# Understanding the interdependent infrastructures that make up Megacities:

## What planners and policy makers can learn from complex systems paradigms

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Main points:

1) Complex infrastructure systems models - display characteristics of "real" data => very important implications for risk analysis

2) Reduced models are complementary to detailed models and can be used to investigate the impact of design and mitigation schemes on risk (can be counter intuitive) => control can increase risk of large failures

3) Decision making can be modeled with controlling agents responding to perceived risk of failure and other factors

The economy (and nation) are also large complex systems!!

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**Workshop on Megacities**
**11 Nov. 2008**

# Motivation

- Large cities as well as society as a whole function on a complex web of interdependent infrastructure systems (power transmission and distribution systems, communication/IT systems, transportation and pipeline systems, economic markets and even human decision making systems).
- Power law tails and long time correlations in many of these complex infrastructure systems [(NERC) blackout data, communications systems data, etc.] suggest need for dynamical model (systems sit near critical point)
- Need models that capture these characteristics to investigate design and mitigation techniques to improve resilience and robustness of the system
- Individual infrastructure systems are tied to other infrastructure systems in a often symbiotic relationship (failure in one can cause, or increase probability of, a failure in the other)
- Need models that capture coupling characteristics to investigate impact of interactions between systems (strength, symmetry, homogeneity)
- What are implications of interdependent interacting infrastructures on the risk of failure in each system?

# Outline

- What is a complex system
- Characteristics of a complex system
- Why should you care about complex systems

# Complex Systems

- What we mean by a Complex System
  - Many nonlinearly interacting parts => overall behavior (dynamics) not the sum of the individual behaviors
- Importance of nonlinear terms (dynamics)
  - Temporal evolution (dynamics) and steady state (equilibrium)
- Low dimensional vs. high dimensional dynamics
  - Chaos vs. complex dynamics
- Usefulness of study of "Complex Systems"
  - Fashionable
  - Universality of dynamics
    - Implies universality of underlying physics?
    - Predictive capabilities?

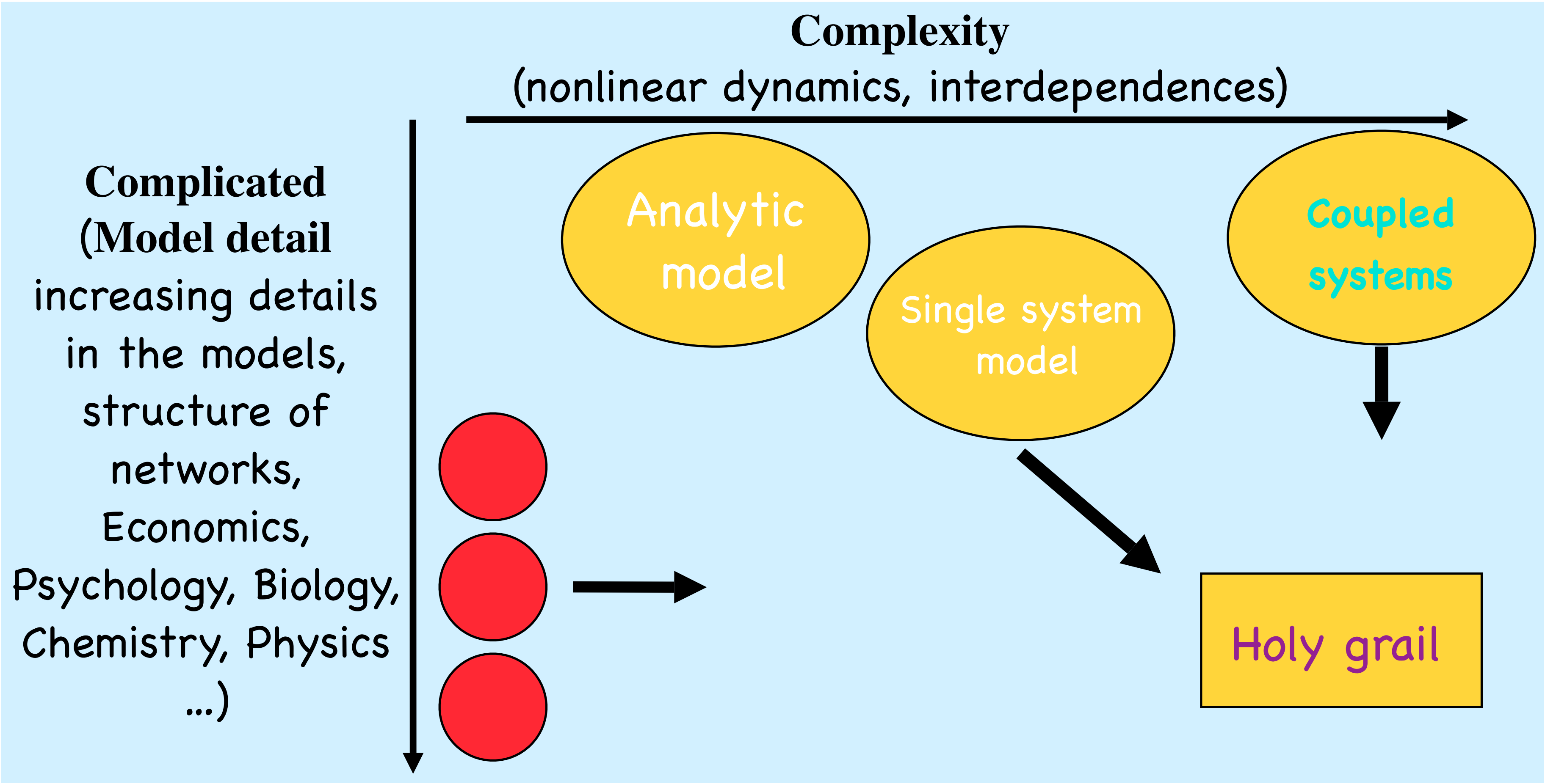
# Complex vs Complicated

(Cars are complicated, traffic is complex)

