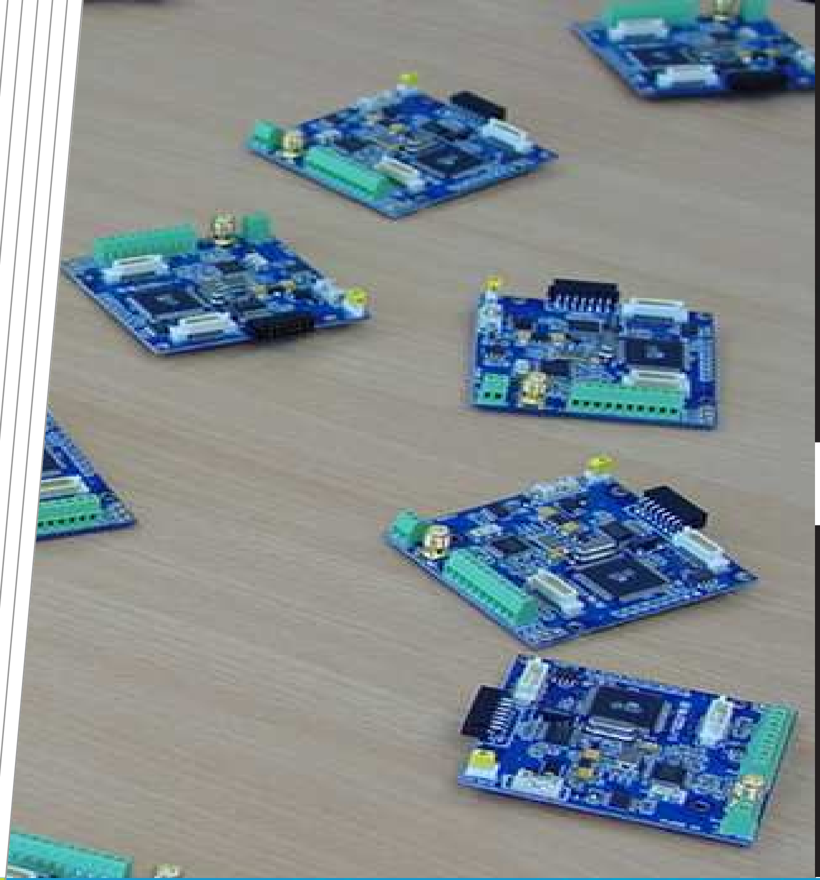

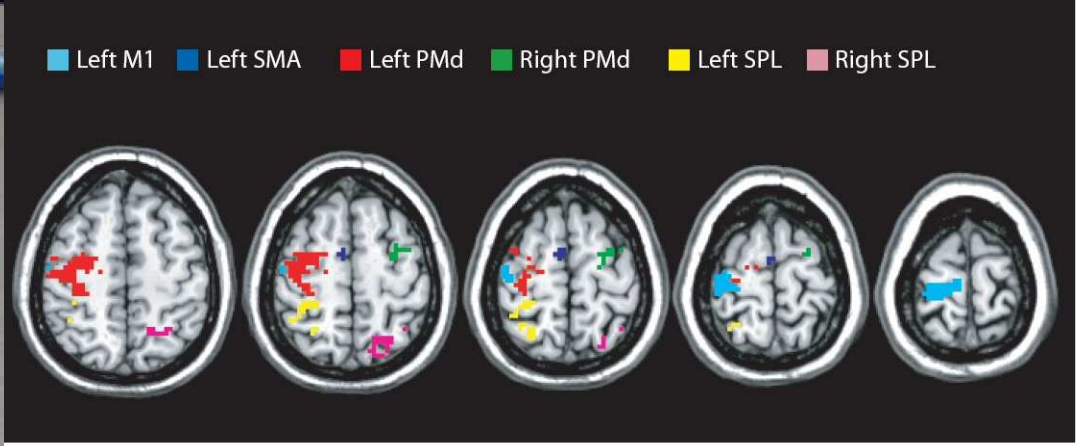

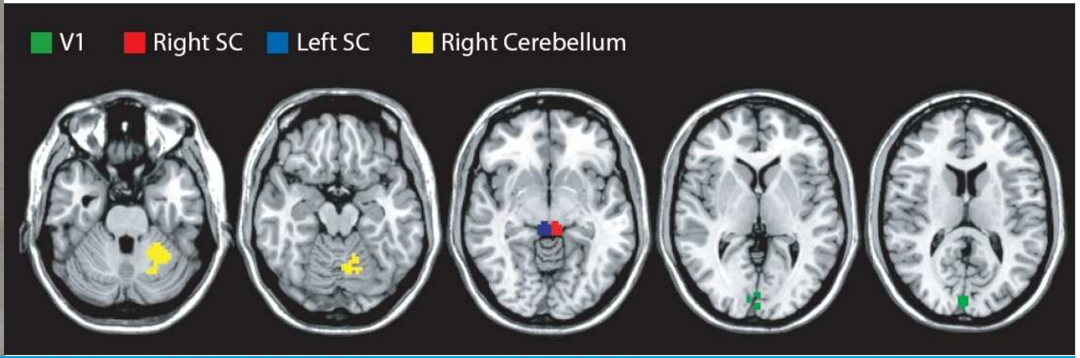

The information dynamics of cascading failures in energy networks

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European Conf on Complex Systems, Coventry, UK, Sept 2009

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Overview

- Small failures in power grids can lead to large cascading failures that cause large and sustained power blackouts.
- There is an obvious need to understand and avoid these events

- Q: How is information intrinsically processed during these events?
  - Key question because network is technically *computing* it’s new stable state (attractor) during these events.
  - Understanding the computation can help understand the dynamics
- We look at information storage and transfer as a function of network capacity.
  - Also examine relationship between local topological structure and information dynamics,
  - And relationships in time between information transfer and cascade spreading.

Cascading failure events

- Energy, comms, transport, financial networks are all subject to cascading failure events:
  - local failures that trigger avalanche mechanisms with large effects over the whole network.
- Our focus is energy networks:
  - Usage has increased faster than investment
