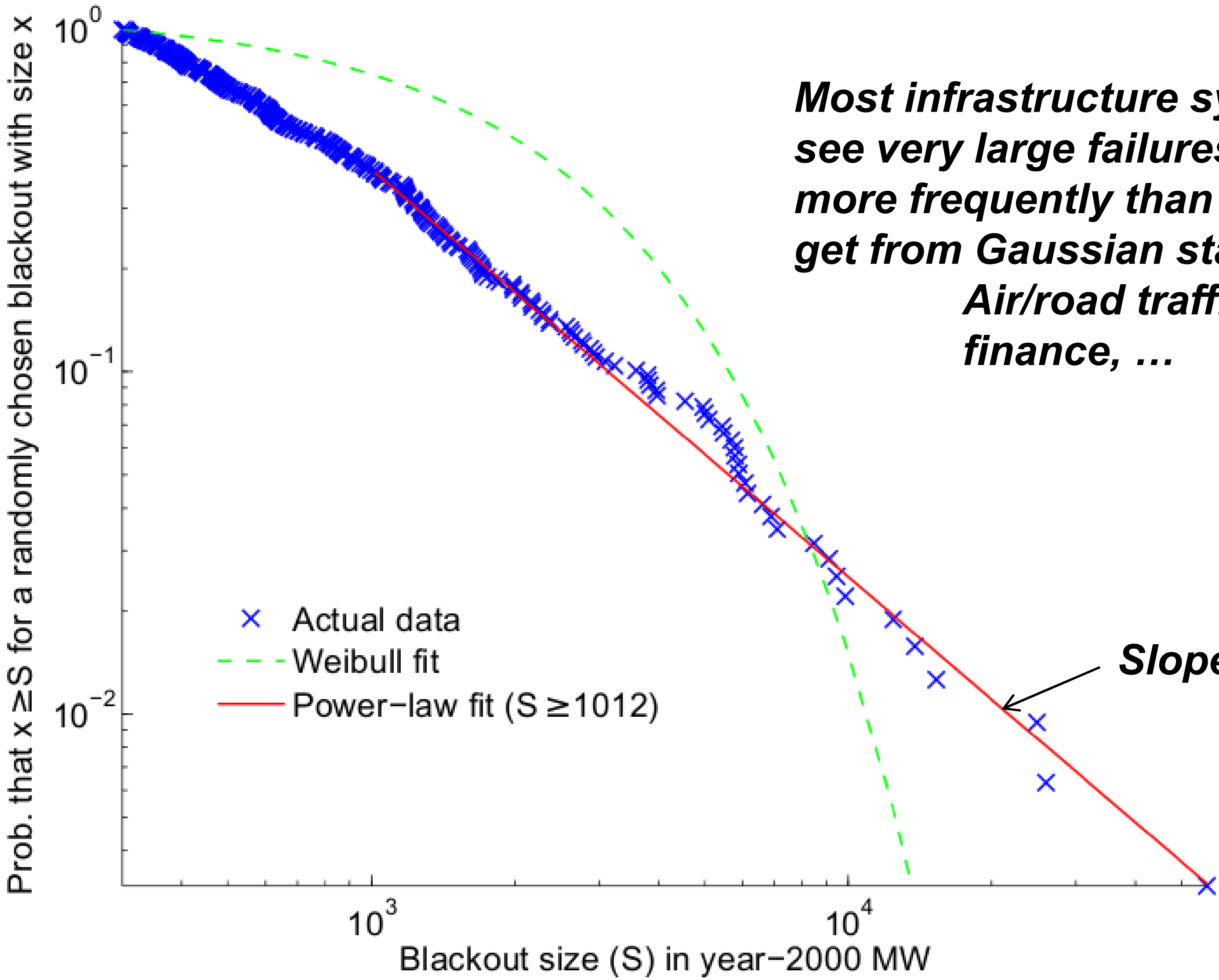
4. Cascading failures



5. Large grid failures are frequent



6. Power-laws in failure sizes

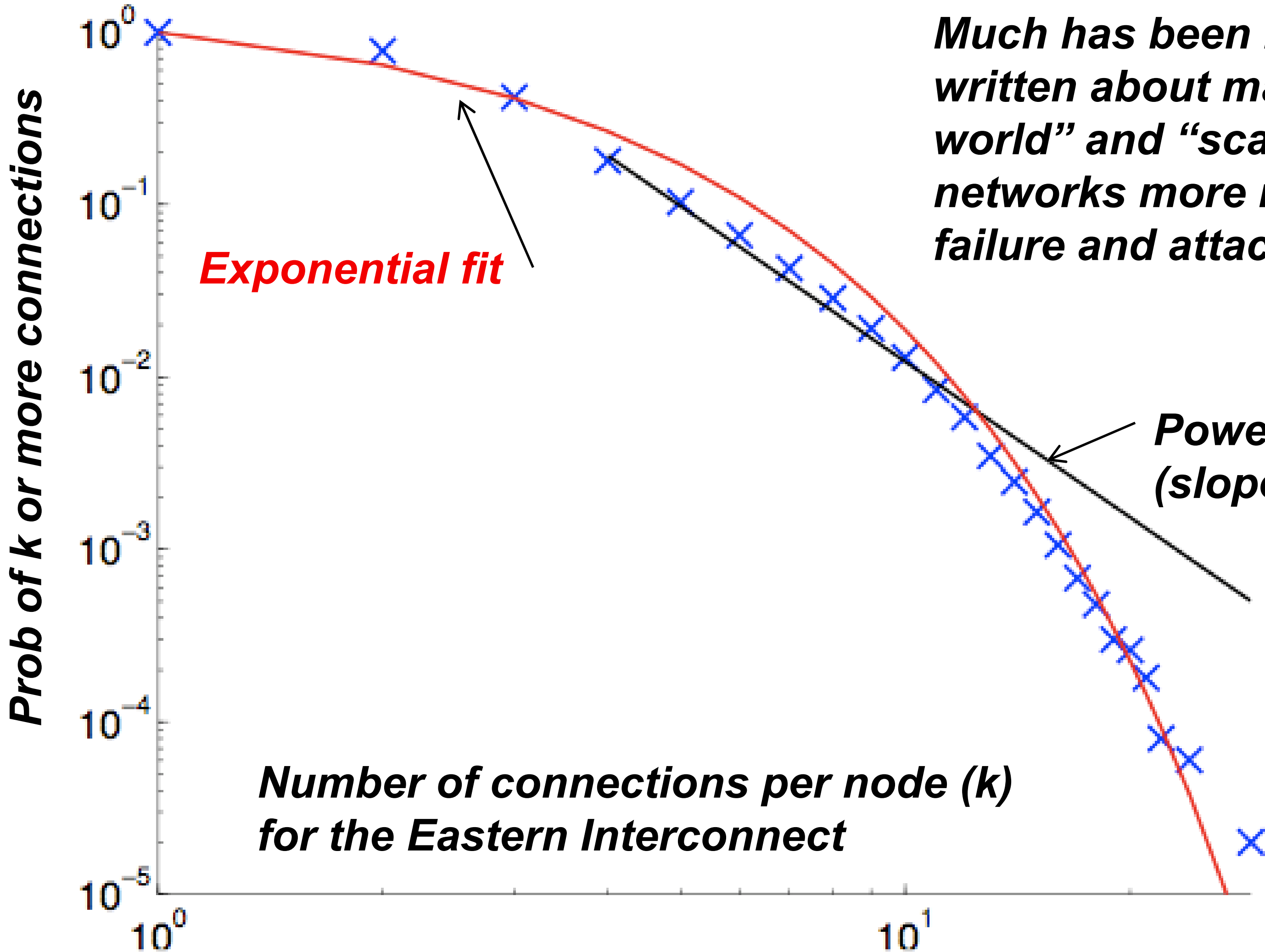


Most infrastructure systems see very large failures more frequently than we would get from Gaussian statistics

