Modeling cascading failure with branching processes

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MONITORING RELIABILITY

Blackouts typically become widespread by cascading failure

Cascading failure is a sequence of dependent failures of individual components that successively weakens the system

- Main current approaches are inhibiting start of cascade (N-1 criterion) and examining sample cascades

Cascading failure; large blackouts

- Rare, unanticipated, dependent events
  + huge number of possibilities and combinations
- Mechanisms include: overloads, oscillations, voltage collapse, transients, control or operator error, ...
- I will discuss ideas for bulk, statistical monitoring using a branching process model.

Estimating cascading blackout extent

- Here blackout extent = number of line outages
Can think of line outages as one diagnostic to track disturbances.

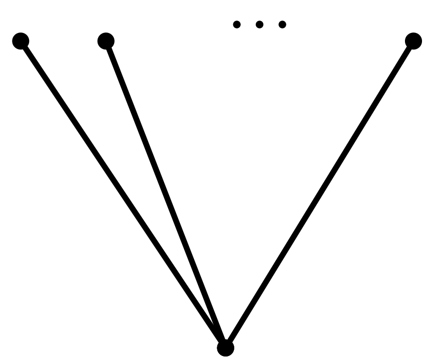
- Blackout extent is random,
so we seek the probability distribution of the total number of lines outaged

Galton-Watson branching process model for cascading failure

- New in risk analysis but applied to many other cascading processes
- Given the initial outages and propagation, can evaluate elegant formulas to compute distribution of the total number of outages

cascading = initial outages + propagation

Branching from one outage

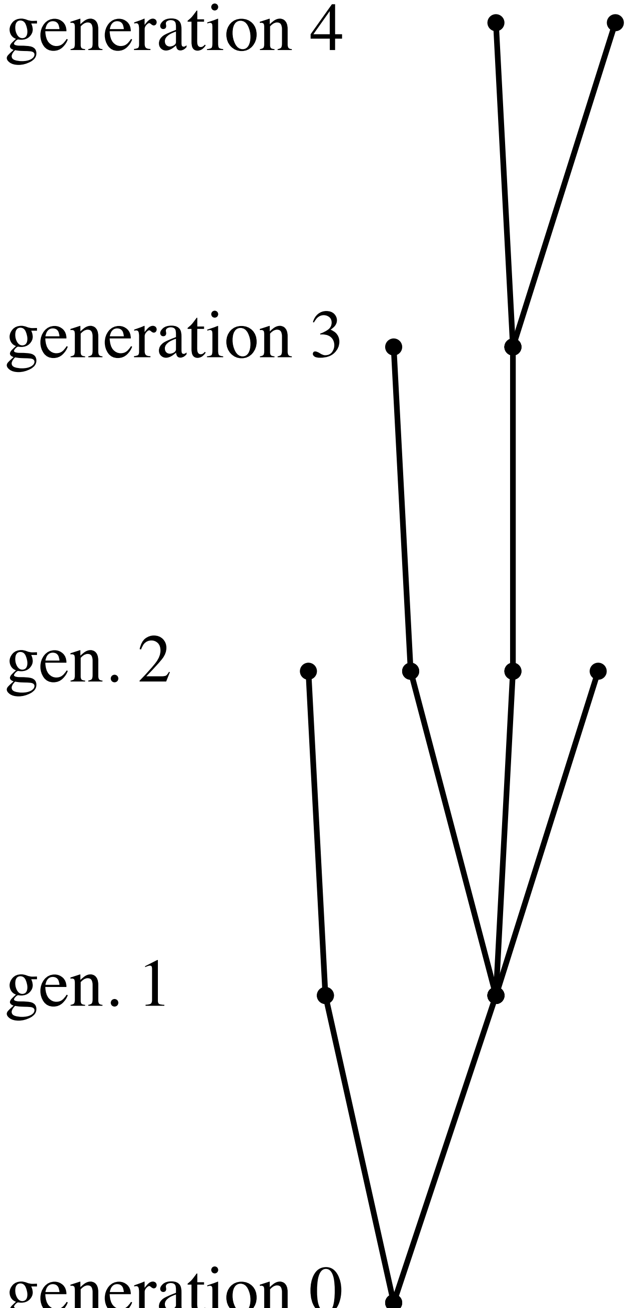


child outages

a parent outage

Random number of child outages according to offspring distribution Poisson(λ).