- Systems can be complicated without being complex  and complex without being complicated

The real world is usually both

# Complex vs. Complicated: Complimentary approaches to modeling System Dynamics



**Complexity**

(nonlinear dynamics, interdependences)

**Complicated**

**(Model detail**

increasing details in the models, structure of networks, Economics, Psychology, Biology, Chemistry, Physics …)

Analytic model

Single system model

Coupled systems

Holy grail

By using models with fewer details => can investigate the complex behavior to extract universal features (critical points, power tails, measures…).

# Complex Systems

- Include among others
    - Infrastructure systems
        - Power transmission
        - Communication (IT)
        - Pipelines
        - Transportation
    - Human systems
        - Markets
        - Policy and decision making
        - Social behavior - trends, learning and reacting
- Physical
    - Plasmas
    - materials
    - biological
    - ecological
    - chemical
    - meteorological and climitalogical
- Coupled systems
    - Take any from the above and mix and match

Some of these have complicated parts, some do not

# Assessing and managing the risk of large blackouts is an example of a complex critical infrastructure

- Large blackouts typically involve complicated series of cascading rare events that are often impossible to anticipate in detail:
  - An example: August 14th, 2003

- These blackouts have important economical and social consequences.

- Our view is that blackouts are inherent to the power grid as well as many other infrastructure systems. Efforts to mitigate or eliminate them can backfire and increase the likelihood of the large cascading blackouts (note: this does not mean system can not be improved and risk lowered).

- We have developed new models and ideas to address the risk of large cascading infrastructure failures from a global, dynamical, complex systems perspective.

# Characteristics of complex systems

- Power law tails (heavy tails)=>large infrequent events can dominate the risk
- Long time correlations => what happens today depends on what happened years ago
  - System often operates near its operational limit

# Probability of large blackouts decreases as a power of their size instead of exponentially

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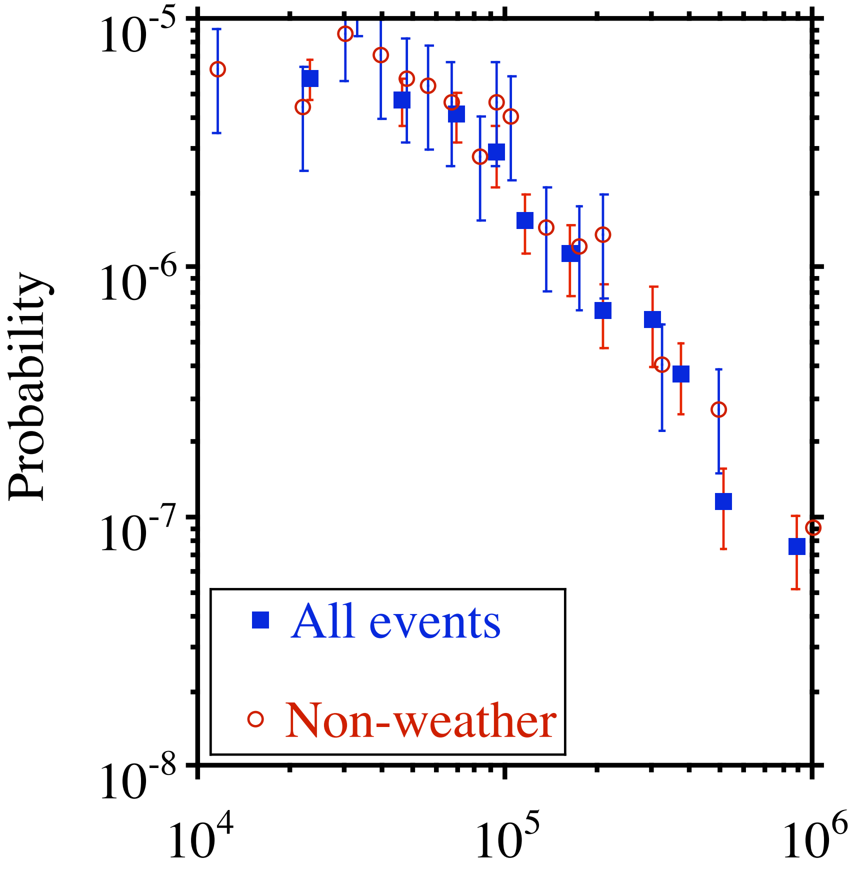
- Our analysis of the NERC data shows power tails in the probability distribution of the size of North American blackouts.
- A long time correlation between the failure events that is found to exist.
- An explanation for this correlation and heavy tail is that the system tends to operate close to critical.