Air/road traffic, internet, finance, …

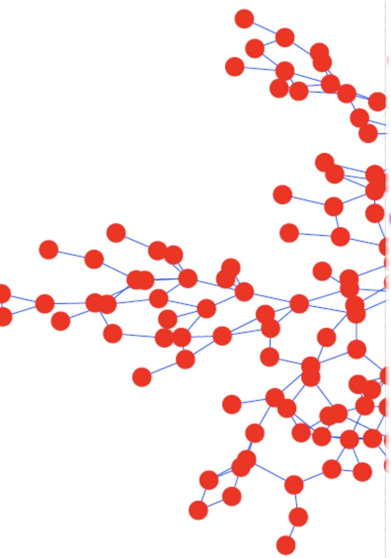
Slope = -1.2

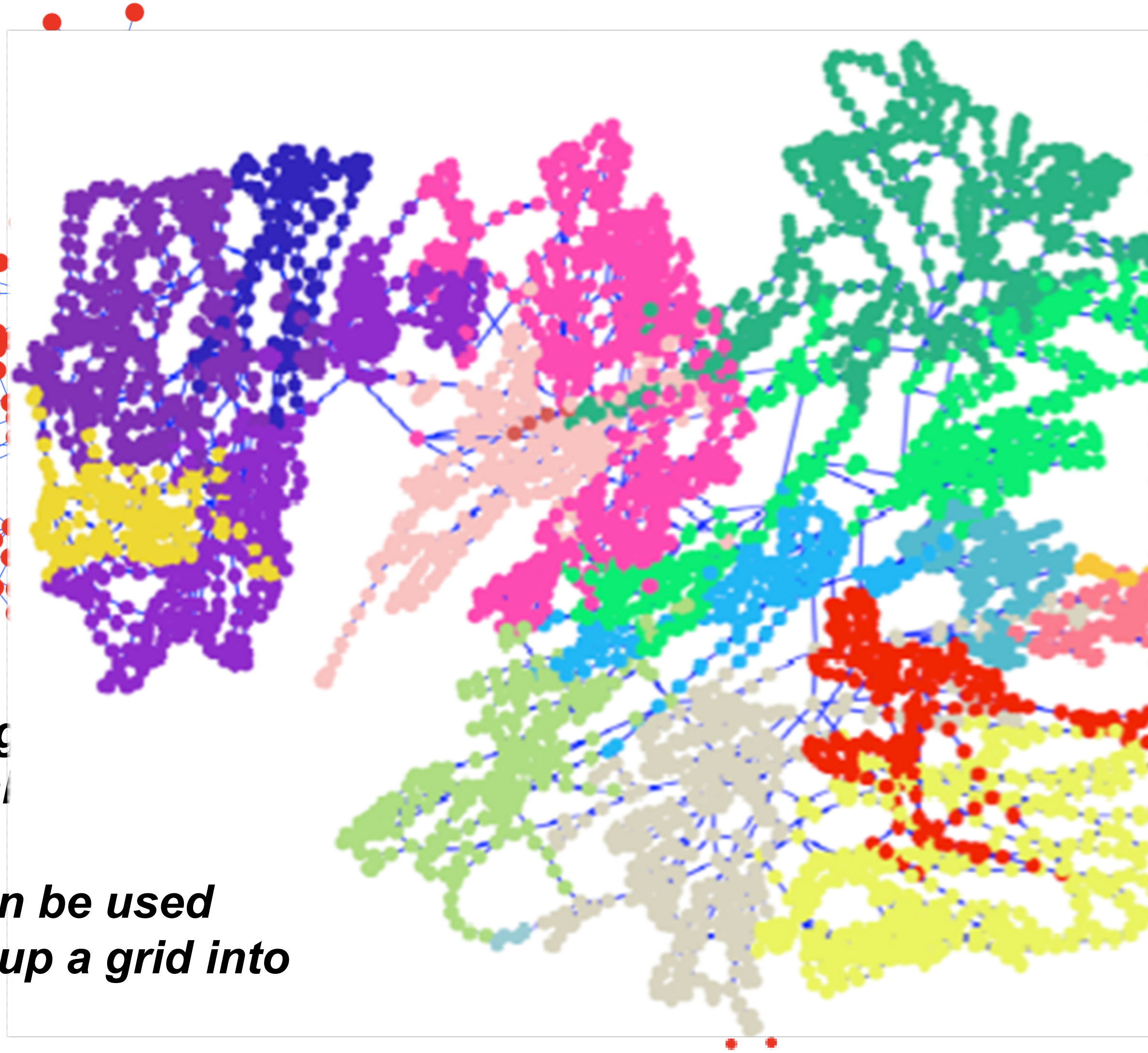
7. ...but, unlike the www, air traffic, many social networks, no power-law in structure

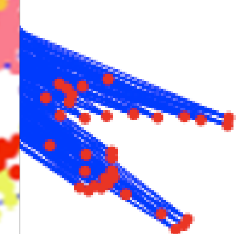


Much has been recently written about making "small-world" and "scale-free" networks more robust to failure and attack.

4. A notable difference between electrical and topological structure







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grid
s)

