Organizational Networks: Information Exchange and Robustness

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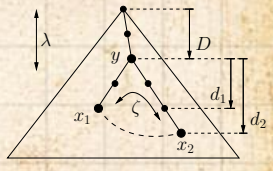
Complex Networks | @networksvox
CSYS/MATH 303, Spring, 2019

Prof. Peter Dodds | @peterdodds

Dept. of Mathematics & Statistics | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont



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- Toyota
- Ambiguous problems
- Models of organizations:

Modelification
- Goals
- Model
- Testing
- Results

Conclusion

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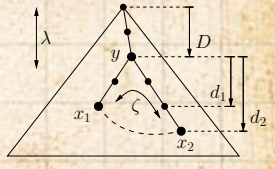

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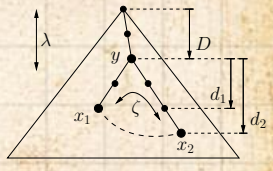

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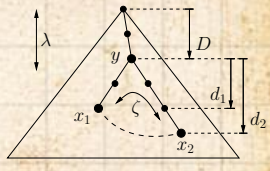

THE SUN
THE GOLDEN AGE OF REDUCTIONISM
THE MANIFESTO
THE WEIL OF SCALES
THE LAWS OF DECAYING POWER
THE UNEXPECTED TRANSFIGURATION
MINISTRY OF RANDOM WALKS
THE RICH GET RICHER
THE DREAM OF EFFICIENT LANGUAGE
THE LAW OF DIGITS FIRST
THE SURPRISE OF BEING ROBUST YET FRAGILE
THE MISREADING OF THE BANK OF ENGLAND
THE MANY TAILS OF MANY TAILS
THE MEASURING
THE DATA POOR
THE POURING DATA
THE CHARMS OF THE MANY WRONG PATHS
THE KNOWLEDGE OF DEAD MINKS
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THE EMERGENCE OF STRUCTURE
THE EMERGENCE OF DESTRUCTION
THE EMERGENCE OF THINKING
It was the best of times,
THE EMERGENCE OF STORIES
THE MECHANICS OF STATISTICAL
THE THRESHOLDS OF PERCOLATION
THE NETWORKS COMPLEX
THE ELEMENTS OF WEBS
THE BIRDS OF A FEATHER
THE BIRDS OF NOT A FEATHER
"I am the Magnetic of the Sea."
THE ARK OF THE RANDOM NETWORK
THE STRANGENESS OF FRIENDS
THE SMALLNESS OF WORLDS
THE THEORY OF SIX DEGREES
THE NETWORKS FREE OF SCALE
CLASSIFIED PHOENIX BIO HAZARD
THE CONTAGION
THE CONFUSION OF CONTAGIONS
THE DISEASE OF RANDOM MIXING
THE UNENDING PANDEMICS
THE THRESHOLDS OF THE MIND
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THE END
THE LIMITS OF ORGANIZATIONS

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Overview

The basic idea/problem/motivation/history:

- Organizations as information exchange entities.

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Ambiguous problems
Models of organizations:
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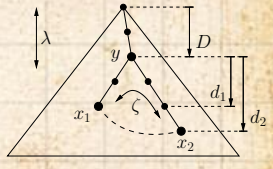

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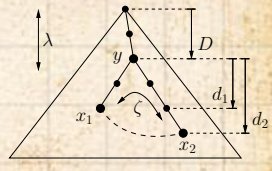

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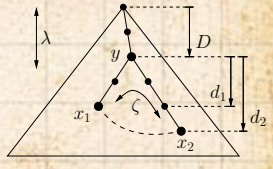

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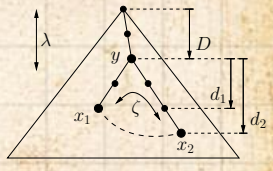

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A model of organizational networks:

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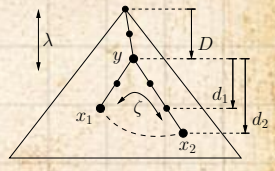

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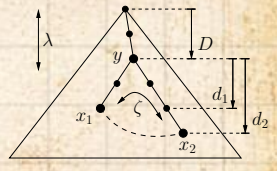

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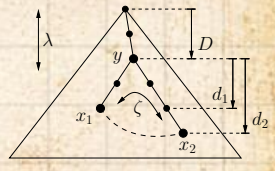

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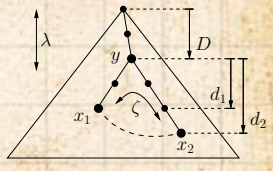

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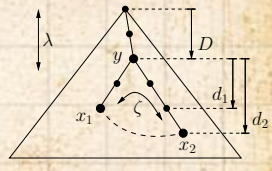

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Aisin (eye-sheen), maker of brake valve parts for Toyota, burns to ground. [4]

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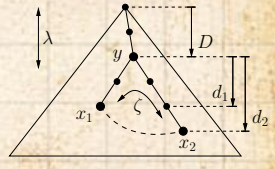

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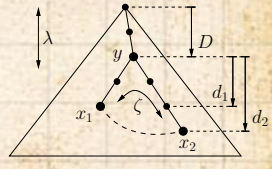

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- 4 hours supply (“just in time”).
- 14,000 cars per day $\rightarrow$ 0 cars per day.

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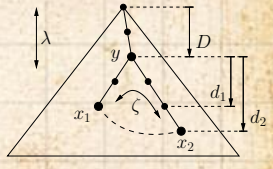

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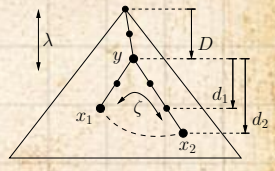

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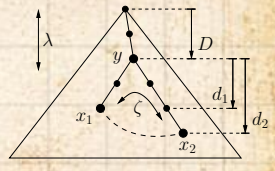

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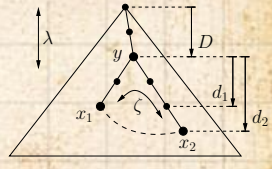

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- Case study performed by Nishiguchi and Beaudet [4]
  “Fractal Design: Self-organizing Links in Supply Chain”
  in “Knowledge Creation: A New Source of Value”

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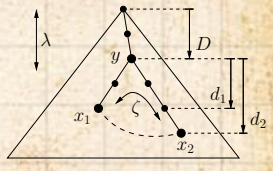
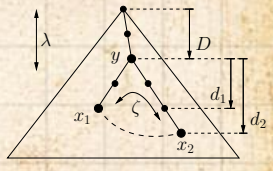


February, 1997:

Some details:

- 36 suppliers, 150 subcontractors



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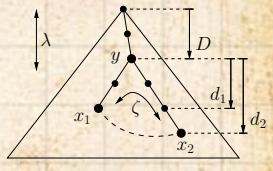
- 50 supply lines



February, 1997:

Some details:

- 36 suppliers, 150 subcontractors
- 50 supply lines
- Sewing machine maker with no experience in car parts spent about 500 man hours refitting a milling machine to produce 40 valves a day.