  - More frequent outages

Theoretical view

- Cascading failures are akin to studies of damage spreading / perturbation avalanches
  - Unanswered questions over the relationship of these events to the concept of information transfer.
    - Is information transfer related to the size of avalanche (e.g. Langton, 1990) or the uncertainty in the size of the avalanche (e.g. Ramo et al, 2007) ?
    - How is information transfer affected by network structure?

- Mitchell (2009): “The phenomena of cascading failures emphasizes the need to understand information spreading and how it is affected by network structure.”

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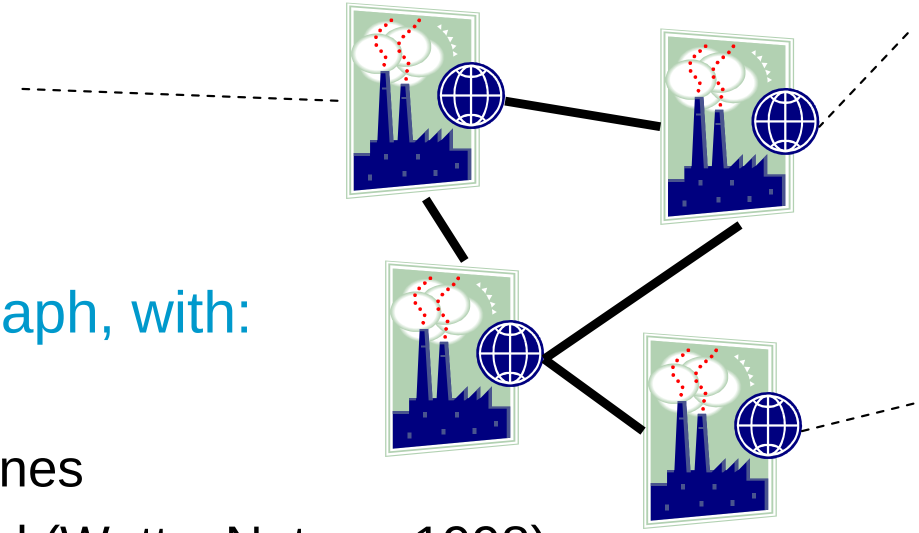
Cascading failures model



From Crucitti et al, PRE, 2004:

- Network is weighted undirected graph, with:
    - Nodes representing substations
    - Edges representing transmission lines
    - Topology of US Western power grid (Watts, Nature, 1998)
- Each edge *ij* has an efficiency $e_{ij}(n) \in (0,1]$, with $e_{ij}(0) = 1$
    - $e_{ij}(n)$ = inverse edge weight
    - Efficiency $\varepsilon_{ij}(n)$ of most efficient path from *i* to *j* is inverse of shortest path length.
- Each node *i* has a load $L_i(n)$ = betweeness centrality of node *i* at time *n*.
- Each node has a capacity $C_i = \alpha L_i(0)$, with $\alpha \geq 1$ the network tolerance.