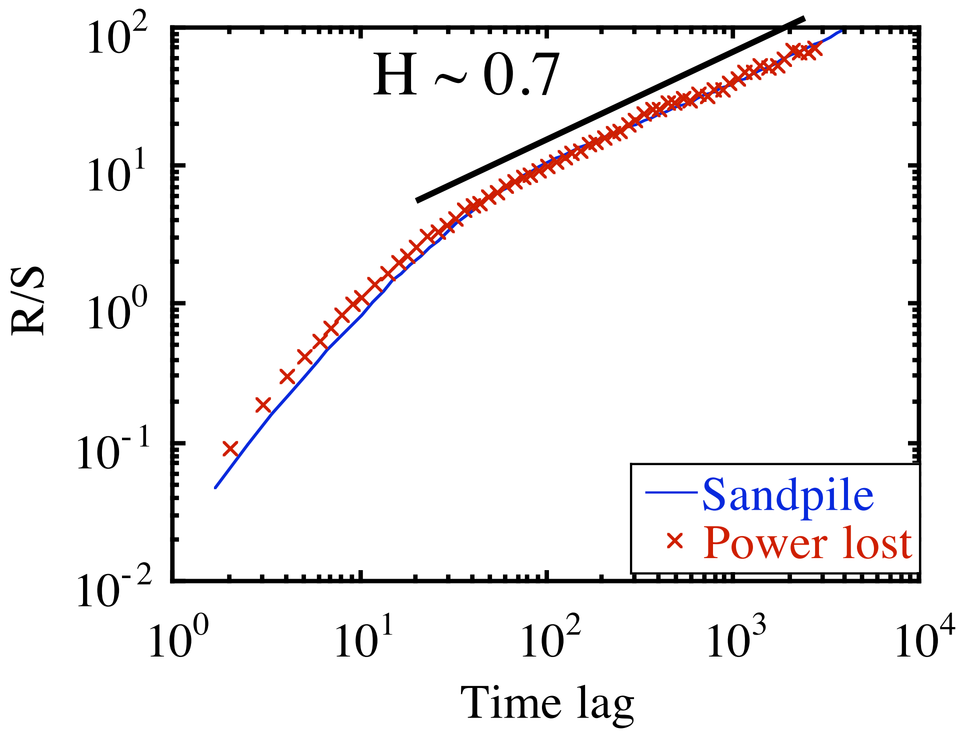


Customers unserved

(August 14 blackout is consistent with this power tail)

# Long-Time Correlation

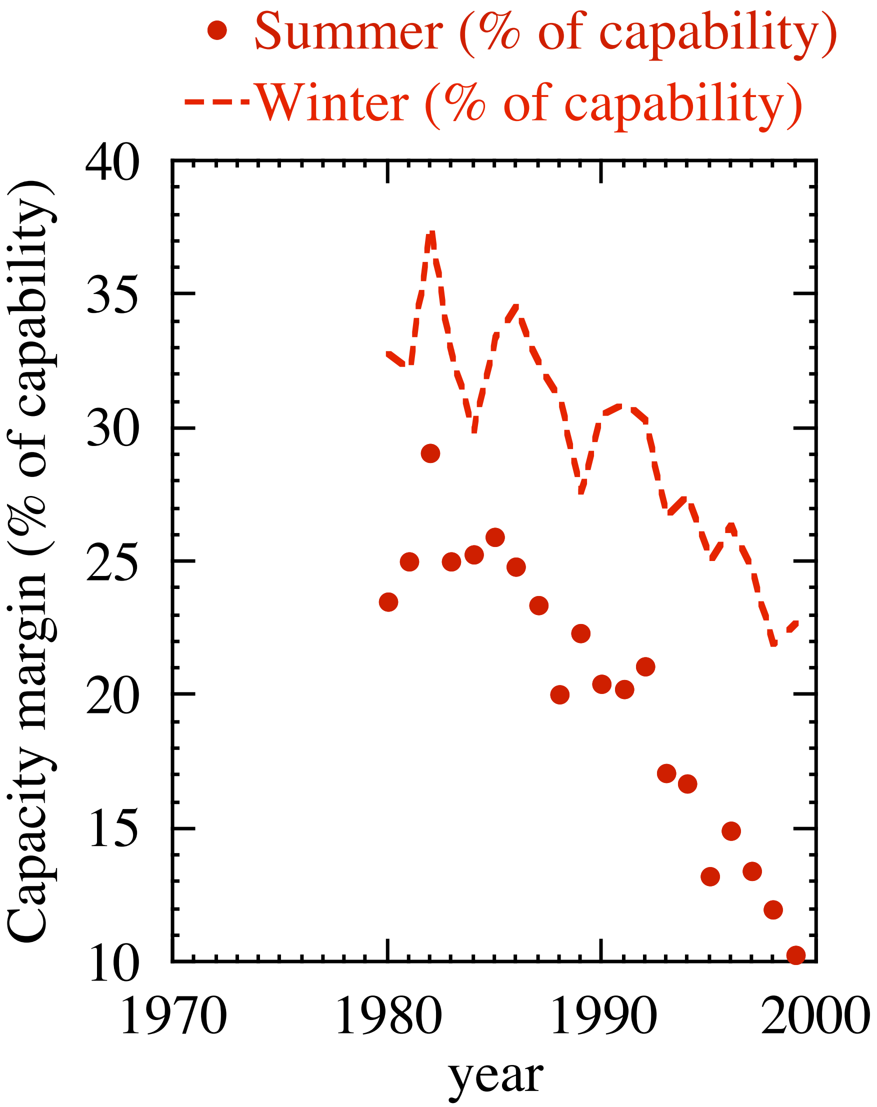
- R/S (long time correlation) analysis of the power grid disturbances consistent with a time series of avalanches generated from a complex systems running sandpile model with the same frequency of events.