The topolog
node, 411 lin

Which can be used to divide up a grid into subgrids

Smart grids

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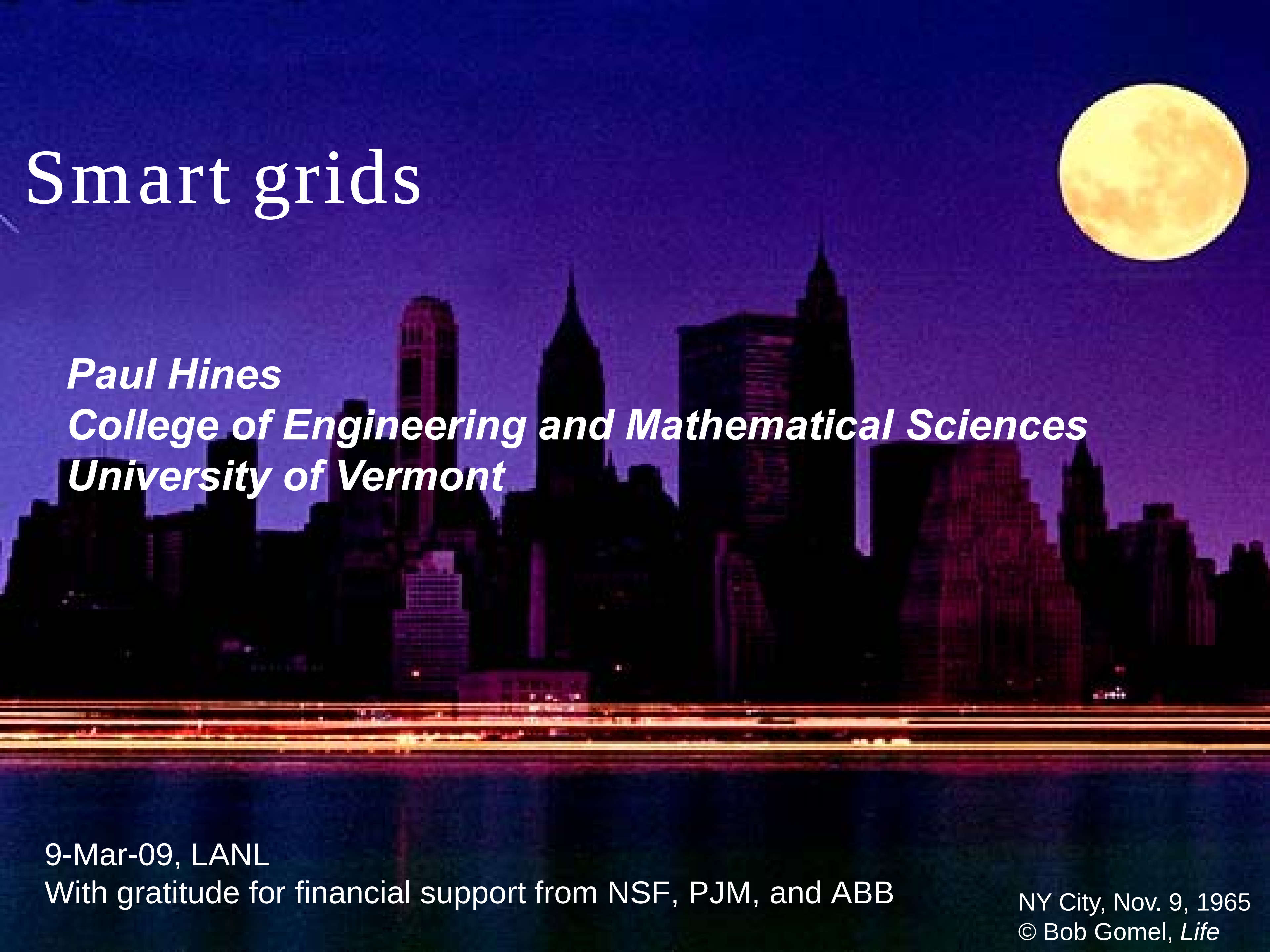

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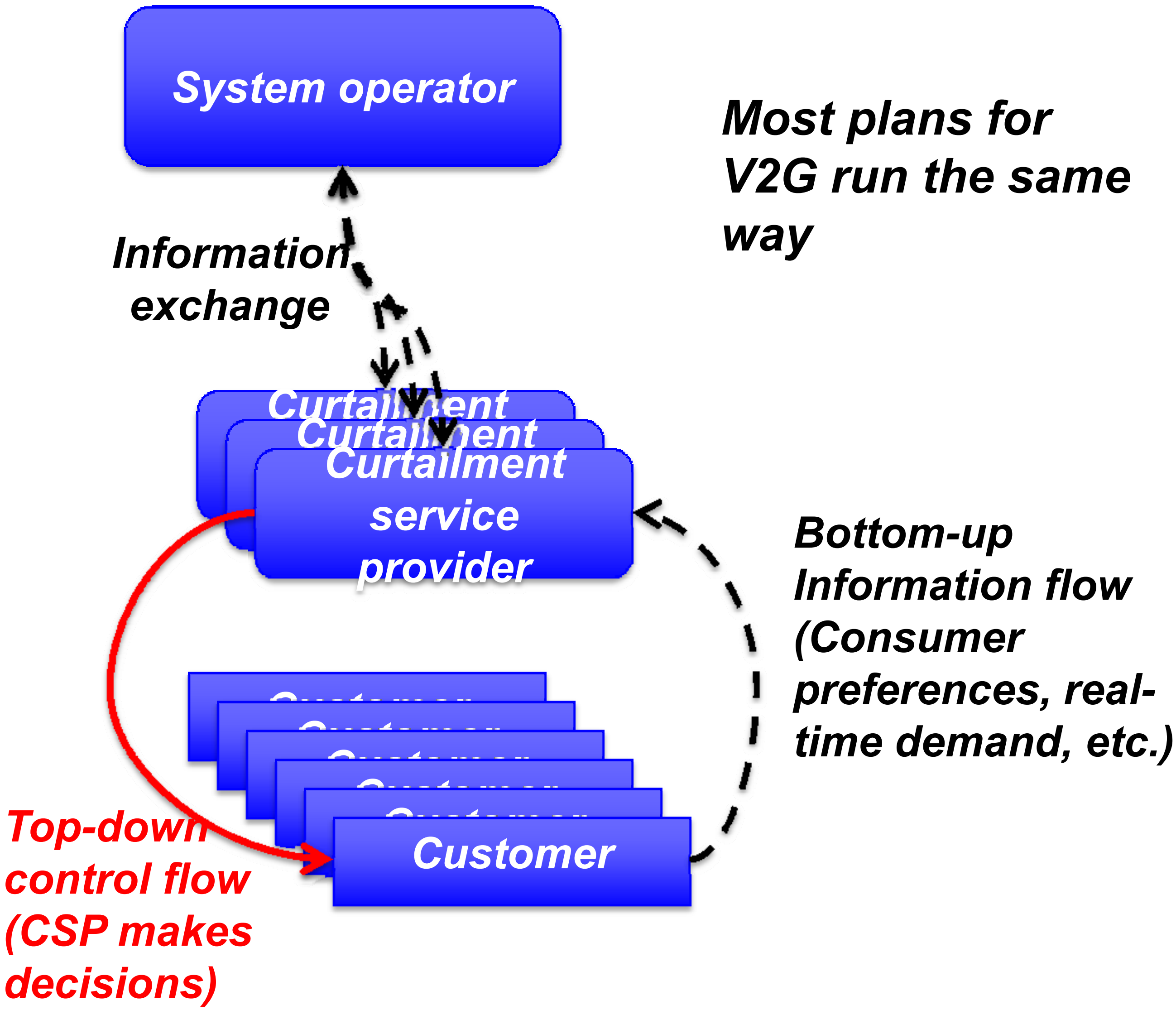
The Smart Meter to the Rescue