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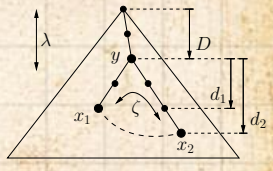

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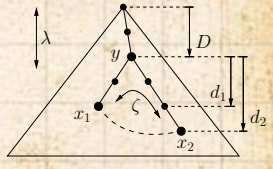
- 36 suppliers, 150 subcontractors
- 50 supply lines
- Sewing machine maker with no experience in car parts spent about 500 man hours refitting a milling machine to produce 40 valves a day.
- Recovery depended on horizontal links which arguably provided:



February, 1997:

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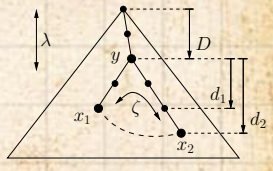

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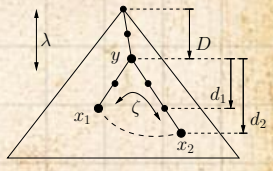

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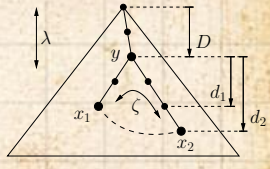

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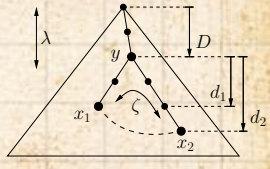

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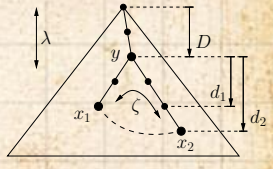

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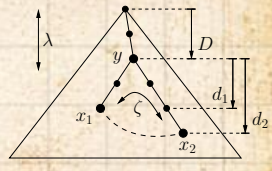
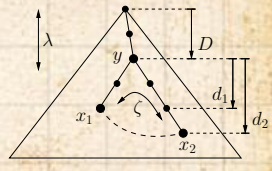


Motivation

Recovery from catastrophe involves solving problems that are:



Motivation

Recovery from catastrophe involves solving problems that are:

- Unanticipated,

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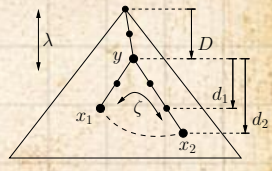

Motivation

Recovery from catastrophe involves solving problems that are:

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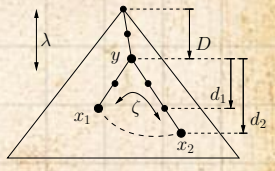

Motivation

Recovery from catastrophe involves solving problems that are:

- Unanticipated,
- Unprecedented,
- Ambiguous (nothing is obvious),

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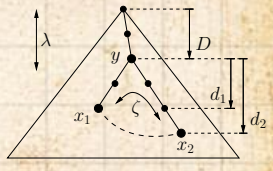

Motivation

Recovery from catastrophe involves solving problems that are:

- Unanticipated,
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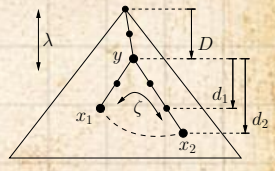

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Recovery from catastrophe involves solving problems that are:

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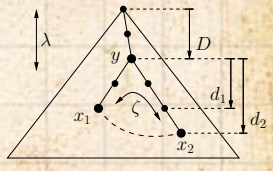

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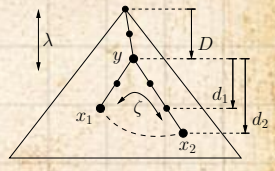

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Recovery from catastrophe involves solving problems that are:

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Frame:

- Collective solving of ambiguous problems

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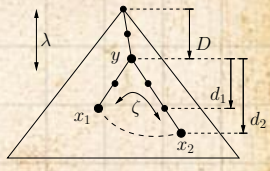

Motivation

Ambiguity:

- Question much less answer is not well understood.

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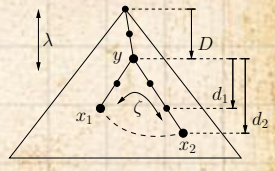

Motivation

Ambiguity:

- Question much less answer is not well understood.
- Back and forth search process rephrases question.

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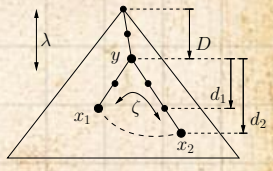

Motivation

Ambiguity:

- Question much less answer is not well understood.
- Back and forth search process rephrases question.
- Leads to iterative process of query reformulation.

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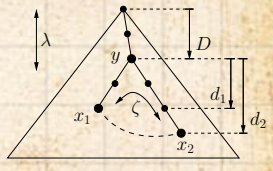

Motivation

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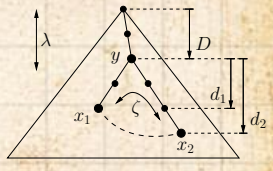
Ambiguity:

- Question much less answer is not well understood.
- Back and forth search process rephrases question.
- Leads to iterative process of query reformulation.
- Ambiguous tasks are inherently not decomposable.



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Ambiguity:

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- Back and forth search process rephrases question.
- Leads to iterative process of query reformulation.
- Ambiguous tasks are inherently not decomposable.
- How do individuals collectively work on an ambiguous organization-scale problem?