H>0.5 => persistence;
H=0.5 => random;
H<0.5 => anti-persistence

# Electricity Demand in the U.S.

- The demand for electrical power has increased as a rate of 2% a year for the last two decades.
- Power generation has respond to this demand. However, the increase in generation is not as fast as the demand.
- The generation capability margin is decreasing.
- Similar problem in transmission capacity
- In this and many critical systems we are operating closer to the edge



# Risk from Power Tails in PDF

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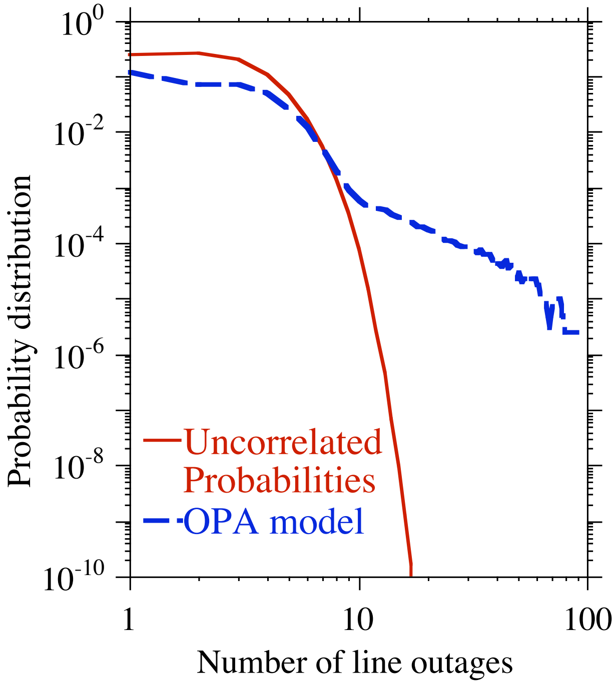
- To find the risk of failure (ie blackout), we need to know both the PDF (frequency, F(Size)) of the failure and its costs, C(Size).

  The cost C(Size) ~ to the size => so

  Risk = F(Size) C(Size)
- For example: the NERC data indicate a power law scaling of blackout frequency with blackout unserved energy as F(Size) ~ $S^{\alpha}$, where $\alpha$ ~ –1.2 to -1.6, => Risk ~ $S^{-0.2}$ to $S^{-0.6}$
- High cost of large blackouts - large blackouts dominate the risk
- If coupling makes tails heavier and reduces critical point this can have major implications for risk (ie large events dominate even more



# Examples of uses of Complex systems models

- OPA Risk analysis
- OPA design/planning analysis (reliability vs redundancy)
- CASCADE and OPA operational analysis (risk averse operation)

# A Dynamical Model (OPA)

Dynamically self adjusting to near nonlinear critical point

- The OPA model consists of:
  - Transmission network model with DC load flow and LP dispatch
  - Random initial disturbances and probabilistic cascading line outages and overloads
  - Underlying load growth and load variations
  - Engineering/economic responses to blackouts: upgrade lines involved in blackouts
  - Upgrade generation in response to increase demand
- The blackout dynamics are the result of opposing forces:
  - Increase demand (and/or economic pressure) => push toward critical point.
  - Engineering/Operational responses to failures

    Upgrades of the transmission system

    Investment in new power plants.

    } push away from critical point
  - Regulatory measures may set constraints in this process