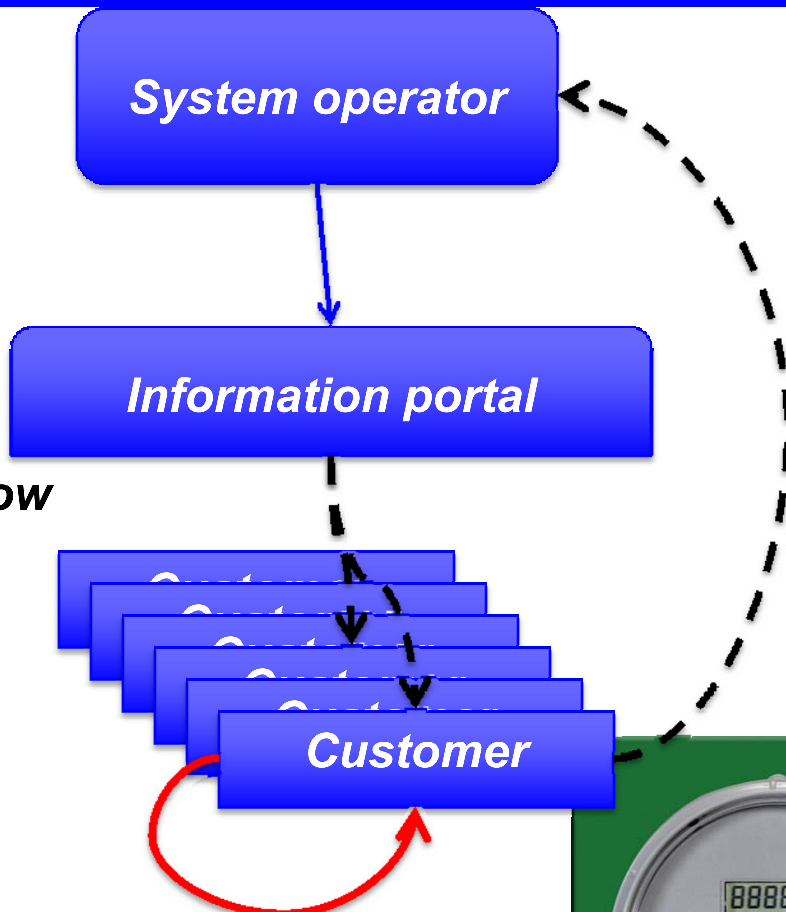
- Lots of $ for smart grids—mostly meters
- If we don't get the signals and architecture right the benefits will under-weigh the costs

Top-down "Smart Grid"

Most plans for V2G run the same way



Bottom-up "Smarter Smart Grid"



Top-down information flow
Prices, incentives, available to consumer, devices

Time-stamped meter readings
Real time or monthly

Local control flow
Consumer controls decisions

Utility meter does only metering, but with time-stamps

Thoughts on smart-meters

- Load that responds to signals will be tremendously better than the existing structure
- If utilities structure things hierarchically not enough people will sign up to make it worth the (massive) $
  - Lots of money for smart meters, public rebellion.

Mitigating failures

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So what?

- We have a system with complex dynamics, large, frequent failures, selfish relays
- We probably won’t eliminate large failures
- How can we make them less frequent and less costly

Mitigating large failures

Method 1 – Survivability

Method 2 – Adaptive reciprocal altruism

Survivability

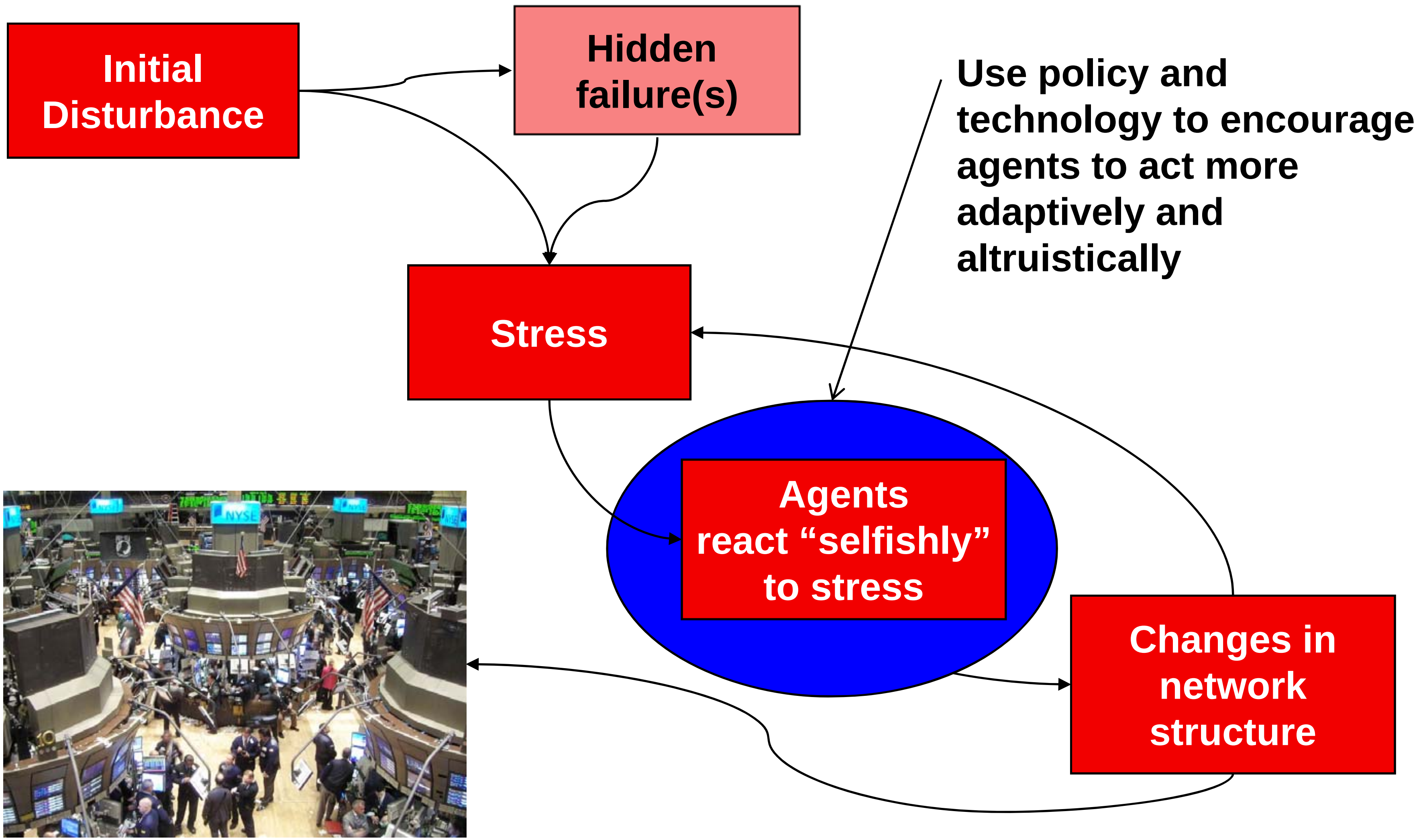
- Make sure that vital services have backup energy
- Link the backup energy sources to create emergency micro-grids
  - PGE program

Mitigating large failures

Method 2 – Adaptive reciprocal altruism

How can we make the power grid components less selfish and a bit more intelligent?