Mean number of children = λ



Branching Process

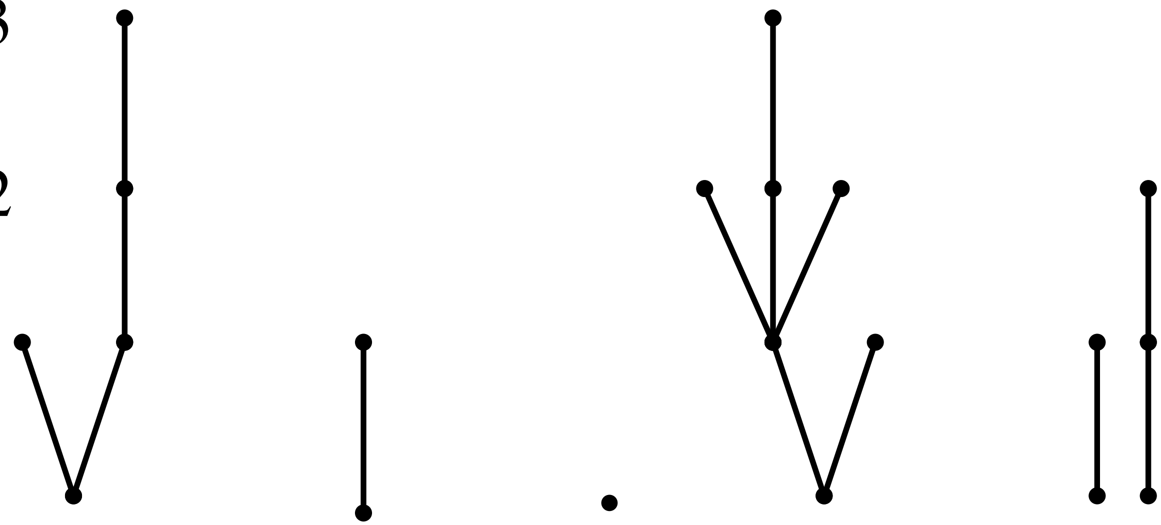
– each outage independently has random number of child outages in next generation

– λ_k = mean number of generation k children per parent outage

ESTIMATING PROPAGATION λ

propagation

sample of 5 cascades



generation 3	2	$\lambda_3 = 2/5$
generation 2	5	$\lambda_2 = 5/7$
gen. 1	7	$\lambda_1 = 7/6$
gen. 0	6	

number of outages in each generation

Branching process can compute extent of cascading

initial outages

propagation
$\lambda_1, \lambda_2, \lambda_3, \ldots$

Branching Process Calculation

Probability distribution of total number of outages

$$\vdots$$

Sample branching process calculation showing generating function of number of outages in each generation

$$e^{-\lambda_1+\lambda_1 e^{-\lambda_2+\lambda_2 e^{-\lambda_3+\lambda_3 e^{-\lambda_4+\lambda_4 s}}}}$$

generation 4

$$e^{-\lambda_1+\lambda_1 e^{-\lambda_2+\lambda_2 e^{-\lambda_3+\lambda_3 s}}}$$

generation 3

$$e^{-\lambda_1+\lambda_1 e^{-\lambda_2+\lambda_2 s}}$$

probabilities of numbers of outages in generation 2

$$e^{-\lambda_1+\lambda_1 s} = e^{-\lambda_1}(1 + \lambda_1 s + (\lambda_1{}^2/2)s^2 + (\lambda_1{}^3/6)s^3 + \ldots$$

s one outage in generation 0

Validating and applying branching processes to simulated cascading data

Objective: efficiently estimate pdf of total number of failures

- Run simulation to produce large amount of data (number of lines outaged in each generation)
- Estimate propagation and initial failures and use branching process to predict pdf
- Compare pdf with empirical pdf to validate branching process
- If validated, can use smaller amount of data to estimate pdf, especially the tail (estimate propagation and initial failures and then calculate pdf with branching process)