# OPA model captures characteristics of system

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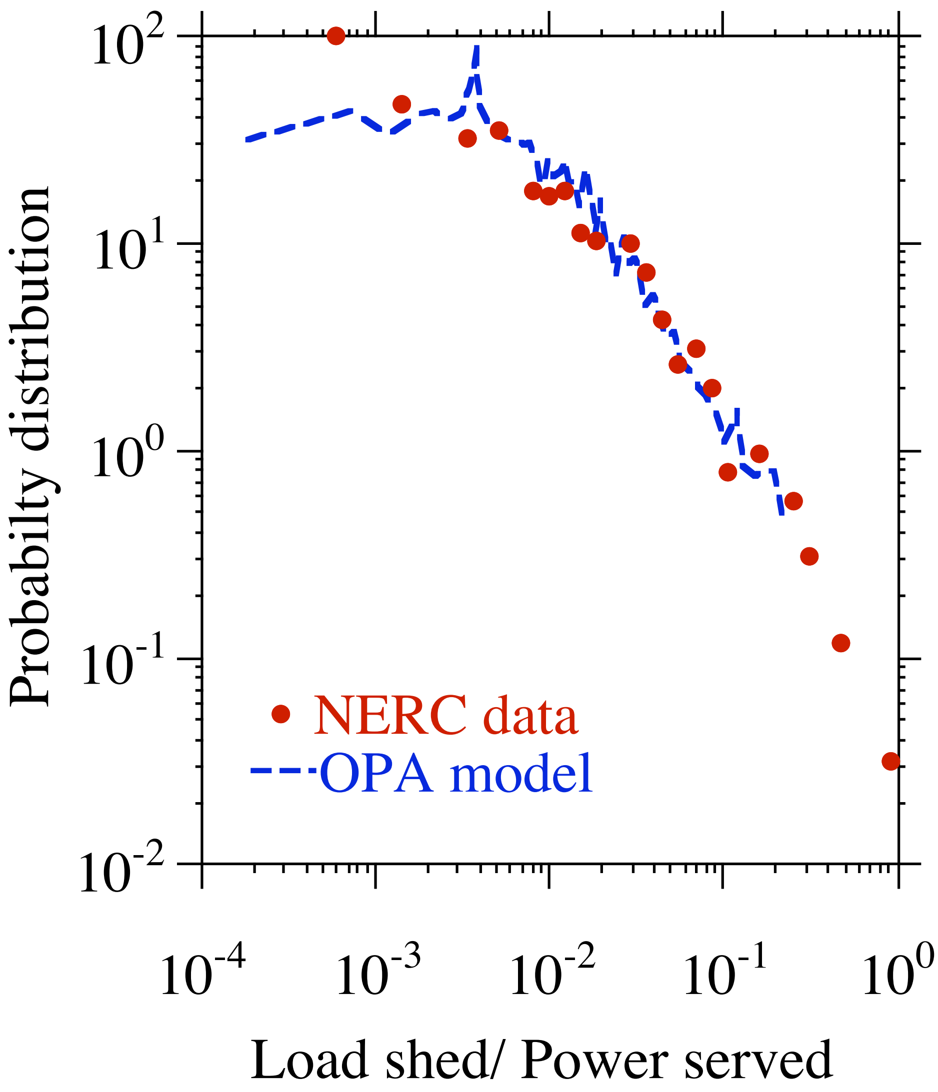
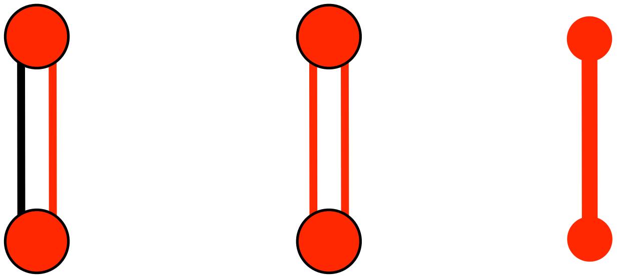
- Useful for investigating system state and relative risks

- Can now be used to explore mitigation and design schemes for their impact on risk



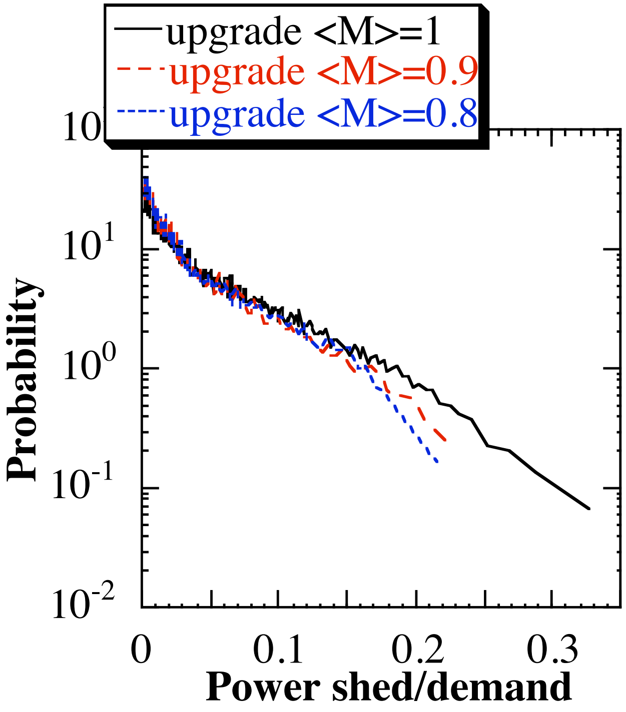
# Engineering: A tale of two methods for improving transmission network robustness

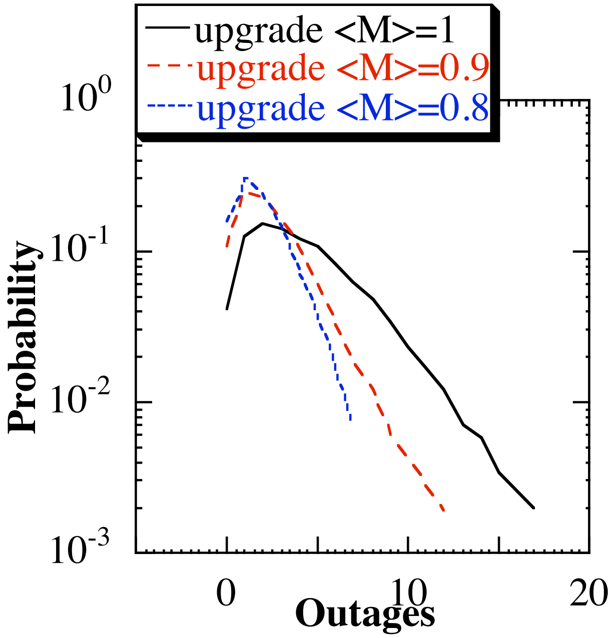
- Reliability (component not network)
  - Component reliability is the complement of component operating margin [$M_R$ vs $(1-M_R)$] in this implementation
  - This is point at which new failure probability grows
- Redundancy
  - True redundancy (not used until needed)(like the old NASA)
  - True doubling but half load carried by each line (danger => pressure and aging)
  - Capacity redundancy (fatter pipe)(danger=> pressure and random)