Mitigating cascading failures



Model Predictive Control

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Model Predictive Control

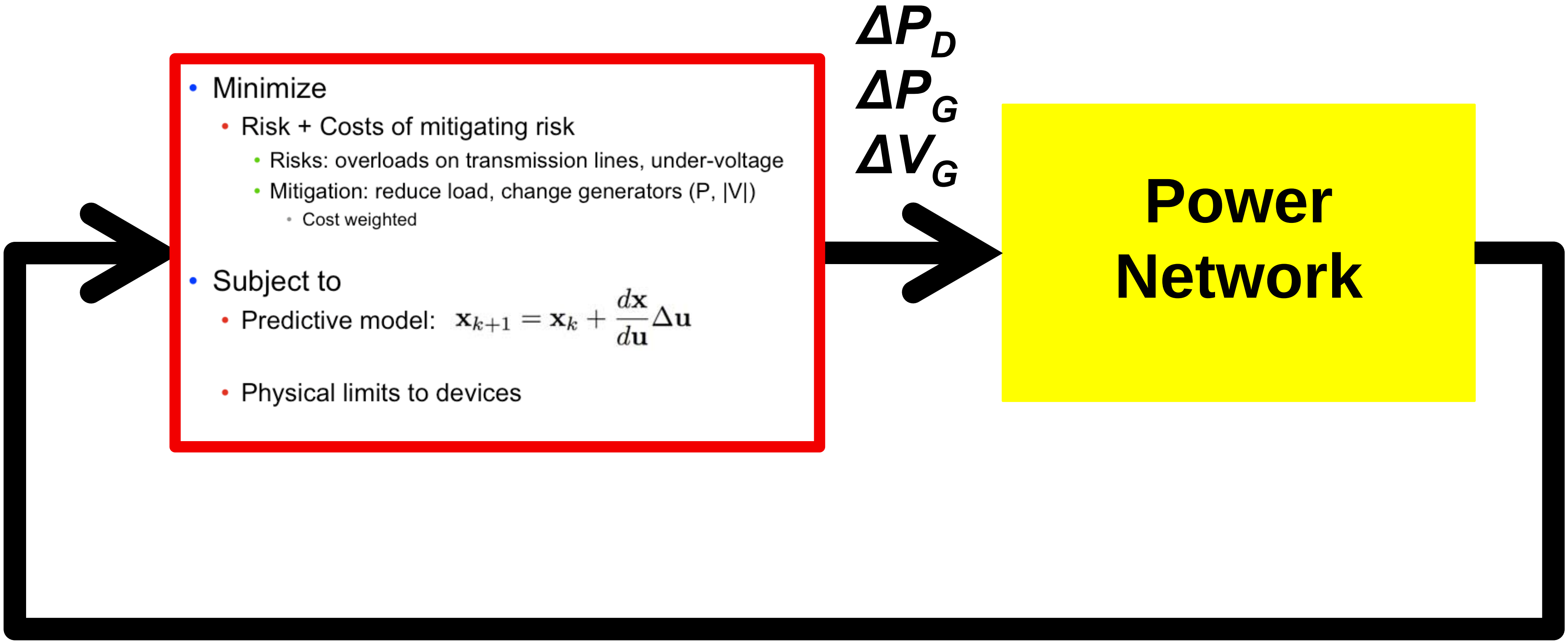
- Agents predict the consequences of their actions, adjust their predictions as they get more information

- MPC:
  - Predictive models
    - Intelligence
  - Feedback
    - Adaption
  - Optimization tools

MPC goals (for power grids)

- Minimize
  - Risk + Costs of mitigating risk
    - Risks: overloads on transmission lines, under-voltage
    - Mitigation: reduce load, change generators (P, |V|)
      - Cost weighted
- Subject to
  - Predictive model: $$\mathbf{x}_{k+1} = \mathbf{x}_k + \frac{d\mathbf{x}}{d\mathbf{u}}\Delta\mathbf{u}$$
  - Physical limits to devices

MPC

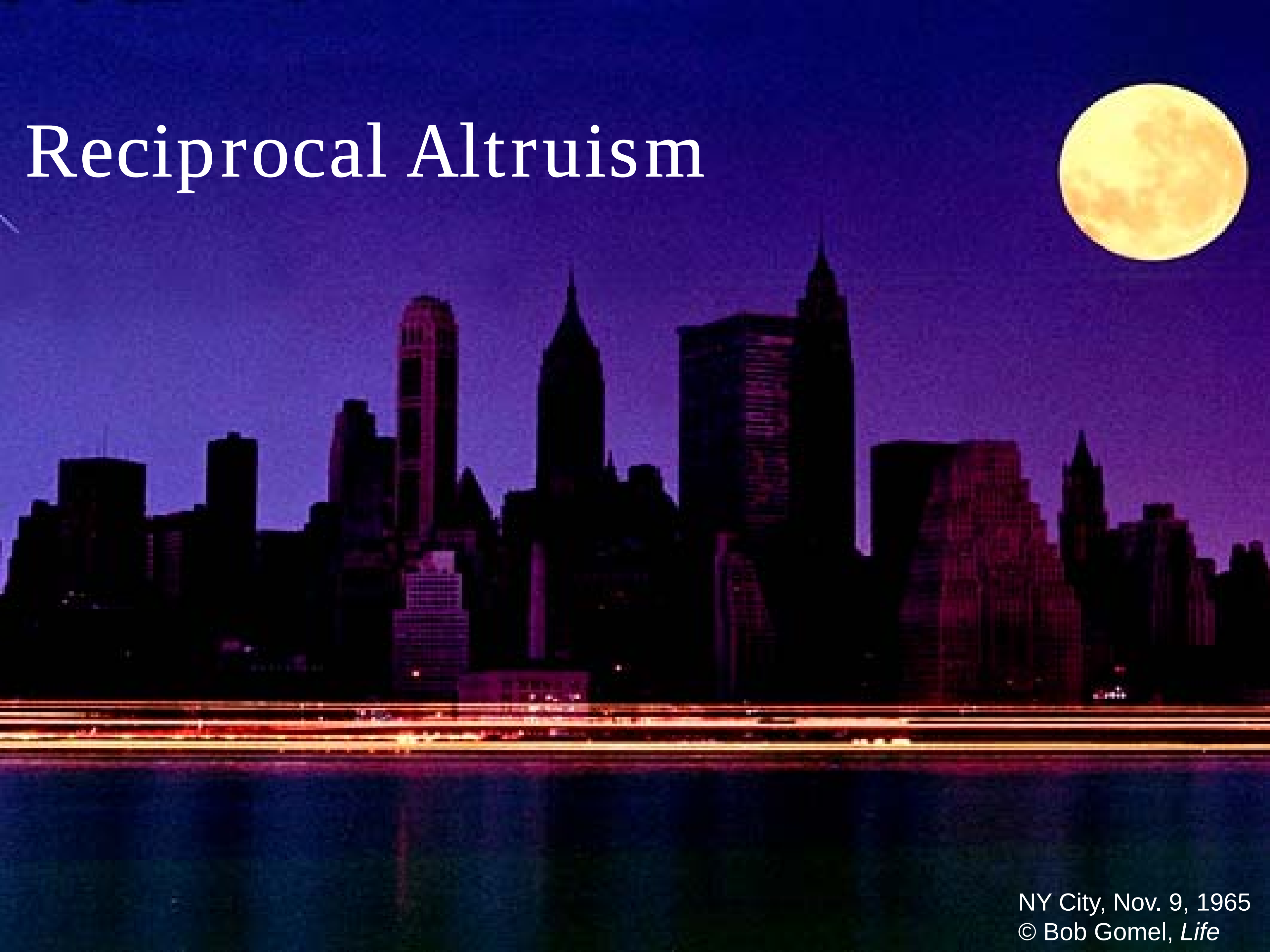


Measured stress (currents, voltages, etc.)