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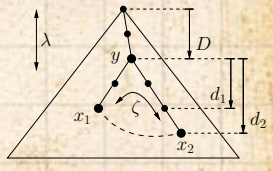

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- Ambiguous tasks are inherently not decomposable.
- How do individuals collectively work on an ambiguous organization-scale problem?
- How do we define ambiguity?

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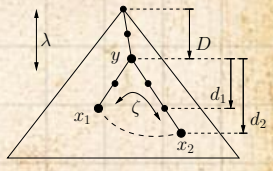
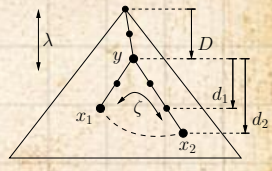


Let's modelify:

Modeling ambiguous problems is hard...



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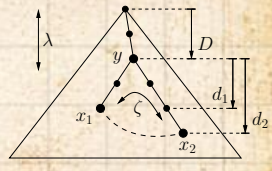
- Model response instead...



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- Model response instead...
- Individuals need novel information and must communicate with others outside of their usual contacts.

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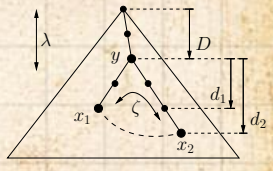

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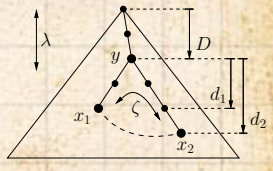

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Focus on robustness:

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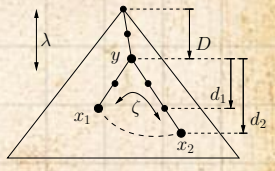

Let's modelify:

Modeling ambiguous problems is hard...

- Model response instead...
- Individuals need novel information and must communicate with others outside of their usual contacts.
- Creative search is intrinsically inefficient.

Focus on robustness:

1. Avoidance of individual failures.

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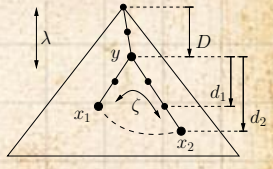

Let's modelify:

Modeling ambiguous problems is hard...

- Model response instead...
- Individuals need novel information and must communicate with others outside of their usual contacts.
- Creative search is intrinsically inefficient.

Focus on robustness:

1. Avoidance of individual failures.
2. Survival of organization even when failures do occur.

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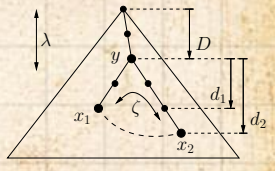

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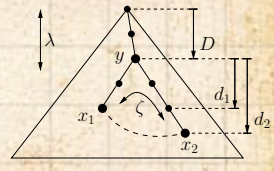

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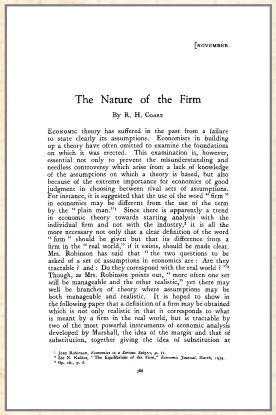

[NOVEMBER

The Nature of the Firm

By R. H. COASE

Economic theory has suffered in the past from a failure to state clearly its assumptions. Economists in building up a theory have often omitted to examine the foundations on which it was erected. This examination is, however, essential not only to prevent the misunderstanding and needless controversy which arise from a lack of knowledge of the assumptions on which a theory is based, but also because of the extreme importance for economics of good judgment in choosing between rival sets of assumptions. For instance, it is suggested that the use of the word "firm" in economics may be different from the use of the term by the "plain man."[1] Since there is apparently a trend in economic theory towards starting analysis with the individual firm and not with the industry,[2] it is all the more necessary not only that a clear definition of the word "firm" should be given but that its difference from a firm in the "real world," if it exists, should be made clear. Mrs. Robinson has said that "the two questions to be asked of a set of assumptions in economics are: Are they tractable? and: Do they correspond with the real world?"[3] Though, as Mrs. Robinson points out, "more often one set will be manageable and the other realistic," yet there may well be branches of theory where assumptions may be both manageable and realistic. It is hoped to show in the following paper that a definition of a firm may be obtained which is not only realistic in that it corresponds to what is meant by a firm in the real world, but is tractable by two of the most powerful instruments of economic analysis developed by Marshall, the idea of the margin and that of substitution, together giving the idea of substitution at

[1] Joan Robinson, *Economics is a Serious Subject*, p. 11.
[2] See H. Kahn, "The Equilibrium of the Firm," *Economic Journal*, March, 1934.
[3] *Op. cit.*, p. 6.

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"The Nature of the Firm"
Ronald H. Coase,
Economica, **New Series, 4**, 386–405, 1937. [1]

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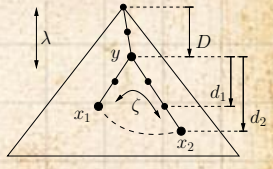

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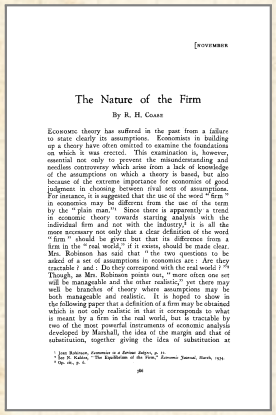

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Notion of Transaction Costs.