Cascading failures model – dynamics

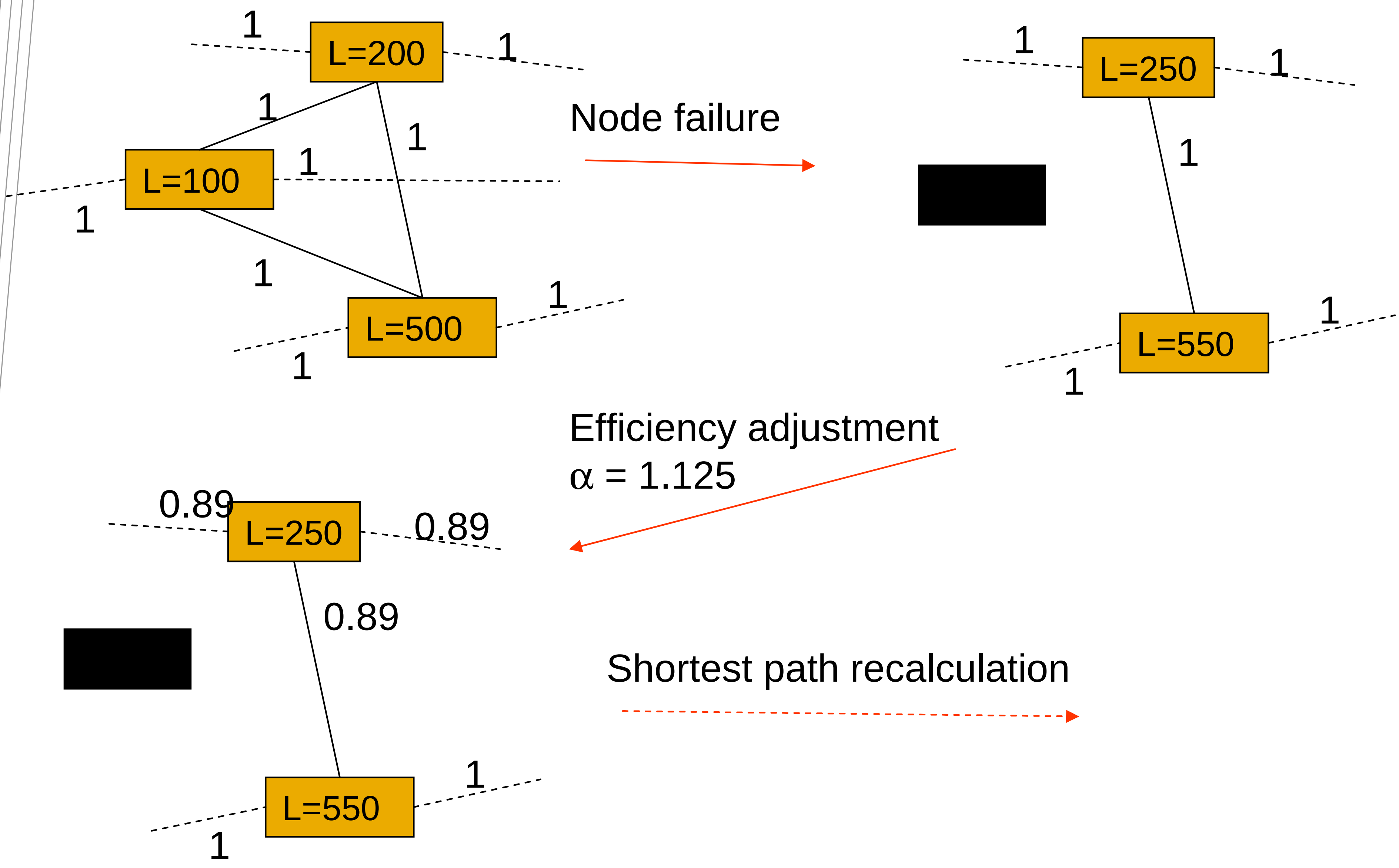
- Edge efficiencies become sub-optimal if (altering original model) either end-point is operating above capacity:

$$e_{ij}(n+1) = \begin{cases} e_{ij}(0)\ \min\left(\frac{C_i}{L_i(n)}, \frac{C_j}{L_j(n)}\right) & \text{if } L_i(n) > C_i \text{ or } L_j(n) > C_j, \\ e_{ij}(0) & \text{otherwise} . \end{cases}$$