Effective in models, but...

- Centralized MPC control is often infeasible
  - Politics (FERC, UTCE)
  - Speed
  - Robustness

Reciprocal Altruism



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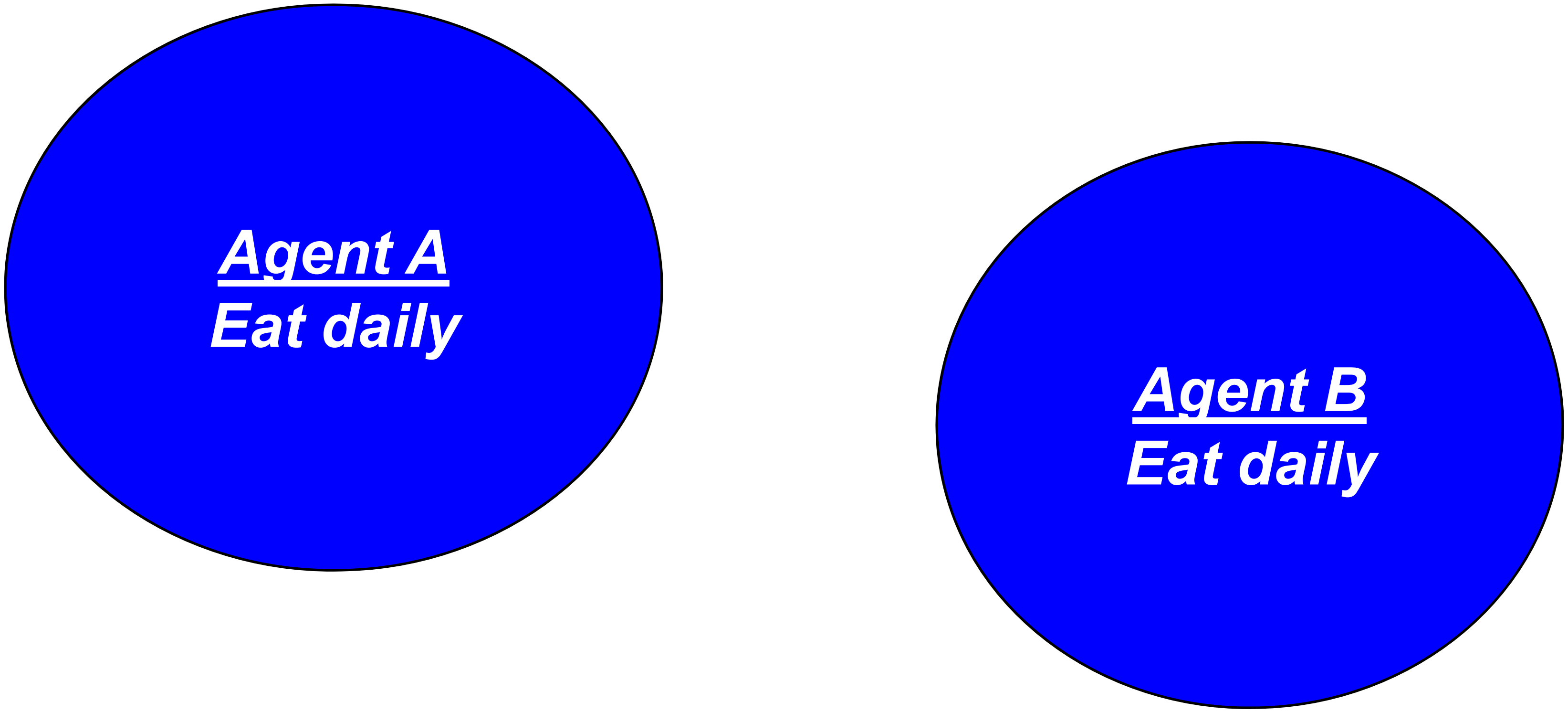
Vampire bats

Trivers (1971): RA is "behavior that benefits another organism, not closely related, while being apparently detrimental to the organism performing the behavior."
(Wilkenson, 1984, Nature)

Reciprocal altruism

Two agents practice "reciprocal altruism" when they choose to consider the other's goals while making local decisions