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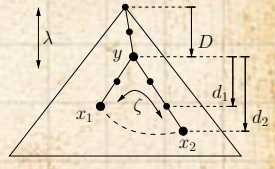
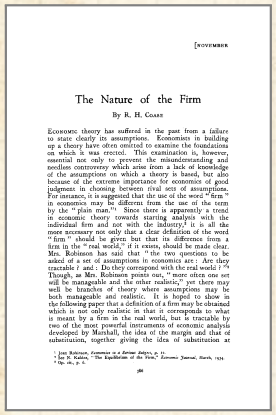


Why organizations exist:



[NOVEMBER

The Nature of the Firm

By R. H. COASE

Economic theory has suffered in the past from a failure to state clearly its assumptions. Economists in building up a theory have often omitted to examine the foundations on which it was erected. This examination is, however, essential not only to prevent the misunderstanding and needless controversy which arise from a lack of knowledge of the assumptions on which a theory is based, but also because of the extreme importance for economics of good judgment in choosing between rival sets of assumptions. For instance, it is suggested that the use of the word "firm" in economics may be different from the use of the term by the "plain man."[1] Since there is apparently a trend in economic theory towards starting analysis with the individual firm and not with the industry,[2] it is all the more necessary not only that a clear definition of the word "firm" should be given but that its difference from a firm in the "real world," if it exists, should be made clear. Mrs. Robinson has said that "the two questions to be asked of a set of assumptions in economics are: Are they tractable? and: Do they correspond with the real world?"[3] Though, as Mrs. Robinson points out, "more often one set will be manageable and the other realistic," yet there may well be branches of theory where assumptions may be both manageable and realistic. It is hoped to show in the following paper that a definition of a firm may be obtained which is not only realistic in that it corresponds to what is meant by a firm in the real world, but is tractable by two of the most powerful instruments of economic analysis developed by Marshall, the idea of the margin and that of substitution, together giving the idea of substitution at

[1] Joan Robinson, *Economics is a Serious Subject*, p. 11.
[2] See H. Kahler, "The Equilibrium of the Firm," *Economic Journal*, March, 1934.
[3] Op. cit., p. 1.

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"The Nature of the Firm"
Ronald H. Coase,
Economica, **New Series, 4**, 386–405, 1937. [1]

- Notion of Transaction Costs.
- More efficient for individuals to cooperate outside of the market.

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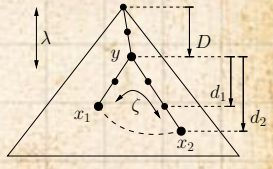

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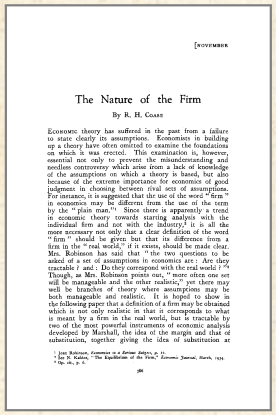

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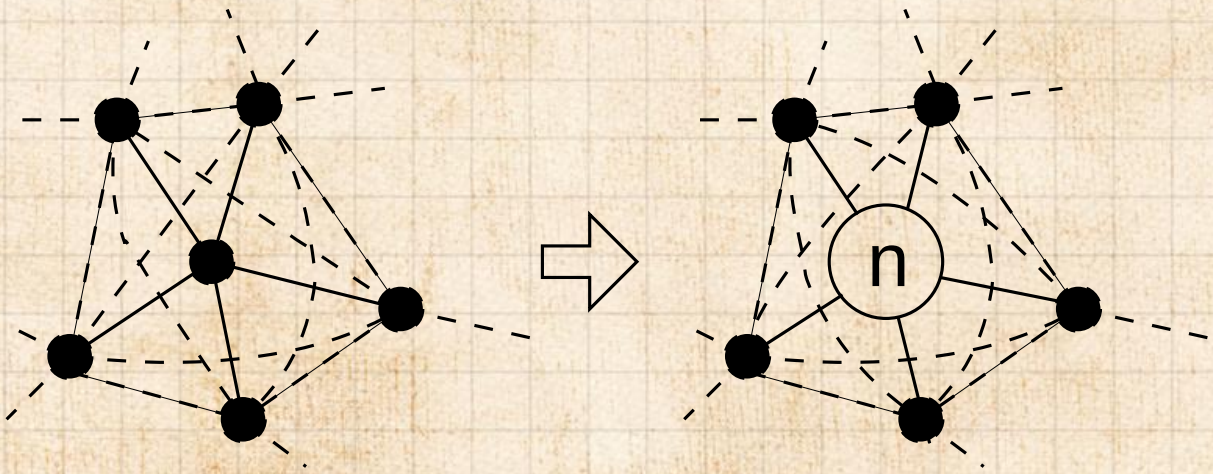

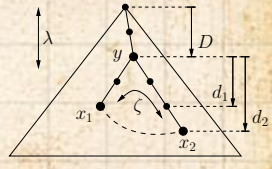

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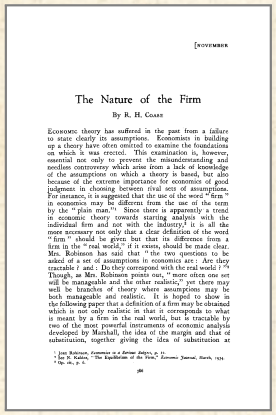

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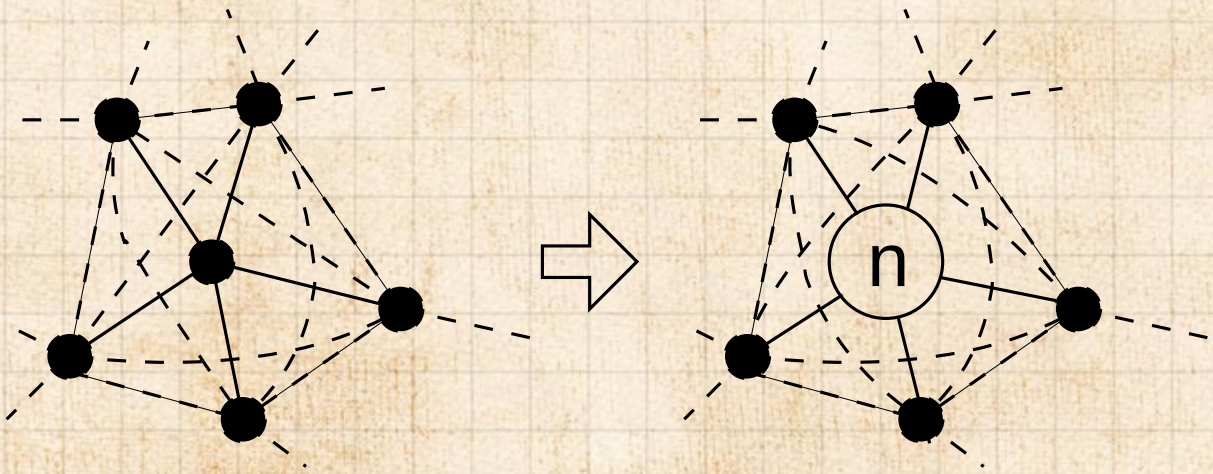

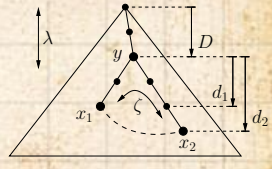

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Real organizations—Extremes

Hierarchy:

- Maximum efficiency,
- Suited to static environment,
- Brittle.