- Changes in edge efficiencies → changes in most efficient paths → changes in load distribution → changes in edge efficiencies …
- Initial network state is stable, but removal of a node (simulating initial substation failure) triggers a dynamical process where loads are redistributed.
    - Could cause other nodes to overload, etc, leading to a cascading failure.
    - Stable state may be oscillatory.
- Performance is tracked using average pairwise efficiency:

$$E(n) = \langle \epsilon_{ij}(n) \rangle$$

Cascading failures model – example

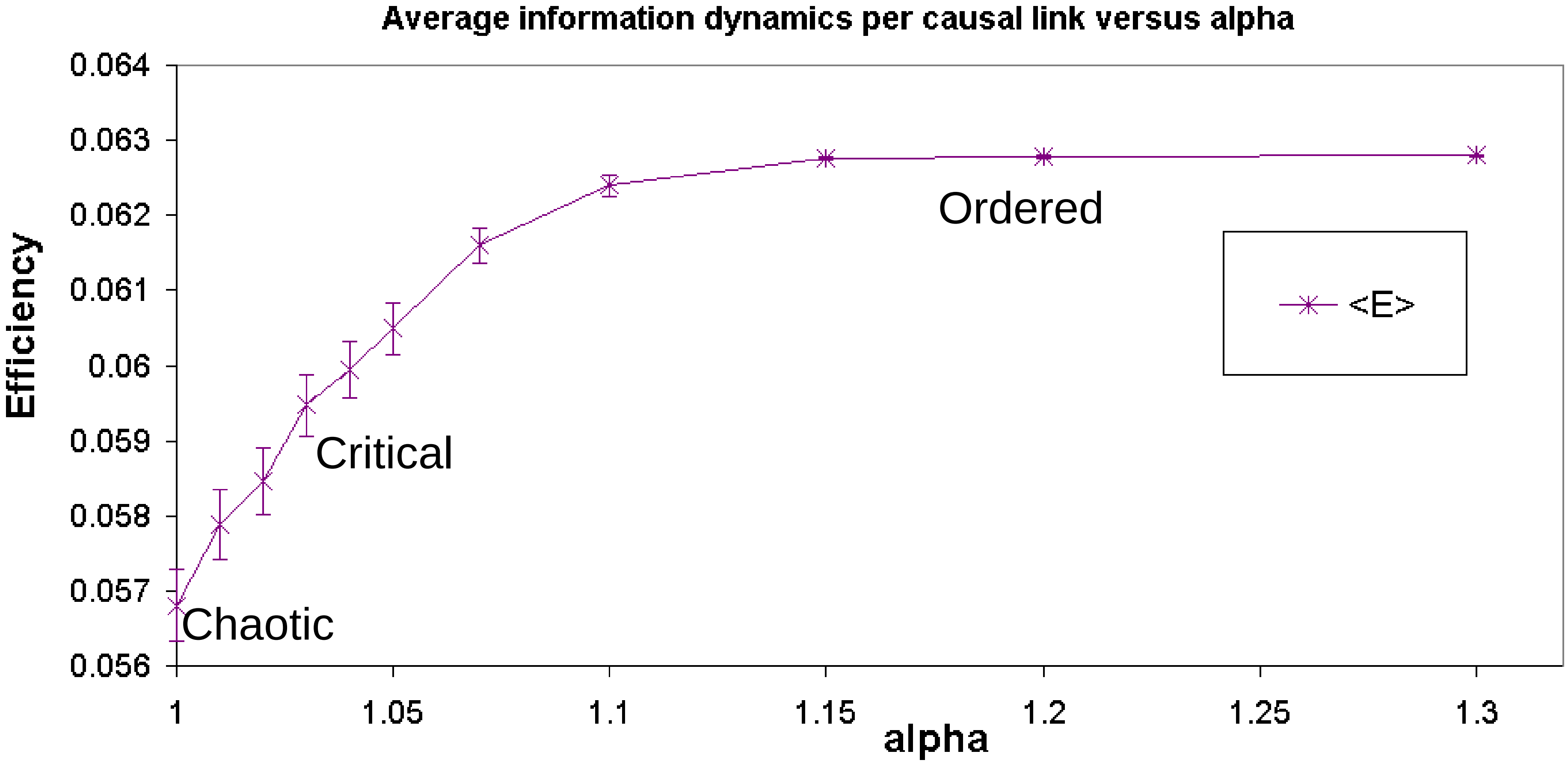


Node failure

Efficiency adjustment
$\alpha = 1.125$

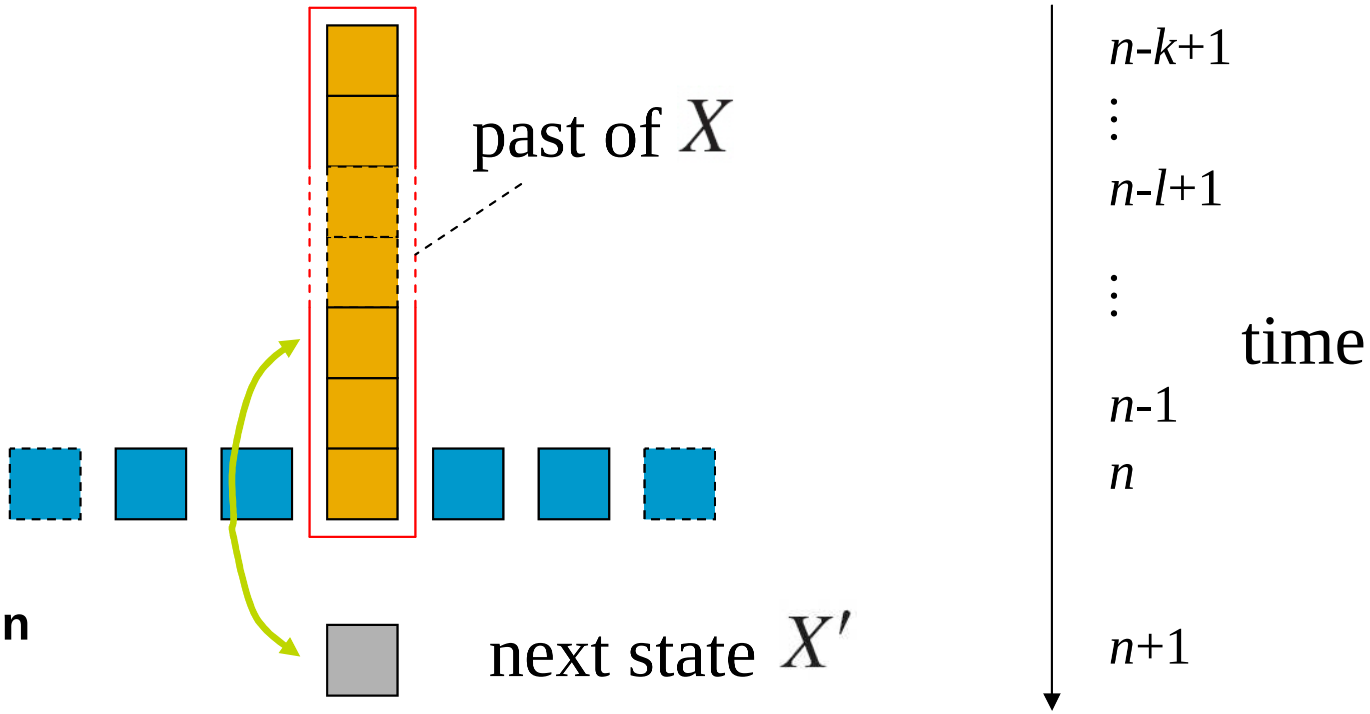
Shortest path recalculation

Phase transition with excess capacity alpha



Active information storage

$$A_X = I(X^{(k)}; X) =< i(x_n^{(k)}; x_{n+1}) >$$



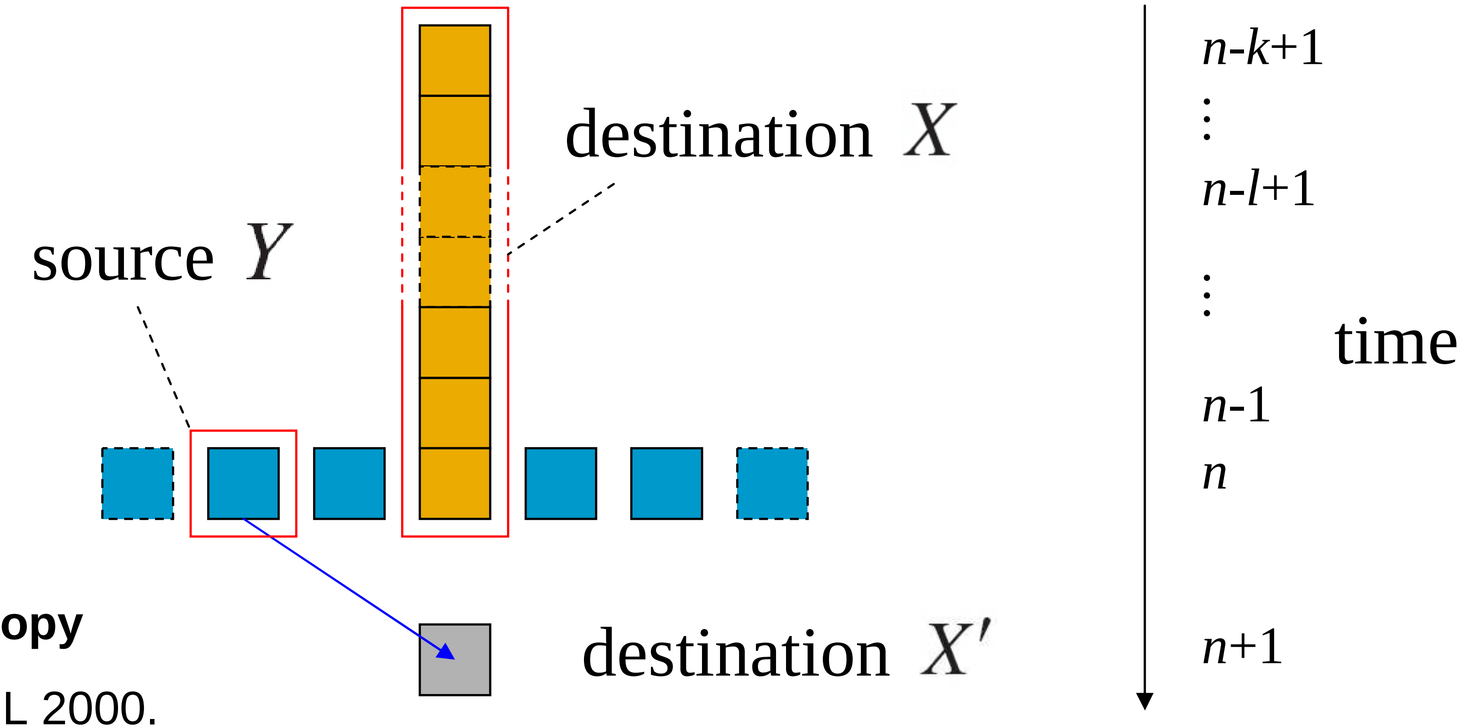
Active information storage

Lizier et al, 2007.