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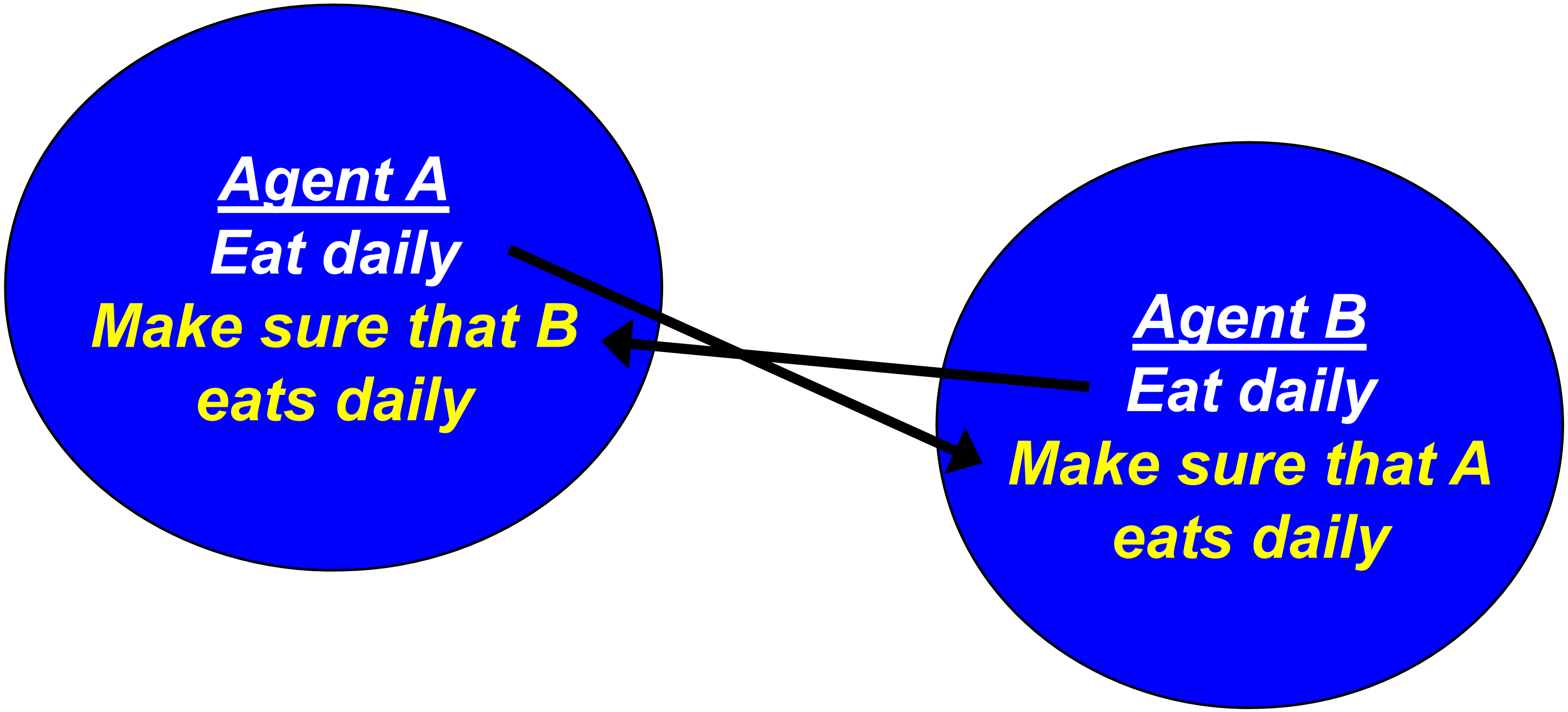
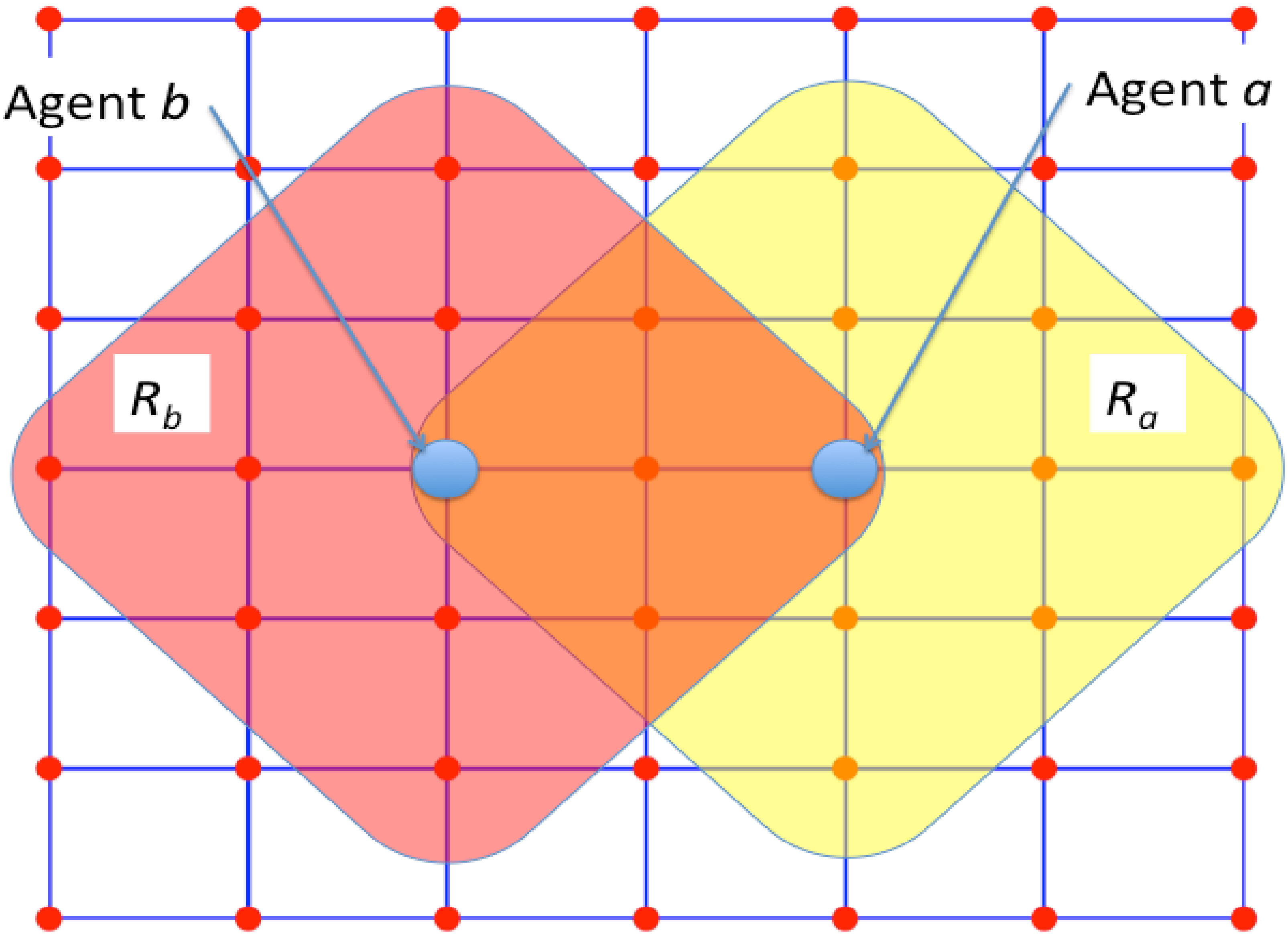
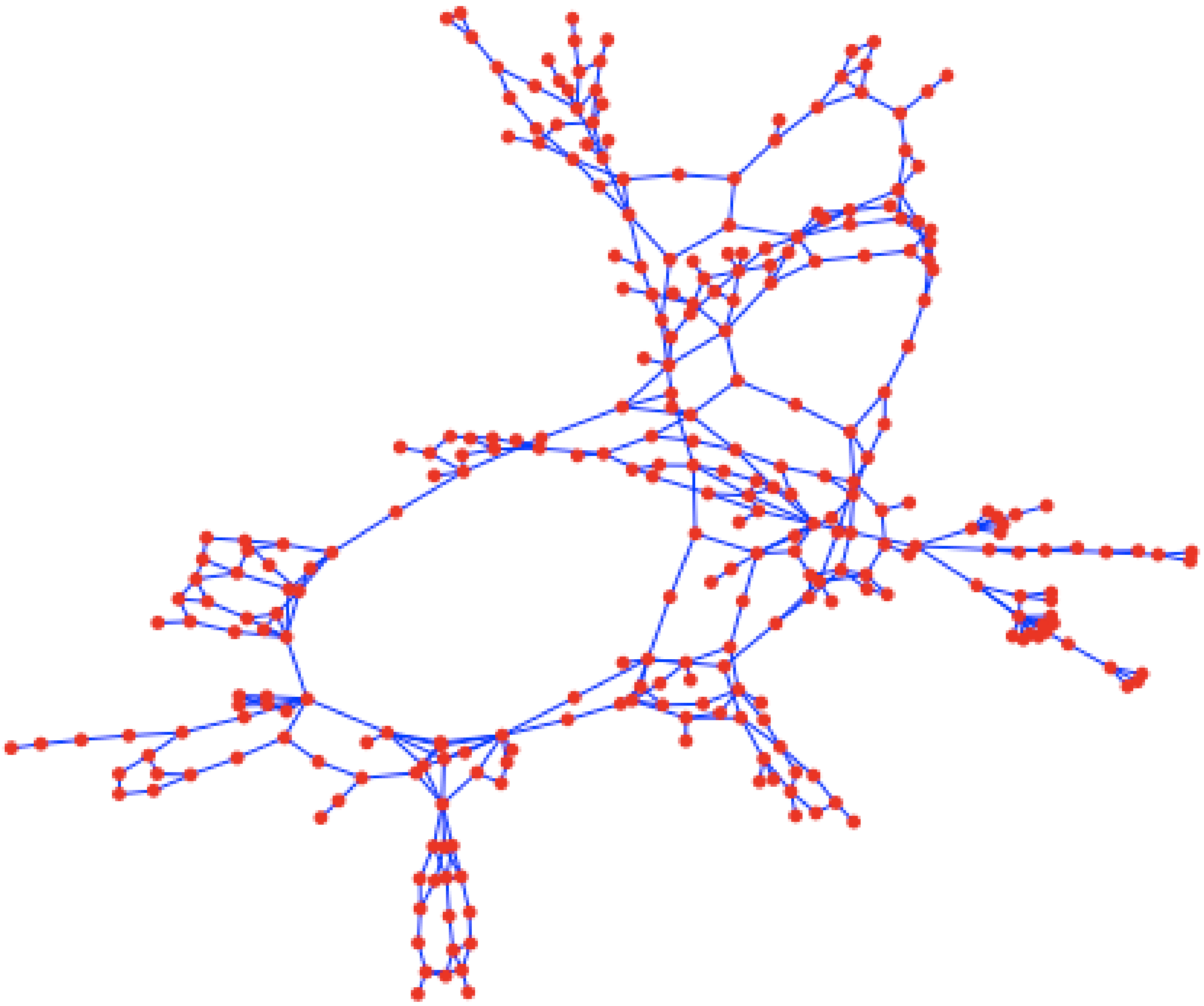