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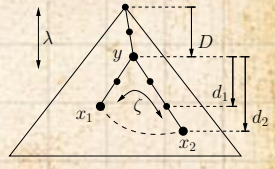

Real organizations—Extremes

Hierarchy:

- Maximum efficiency,
- Suited to static environment,
- Brittle.

Market:

- Resilient,
- Suited to rapidly changing environment,
- Requires costless or low cost interactions.

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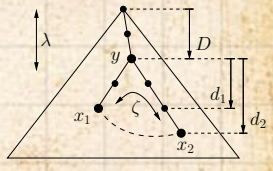

Organizations as efficient hierarchies

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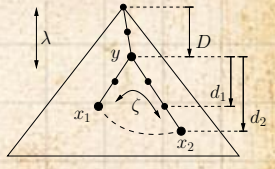
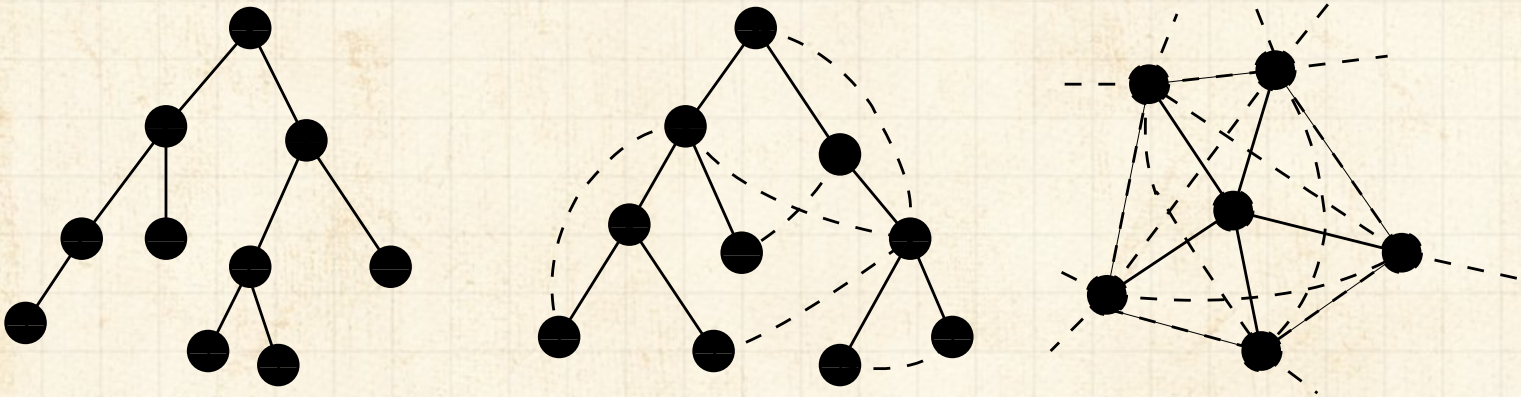
- Economics: Organizations ≡ Hierarchies.
- e.g., Radner (1993) [5], Van Zandt (1998) [7]
- Hierarchies performing associative operations:



Real organizations...

But real, complex organizations are in the middle...



"Heterarchy"

David Stark,
The Biology of Business: Decoding the Natural Laws of theEnterprise., **New Series, 4**, 153–, 1999. [6]

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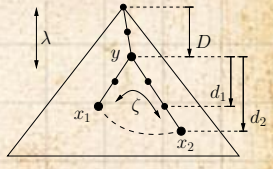
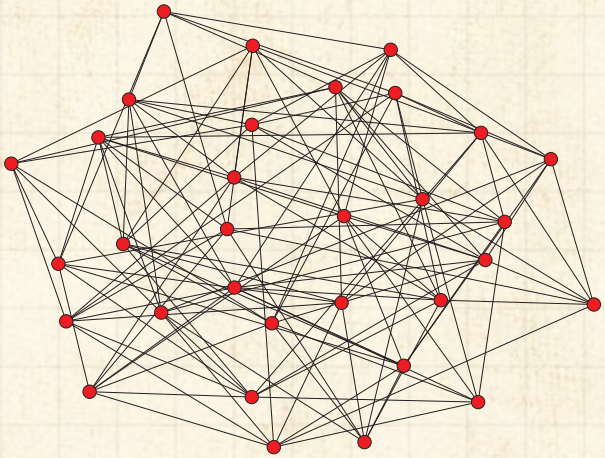
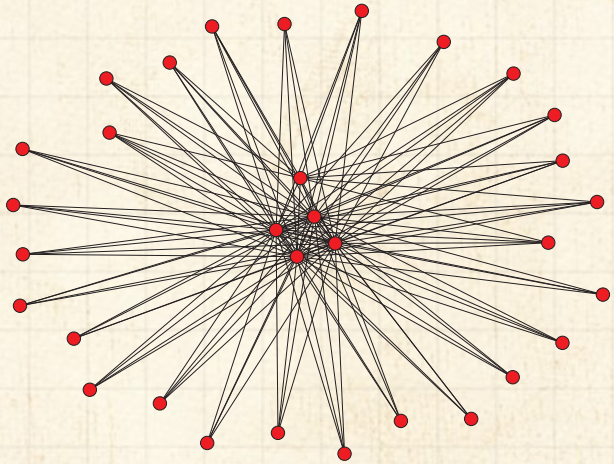


Optimal network topologies for local search

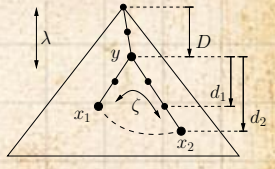
"Optimal network topologies for local search with congestion"

Guimerà et al.,
Phys. Rev. Lett., **89**, 248701, 2002. [3]