Active info storage = stored information that is currently in use

Information transfer

$$T_{Y\to X'} = I(Y;X'|X) = H(X'|X) - H(X'|X,Y)$$

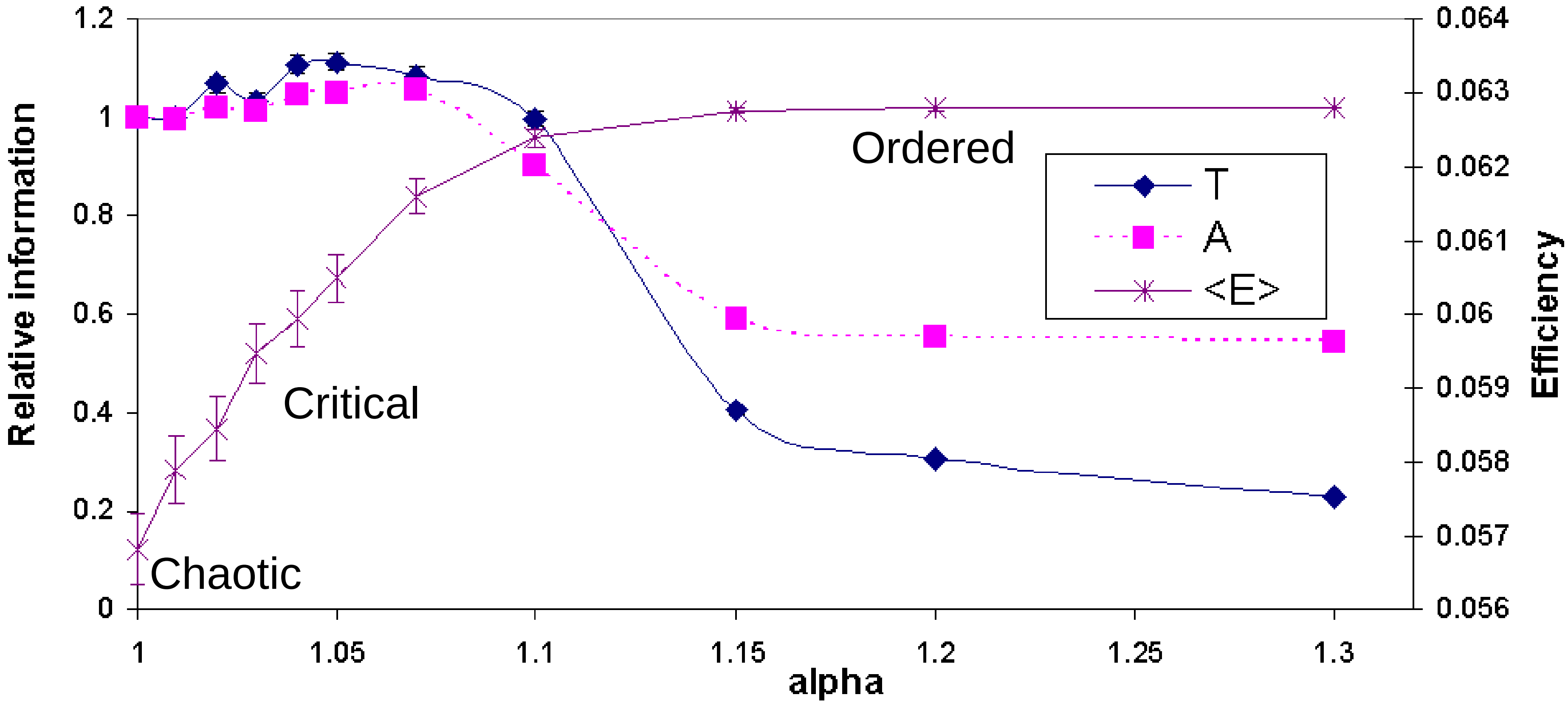