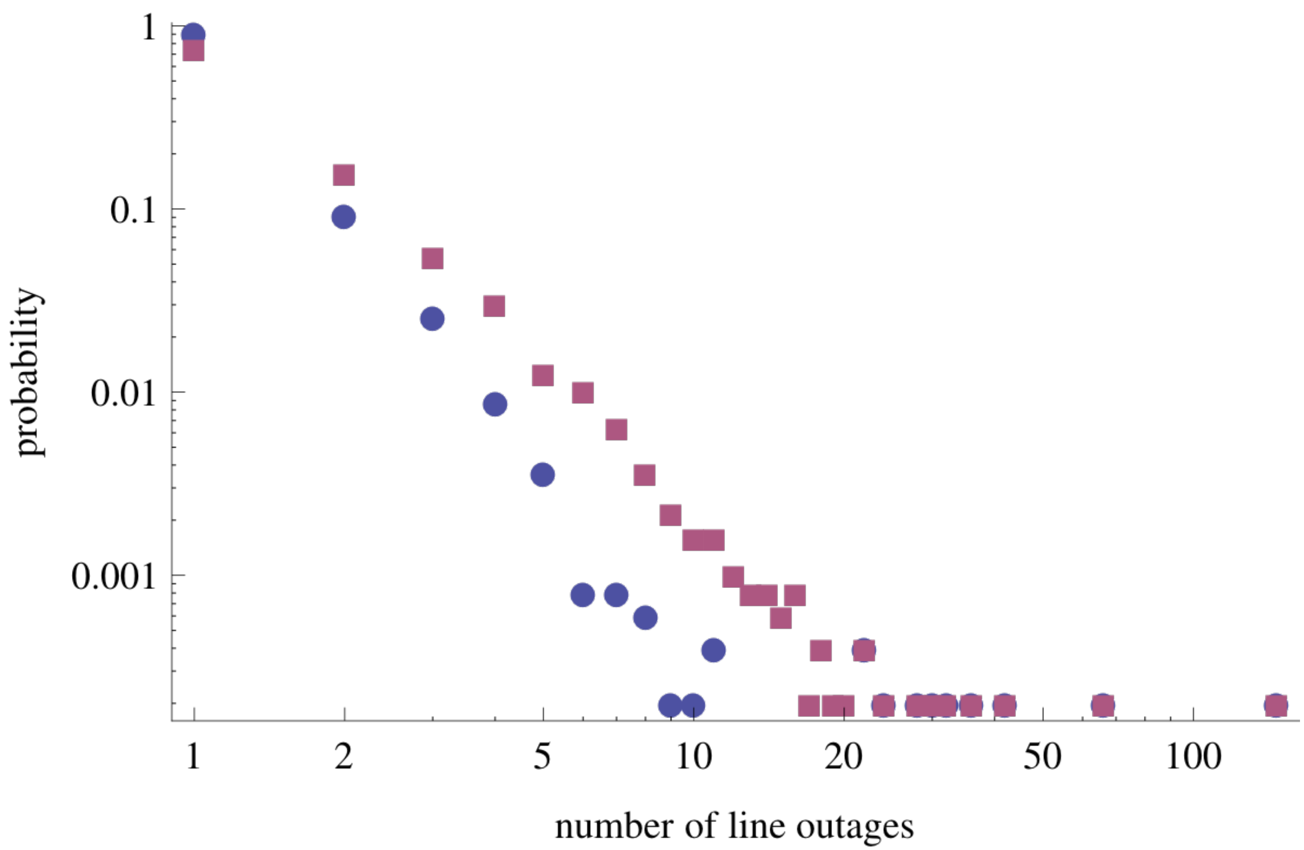
…see paper Dobson, Kim, Wierzbicki in Risk Analysis 2010

PROCESSING OBSERVED TRANSMISSION LINE OUTAGES

- Approximately 8600 automatic line outages over 10 years in utility data
- This is from data that must be reported to NERC
- Only look at time of outages
- Group outages into 5227 cascades and then into generations by their timing
- This gives
  6254 outages in generation 0,
  1143 outages in generation 1,
  434 outages in generation 2, etcetera…