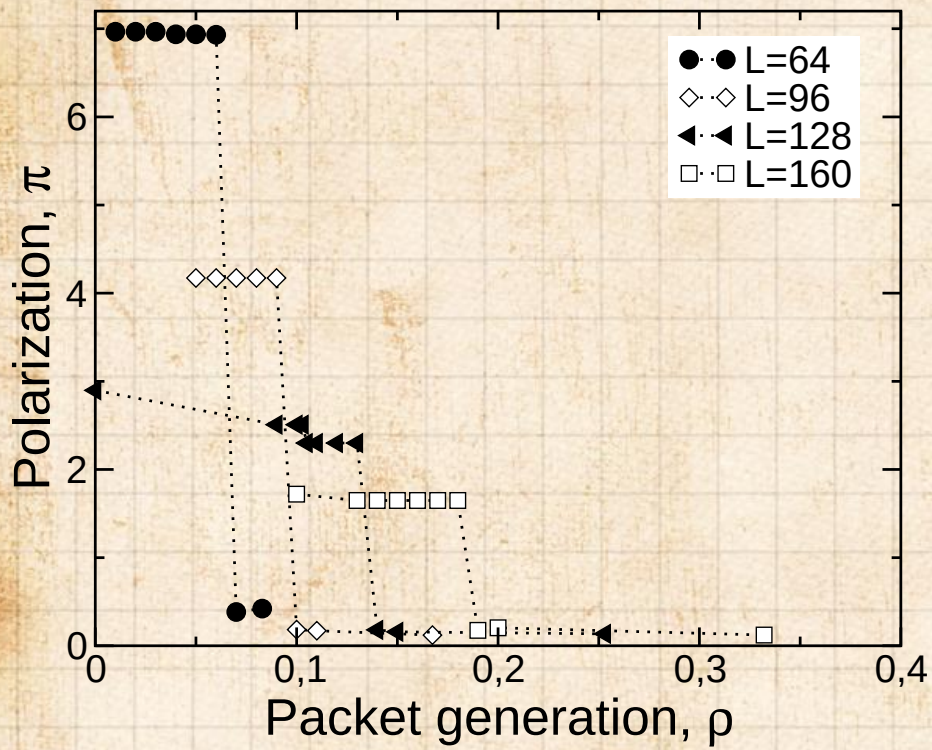




- Parallel search and congestion.
- Queueing and network collapse.
- Exploration of random search mechanisms.



Optimal network topologies for local search

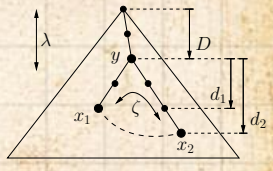


- Betweenness: β.
- Polarization:

$$\pi = \frac{\max\beta}{\langle\beta\rangle} - 1.$$

- L = number of links.

- Goal: minimize average search time.
- Few searches $\Rightarrow$ hub-and-spoke network.
- Many searches $\Rightarrow$ decentralized network.
- Phase transition?



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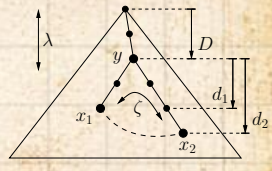
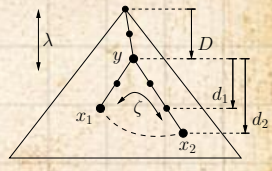


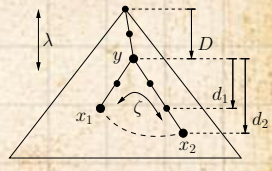
Desirable organizational qualities:

1. Low cost (requiring few links).



Desirable organizational qualities:

1. Low cost (requiring few links).
2. Scalability.



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3. Ease of construction—existence is plausible.

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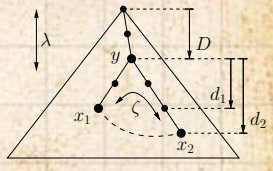

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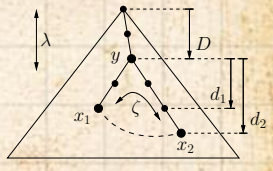

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5. ‘Ultra-robustness’:

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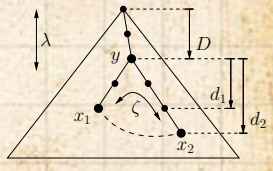

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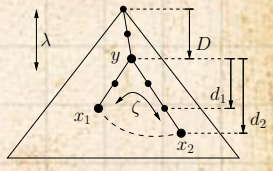

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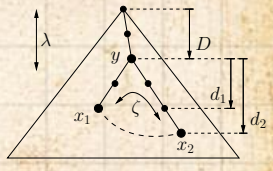

Searchability

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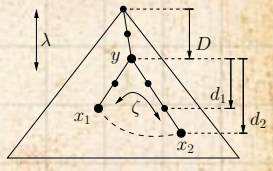
Small world problem:

- Can individuals pass a message to a target individual using only personal connections?
- Yes, large scale networks searchable if nodes have identities.
- “Identity and Search in Social Networks,” Watts, Dodds, & Newman, 2002. [8]



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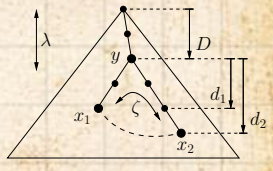

Information exchange and the robustness of organizational networks

"Information exchange and the robustness of organizational networks"

Dodds, Watts, and Sabel,
Proc. Natl. Acad. Sci., **100**, 12516–12521, 2003. [2]

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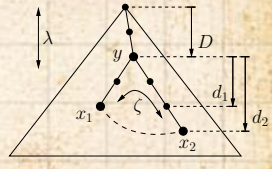

Information exchange and the robustness of organizational networks

Peter Sheridan Dodds*, Duncan J. Watts†‡, and Charles F. Sabel§

*Department of Mathematics, Columbia University, 2990 Broadway, New York, NY 10027; †Department of Sociology, Columbia University, 2990 Broadway, New York, NY 10027; ‡Yahoo! Research, 111 West 40th Street, New York, NY 10018; and §Columbia Law School, Columbia University, 435 West 116th Street, New York, NY 10027

Communicated by Harrison C. White, Columbia University, New York, NY, July 23, 2003 (received for review April 15, 2003)

Many systems of information exchange are important but vulnerable to failure because of the tendency of individuals to conform cheap talk in a wide range of distributed systems, both human and natural. Here we examine the robustness of a class of information exchange networks to a hierarchical backbone, in which links are added incrementally in a hierarchical fashion to a fully connected network. We find that this class of information exchange has many ways to be disastrous in a wide range of environments. We identify three distinct modes of failure, the slightest deviation from which is sufficient to cause the information exchange to collapse. We call the most robustness-enhancing of these networks "tall," and we find that the most robust of tall networks are those that are nearly fully connected. Our results suggest that organizational networks can be guaranteed to be efficient and reliable only if they are highly redundant. In the case of networks that must solve distributed problems, such as organizational networks, the distributed problem-solving, first-organization-then-execution strategy is not robust to environmental uncertainty.