# Reliability/Margin

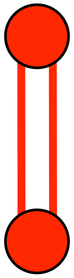
- Probability of larger blackouts/more outages increases as reliability increases (or margin decreases)
- Small outages can decrease

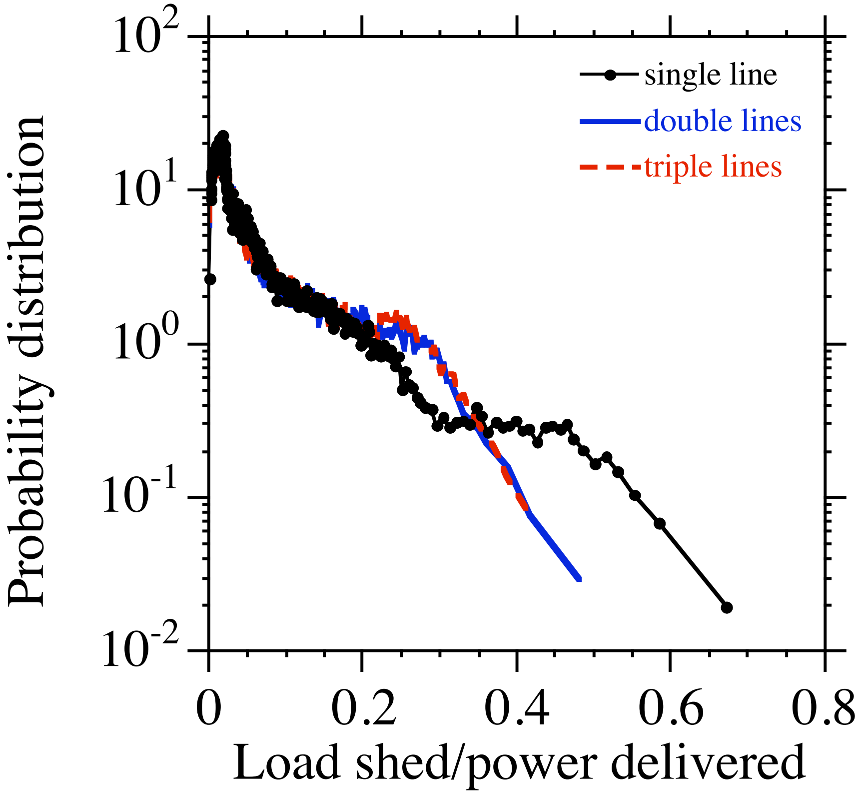




# Redundant lines can improve system robustness

- Redundant lines can reduce large blackouts
- Triple lines have little further effect (good thing!)
- Small blackouts are not increased (improved system reliability??)





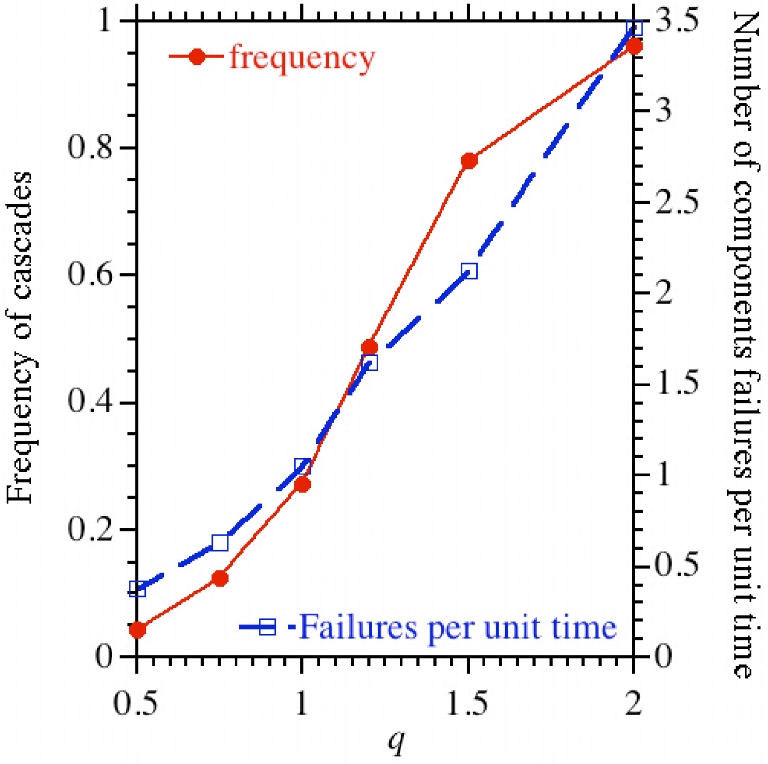
# Operations: Risk aversion mechanism within model