Distributions of line outages

Probability

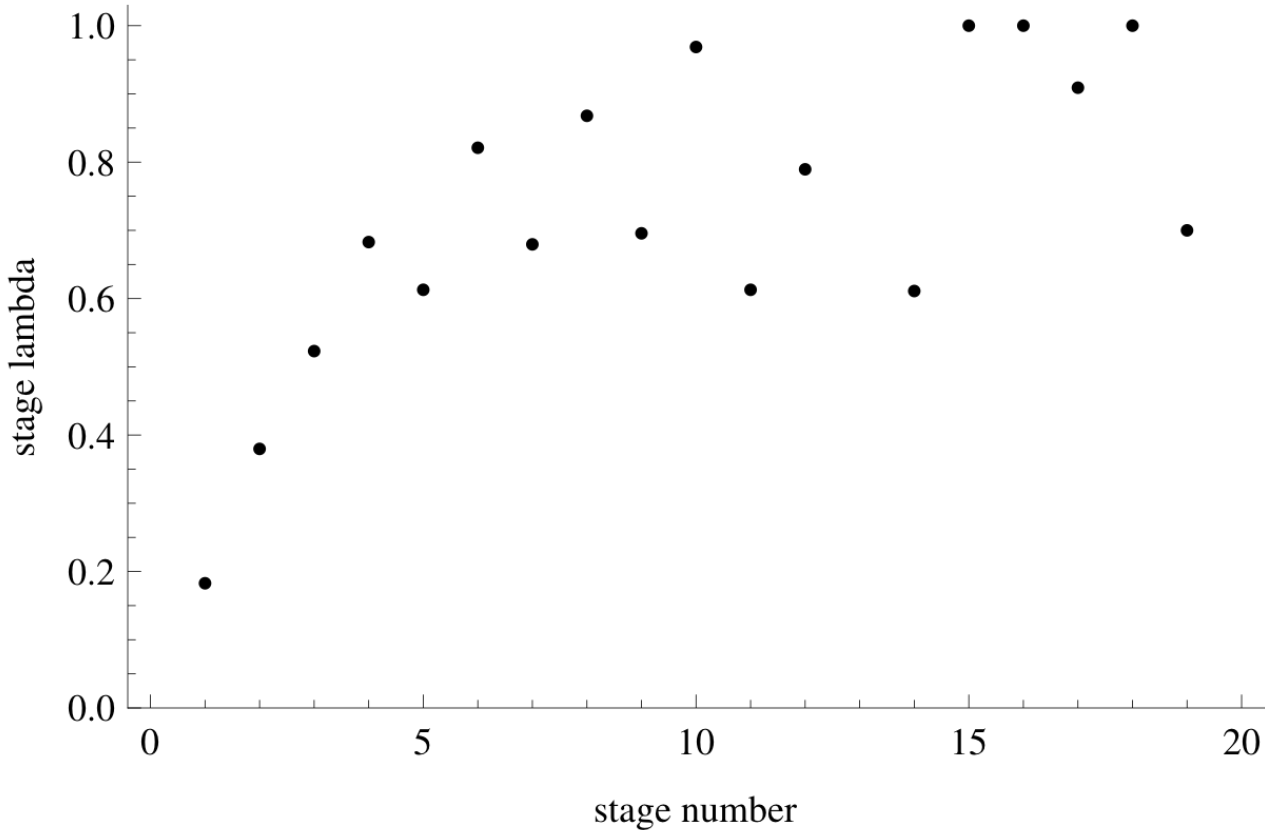


Number of line outages

Blue dots: initial line outages (generation 0) in each cascade
Red squares: total line outages in each cascade