Information exchange is central to the performance of a wide range of networked systems, including information nodes on the Internet (1), airline, postal, and transportation networks, a variety of social networks (2–4), and communication among neurons and muscle cells in multicellular organisms (5). In each of these systems, the structure of the network—the pattern of connections between nodes—is known to affect the efficiency of information exchange. In networks that attempt to solve problems, for example, the speed with which individuals can call organizational networks, networks where participants are connected to many others tend to be more efficient at information. In focusing on information exchange, our goal is to construct a framework for exploring organizational networks that are robust to the failure of communication (6–8).

The topic of network organization is also one to which the tools of network science (9–11) are well suited, because of their focus on efficiency rather than robustness. As a result, the consequences of network structure for robustness are poorly understood. Scientific theorists—nodes understand forwarding networks of relatively simple agents—have begun to study the robustness of network models to their intended tool results. By contrast, the robustness of organizational networks, which are the result of human networking, a form of communication with a "cheap talk" (12–14) component, has received little attention. Yet because organizational networks can be guaranteed to be efficient and reliable only if they are highly redundant, the robustness of organizational networks is of considerable importance. In the case of networks that must solve distributed problems, such as organizational networks, the distributed problem-solving, first-organization-then-execution strategy is not robust to environmental uncertainty.

Under these circumstances, the chief problem facing an organization is to coordinate the actions of its members, which is addressed by maximizing the number of tasks that can be performed independently of one another (15–17). Although this solution has been pioneering individualization, from being overturned by the rise of information technology and the attendant growth in the power of self-knowledge, and on the other hand, preserving the hierarchical structure of authority that is necessary to bring individual talents to bear together. More specifically, when individuals are confronted with unfamiliar problems, they tend to exchange information with other problem solvers (18–21) and to use with each other information about potential partners in order to find the most appropriate person to help solve a problem (22). In such cases where the information is exchanged with (e.g., via e-mail, telephone, or face-to-face meeting), the process of problem solving begins. The leaders respond to any single consultation with a recommendation of how to proceed, or alternatively, with a referral to other, more knowledgeable individuals (23). Although this process of information exchange is central to the performance of organizational networks, such as the Internet, other networks, such as those of neurons and muscle cells, are also important. Organizational networks that maximize the likelihood of resolution are those that maximize the likelihood of resolution. Organizational networks that maximize the likelihood of resolution are those that maximize the likelihood of resolution.

Although there is a growing literature on this level of individual-to-individual organizational networks must continue to function, despite the failure of some of their links. Here we investigate the performance of the class of networks that are formed by adding links to a hierarchical backbone, one at a time, in such a way that the network remains fully connected. We find that networks with regard to (seemingly) catastrophic breakdown in their ability to function.

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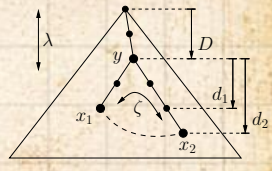

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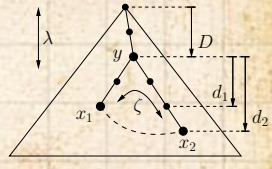
Formal organizational structure:



Information exchange and the robustness of organizational networks

Peter Sheridan Dodds*†, Duncan J. Watts*‡§, and Charles F. Sabel¶

*Institute for Social and Economic Research and Policy, Columbia University, 420 W. 118th Street, New York, NY 10027; ‡Department of Sociology, Columbia University, 420 W. 118th Street, New York, NY 10027; §Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501; and ¶Columbia Law School, Columbia University, 435 W. 116th Street, New York, NY 10027

Communicated by Harrison C. White, Columbia University, New York, NY, July 23, 2003 (received for review April 15, 2003)

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Formal organizational structure:

- Underlying hierarchy:

COcoNuTS @networksvox

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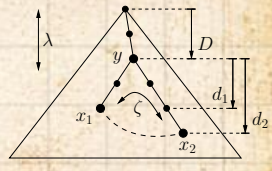

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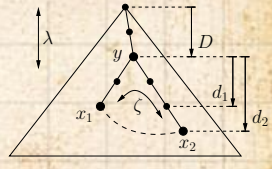
Formal organizational structure:

- Underlying hierarchy:
  - branching ratio b



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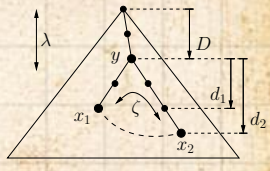
Formal organizational structure:

- Underlying hierarchy:
  - branching ratio b
  - depth L



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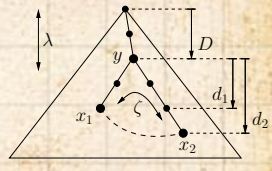
Formal organizational structure:

- Underlying hierarchy:
  - branching ratio b
  - depth L
  - $N = (b^L - 1)/(b - 1)$ nodes



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  - $N - 1$ links

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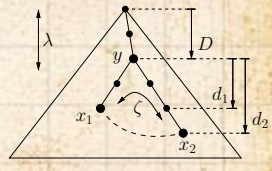

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- Additional informal ties:

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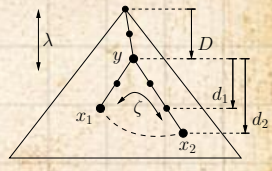