Transfer entropy

Schreiber, PRL 2000.

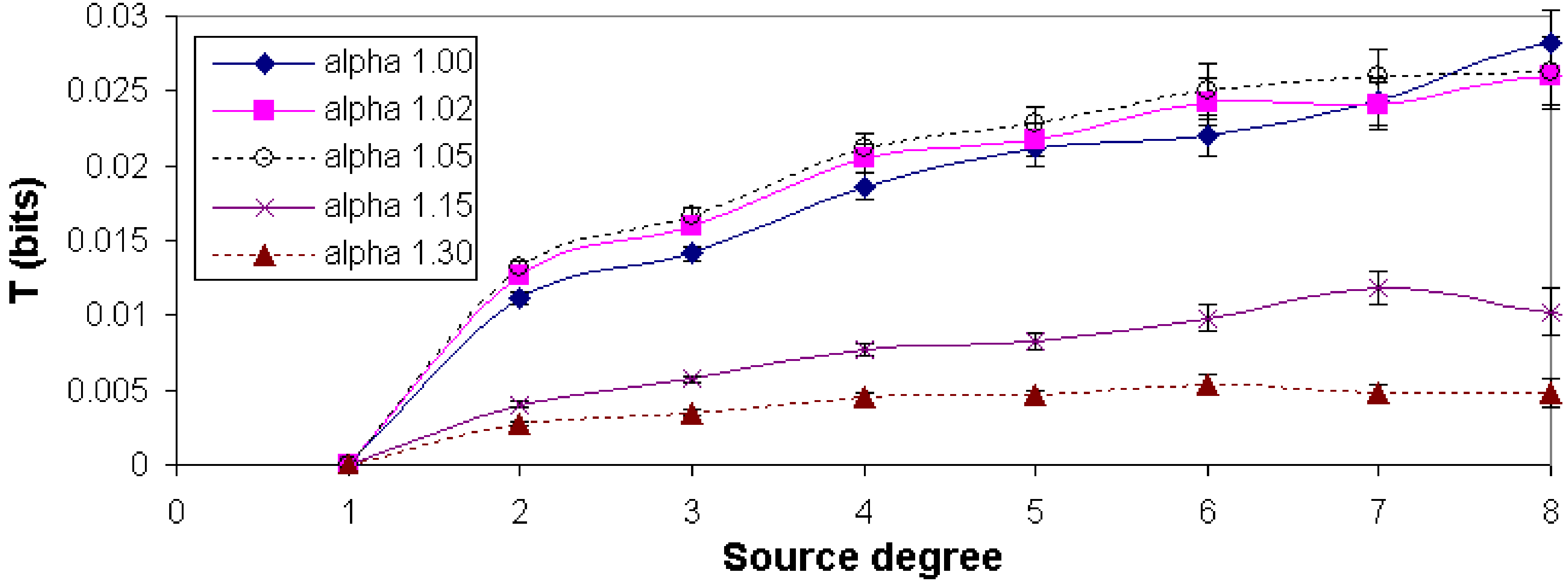
$$\begin{aligned} T_{Y\to X} &= < t_{Y\to X}(n) > \\ &= < i(y_n; x_{n+1}|x_n^{(k)}) > \end{aligned}$$