The increasing propagation λ from data

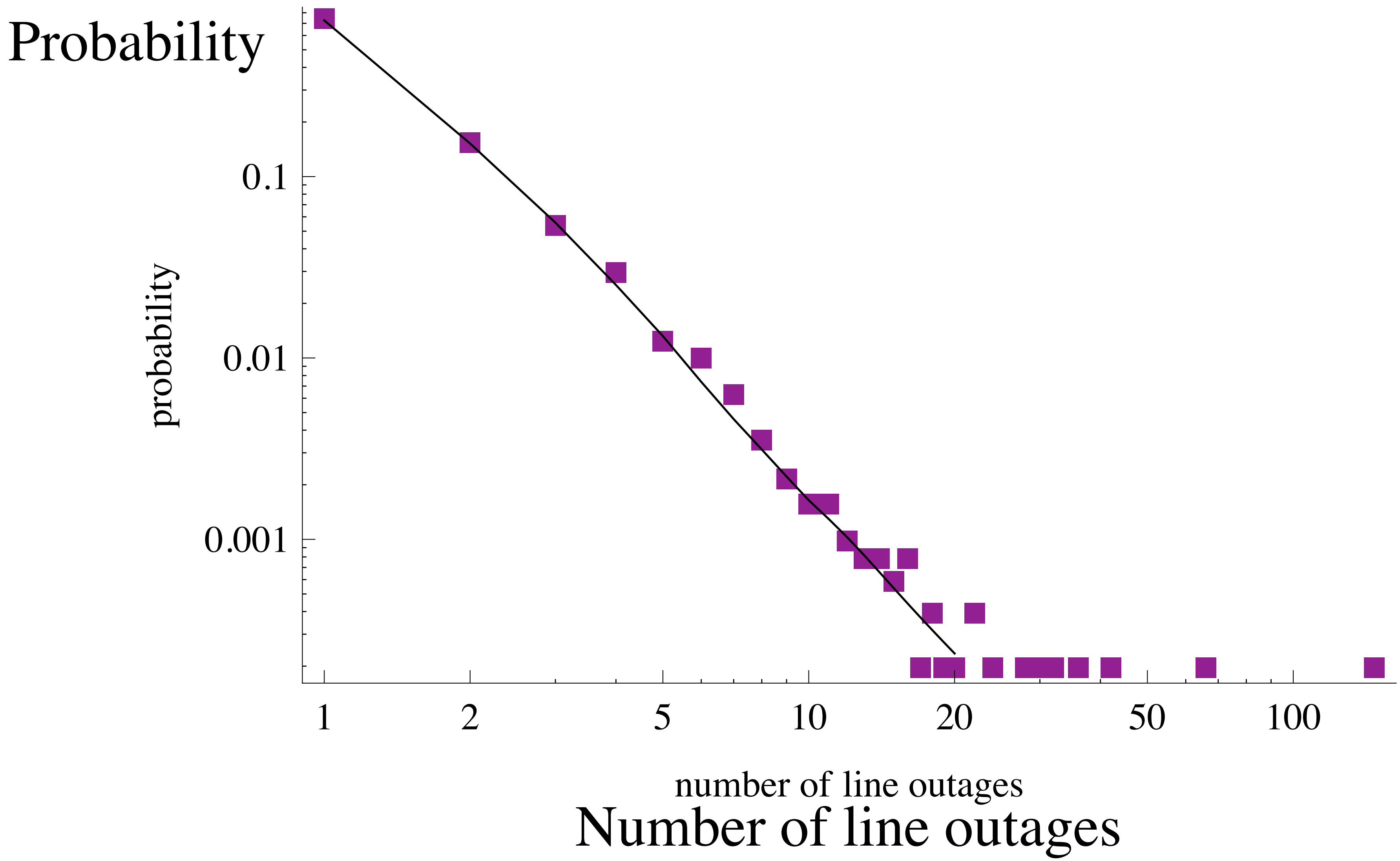
Propagation
λ
in each
generation



Generation number

$\lambda 1 = 0.18$, $\lambda 2 = 0.38$, $\lambda 3 = 0.52$, $\lambda 4 = 0.68$, $\lambda 5+ = 0.70$

Distributions of outages; testing branching model



Purple squares: Observed data

Line: Predicted by branching process with the varying λ

Illustrative application: Large blackout sensitivity to propagation

$\lambda_1 = 0.18,\ \lambda_2 = 0.38,\ \lambda_3 = 0.52,\ \lambda_4 = 0.68, \lambda_{5+} = 0.70$

Probability at least 20 lines out = 0.0024

- decrease λ_1 by 0.1 reduces Probability by 0.0014
- decrease λ_2 by 0.1 reduces Probability by 0.0007
- decrease λ_3 by 0.1 reduces Probability by 0.0005
- decrease λ_4 by 0.1 reduces Probability by 0.0004