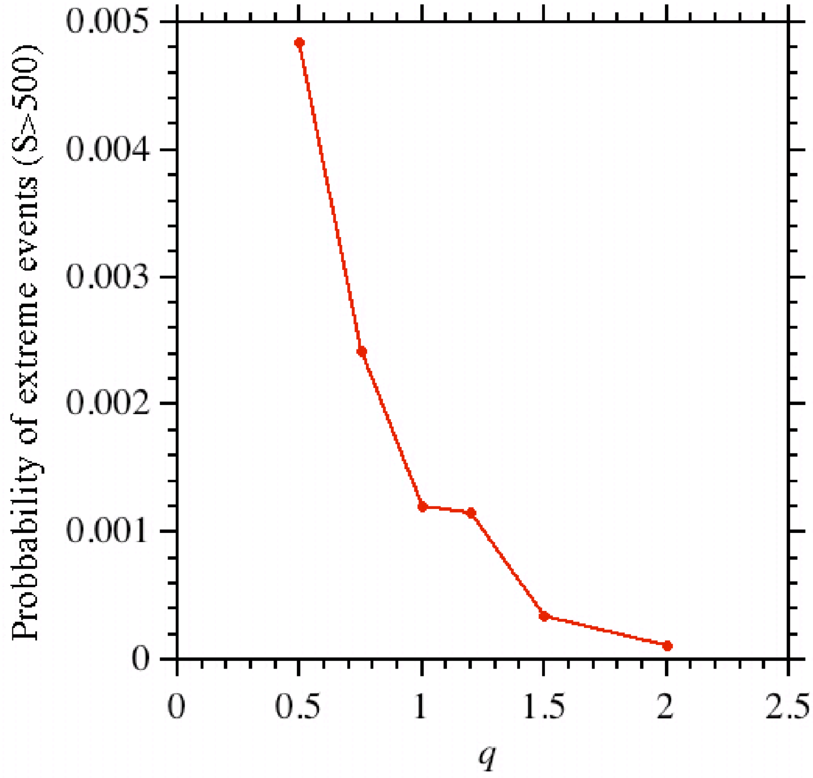
- Decisions on how to respond (on both short and long time scales) to an incident depend on the real and perceived risk from, and of, the incident
    - How bad was it, how bad is another likely to be, how probable is another incident
- As society gets "safer" risk of smaller incidents take higher priority (moving target)
    - This can skew our perception and response => can have important implications for real risks
    - This stems in part from our natural tendency to assign blame whenever something goes wrong
- Need model that captures characteristics of reaction to "risk" in order to include in decision making models
    - For coupling to infrastructure systems models
    - As a learning tool for improved response
- How much risk is acceptable?
- What are characteristics of a response to incidents with various levels of risk aversion?

# Risk aversion good or bad?

- Good?

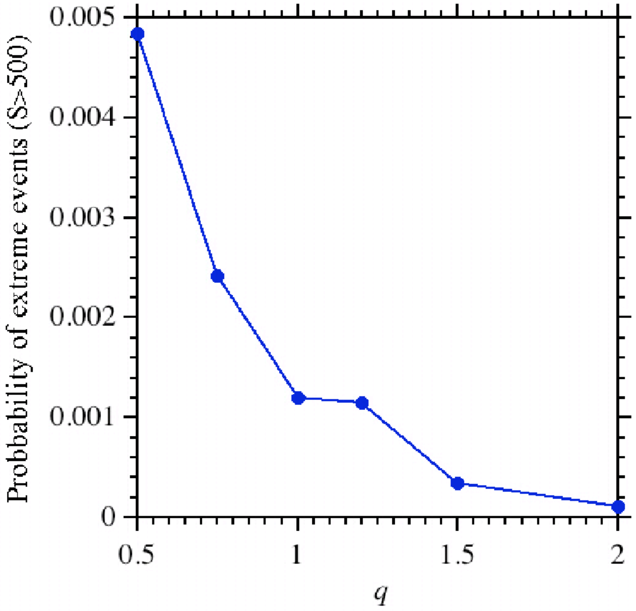
Bad!





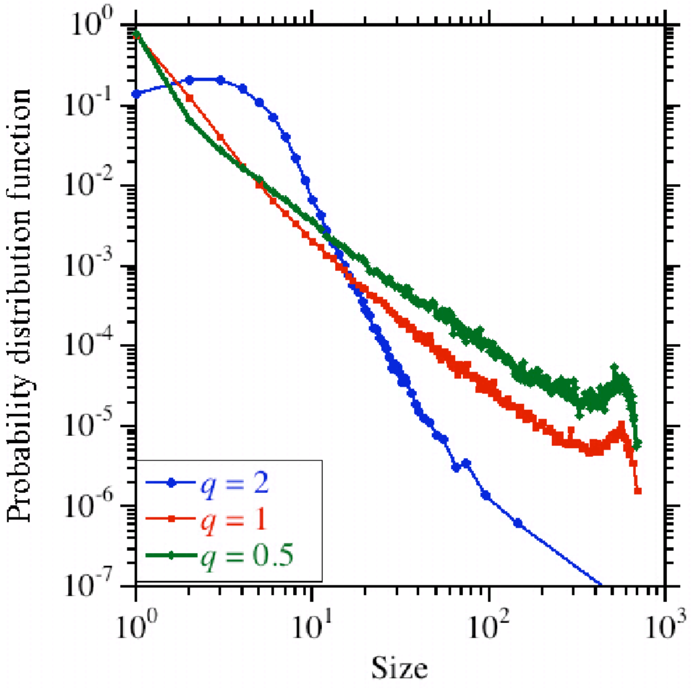
- Although the averaged number of failing components is reduced, the probability of an extreme event increases

# Large events dominate critical risk averse operation



Largest events become more probable with increased risk aversion

PDF of size changes from weaker exponential in risk taking case to heavier tail in risk averse operation