Results: 1.Info dynamics through phase transition



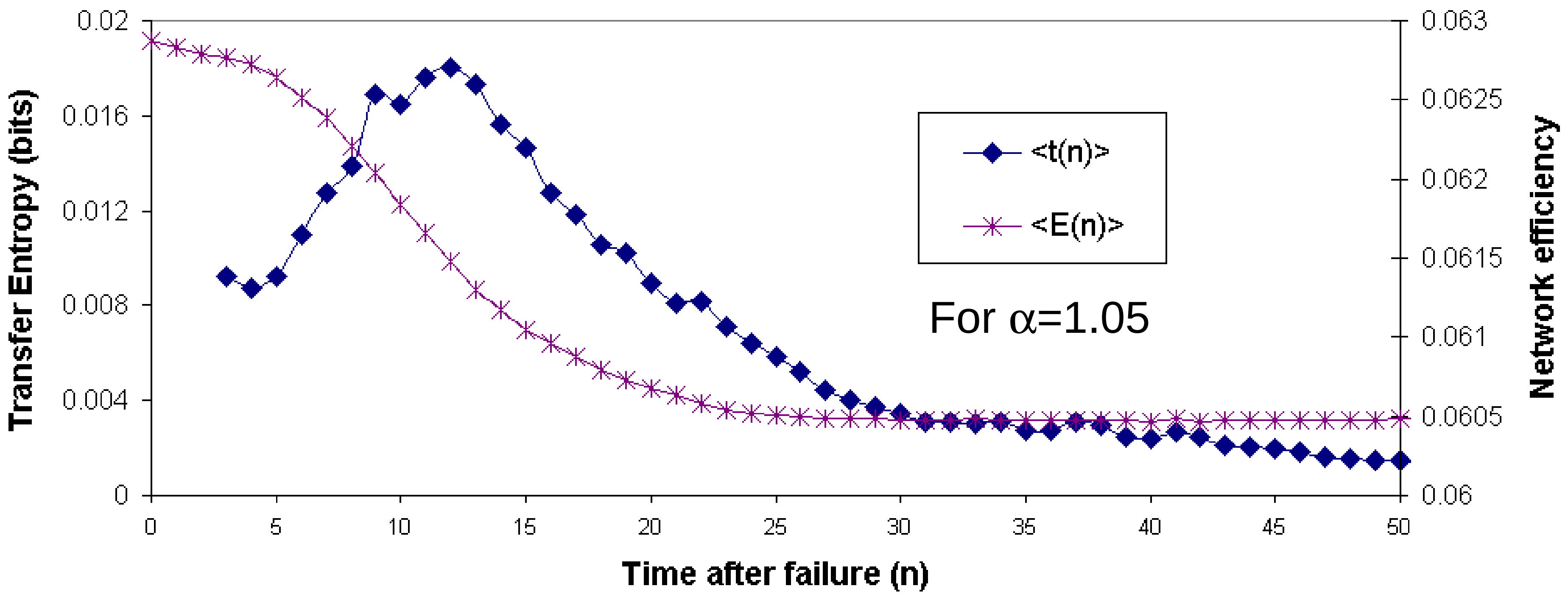
- Both *computational capabilities* are maximised near the phase transition in efficiency.
- They change sharply well before efficiency – could be useful early indicators of critical loading.

Results: 2.Info transfer correlated with source degree



- In vicinity of phase transition, info transfer is correlated with degree of source node.
  - More neighbours = more diversity => more info to transfer
- Also a small correlation between info transfer and initial load (b/w centrality) of source node.

Results: 3. Info transfer evolution in time



- Peak in transfer lags the failure event, but coincides with steepest drop in efficiency.
- Large correlation b/w transfer and change in efficiency.
- No correlation to local loads – this seems to be an emergent effect.

Conclusion

- Characterised information dynamics of the intrinsic computation during cascading failures:
  - Application-independent information theory characterises phase transition also.
  - Info measures may be useful early indicators of critical loading.
  - Encouragement to further investigate local measures.
- Future work
  - Alter model to more realistically reflect power loads
  - Effect of altering topology of power grid, especially including mini-grids
  - Can our knowledge be used to control cascade events?
  - Focus on local info dynamics, e.g. during control of cascades

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This trip was supported by funding from CSIRO's Energy Transformed flagship via the Smart Grids and Secure Grids projects.

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Thank you