More effective to reduce propagation at early generations

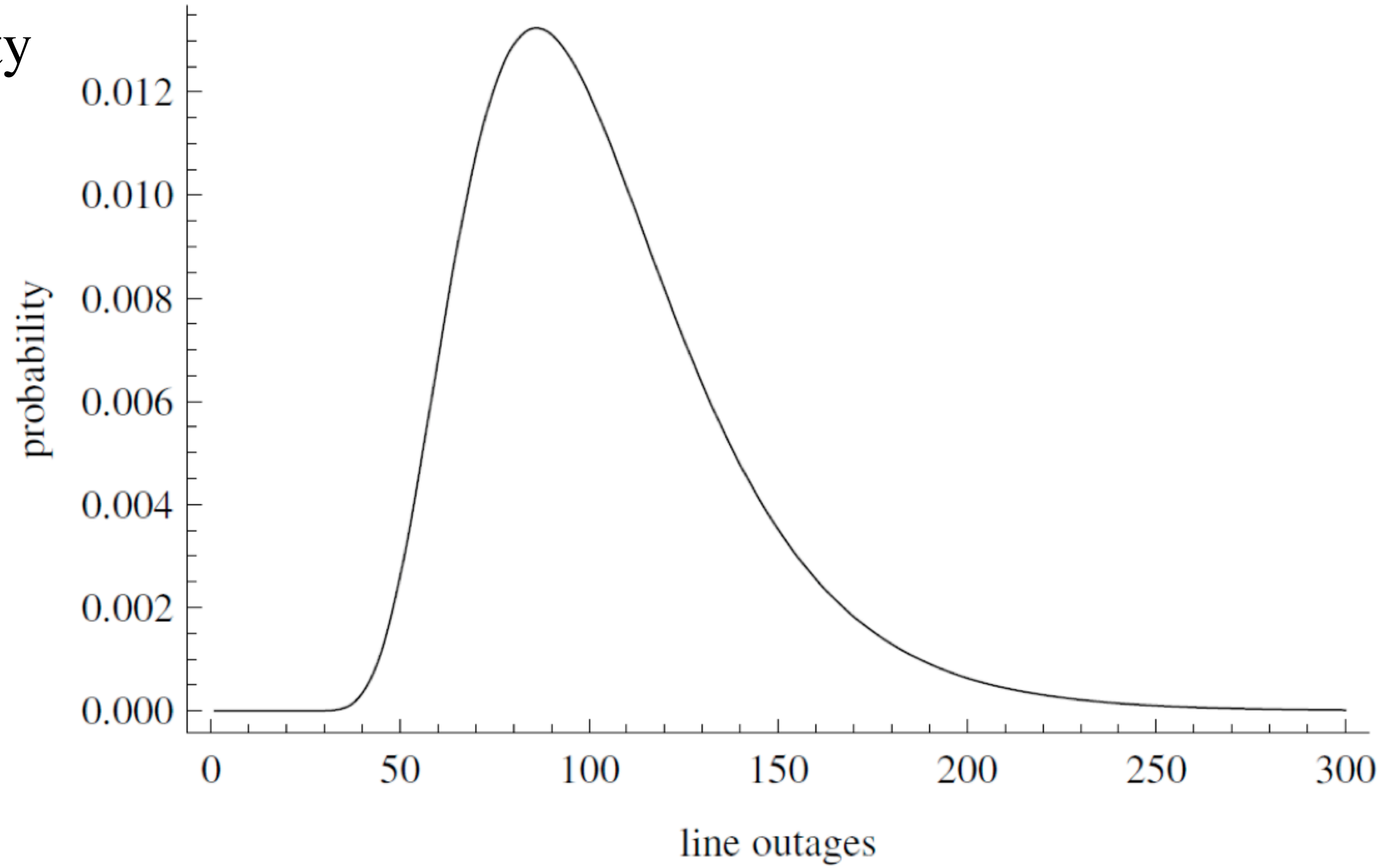
Illustrative application: cascading due to a large initial disturbance

What is the risk of an initial disturbance propagating?

Do lights go out in Santa Fe if there is a quake in Bay Area?

- Initial disturbance could be due to earthquake, attack, …
- Need better propagation data, but do initial calculation
- Assumptions:
  - 26 lines initially outaged
  - use propagation observed in utility data
  - estimate distribution of total number of lines outaged with branching process

Probability



Number of line outages

Probability distribution of total number of line outages assuming 26 initial line outages

Conclusions

- Branching process model of propagating line outages consistent with the utility data
- Can estimate cascading blackout extent from given initial outages based on observed data (conventional risk analysis can estimate initial outages)
- Data used is in required reports to NERC
- Can quickly estimate pdf tails from simulated cascading data
- λ is a metric of propagation and resilience
- New capability and practical method to quantify effect of cascading based on data

Next steps for monitoring cascading

- Statistical analysis of number of observations
- More testing; get more data
- Mitigate propagation as well as initial outages?
- challenge: Extend to load shed (blackout size)
- Cascading between infrastructures

for more details, google Ian Dobson papers