# Where are we going/what can we learn with these types of models

- Relative risk assessment
- Evaluation of mitigation and design schemes
- Metric for system state (non trivial for coupled systems)
- More agents

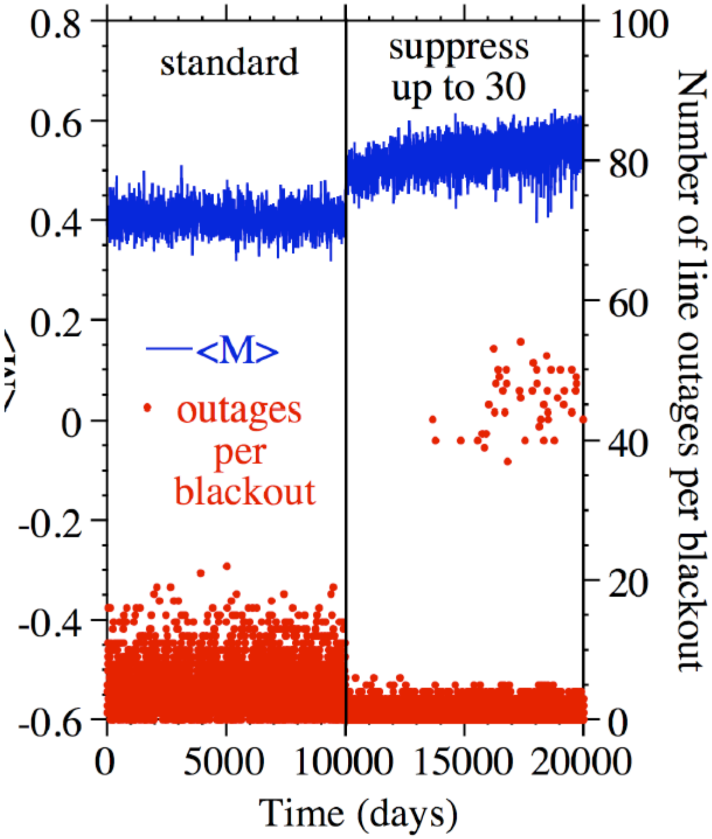
# Conclusions

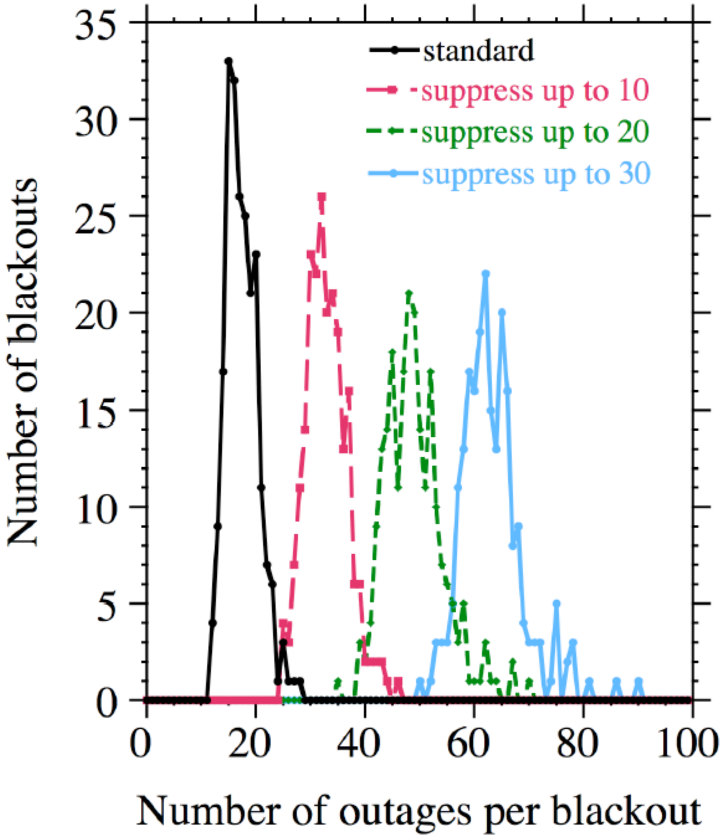
What are they? What are their characteristics? What can they do for you?

- There is evidence that many infrastructure systems such as power transmission systems, communication systems etc, behave as complex dynamical systems. Strong but fragile - house of cards
- Such dynamics imply the intrinsic unavoidability of cascading events in such a system when driven(operated) near its operational limits
  - Understanding and avoiding a particular failure mode does not necessarily reduce the risk of disruption. (Control and mitigation can have counter intuitive effects)
- The characteristic power law PDF implies that blackouts up to the size of the full system are possible and Gaussian statistics can not be used in risk analysis
- Agents can be very useful even in the simple CASCADE model for modeling the interaction between upgrade and replacement forces and including cost/risk of failure
- Risk averse behavior (or response to large events) can be very counter productive (even with learning/ forgetting modeled)
- Complex systems models (while not accurately representing the details) are very useful in design, characterization and control studies.

# Suppression of small failures can increase large failures

- Suppression of failures below size 30 in steady state increases the largest events





# Ramifications of Complex System Dynamics

- Large events are unavoidable
- Macroscopic dynamics relatively insensitive to microscopic dynamics (i.e. overall pattern is insensitive to individual changes...this is counter-intuitive)
- Dynamics over many time and space scales
  - long time correlations
- Trends in short time records can be unreliable

Attempts at control can have unintended consequences