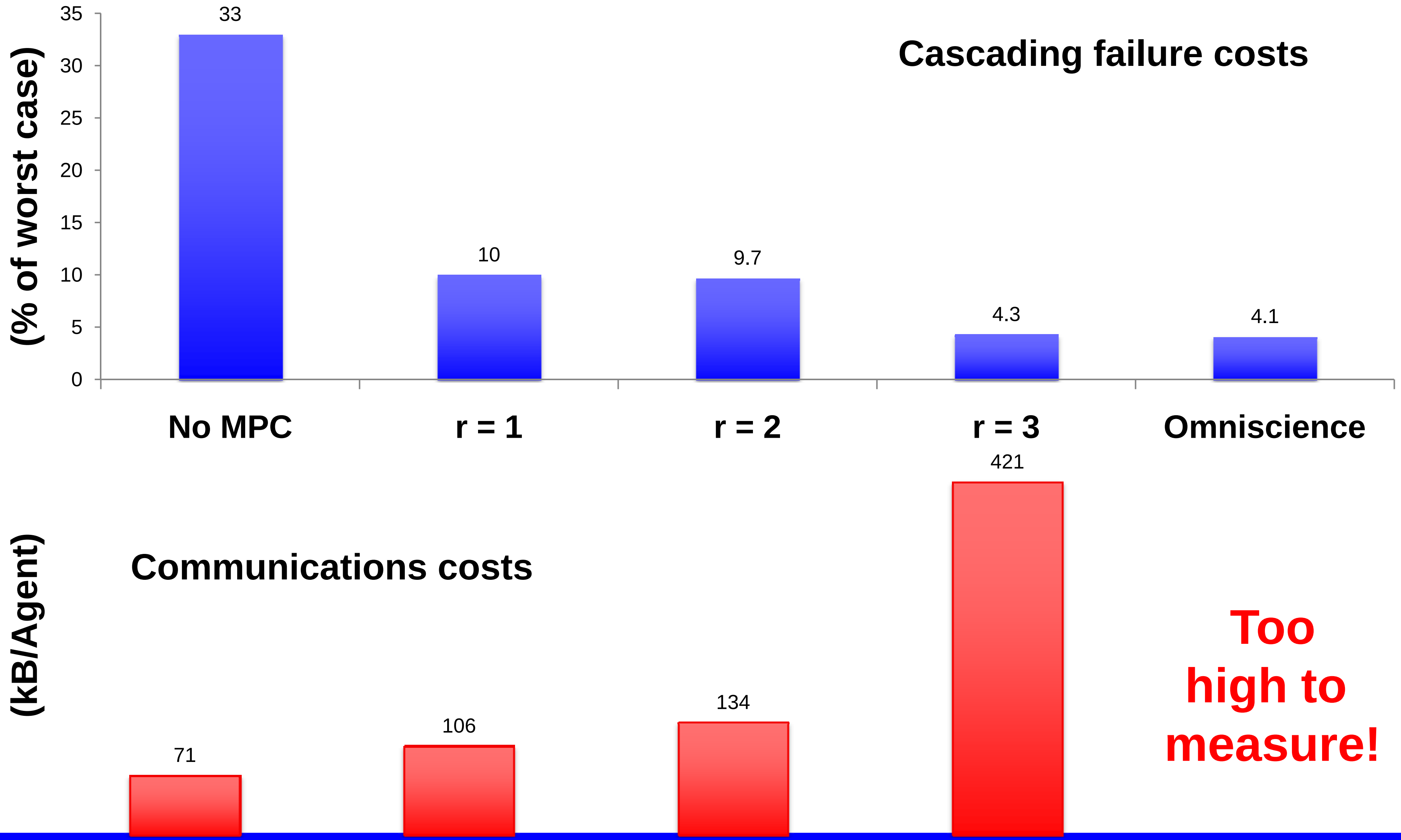
RA in a network



Apply severe, random failures to a 300 node system



Results



(% of worst case)
35
30
25
20
15
10
5
0
33
10
9.7
4.3
4.1
Cascading failure costs
No MPC
r = 1
r = 2
r = 3
Omniscience
(kB/Agent)
Communications costs
71
106
134
421
Too high to measure!

Conclusions

- Cascading failures are inherent to infrastructure systems

Conclusions & Future work

- Electricity grids (and other infrastructures) differ from social networks, www
  - Much can be learned from the science emerging from study of these networks.
  - We need to understand the structure of network before we can improve it most effectively
- The smart grid needs careful thought
- Cascading failures appear to be a fundamental property of tightly connected networks
  - We can learn from biological systems to make infrastructure services survivable, resilient and adaptive


Questions?
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