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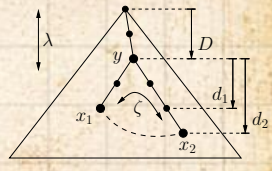
  - $N = (b^L - 1)/(b - 1)$ nodes
  - $N - 1$ links
- Additional informal ties:
  - Choose m links according to a two parameter probability distribution



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  - depth L
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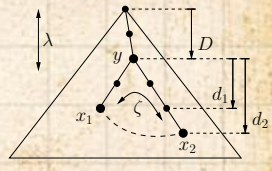
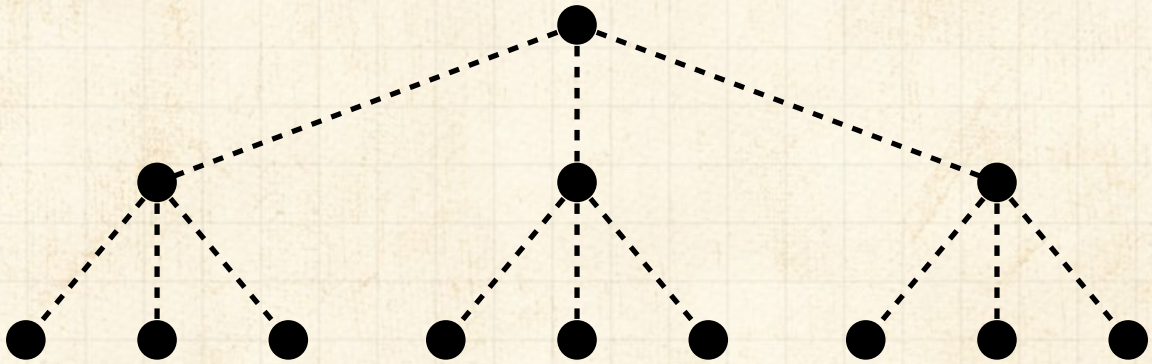
  - $N - 1$ links
- Additional informal ties:
  - Choose m links according to a two parameter probability distribution
  - $0 \leq m \leq (N - 1)(N - 2)/2$

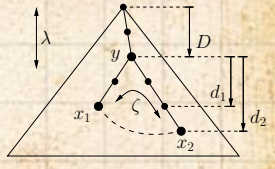


Model—underlying hierarchy

Model—formal structure:



$$b = 3, \quad L = 3, \quad N = 13$$



Model—addition of links

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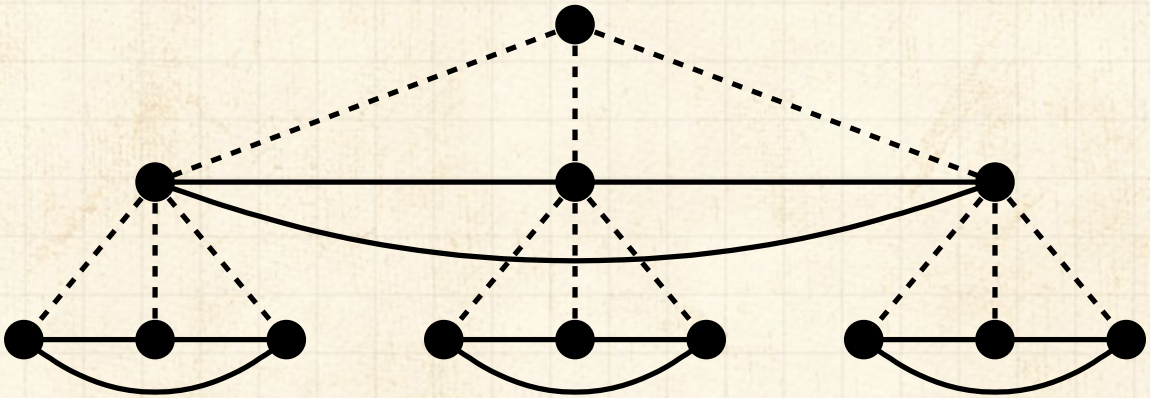
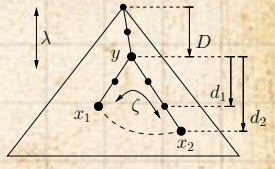
Team-based networks ($m = 12$):





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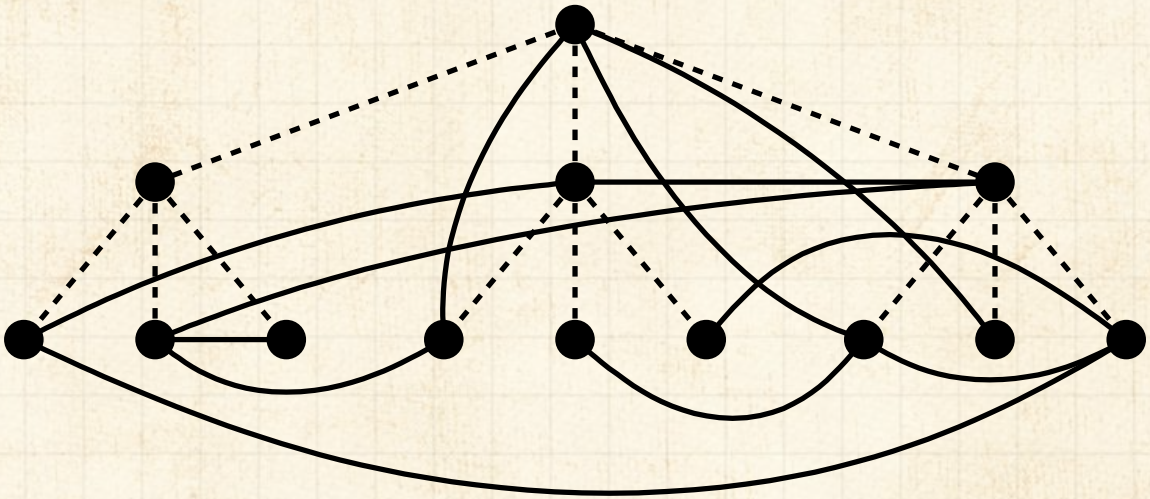
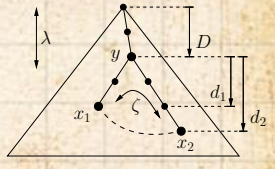
Random networks ($m = 12$):





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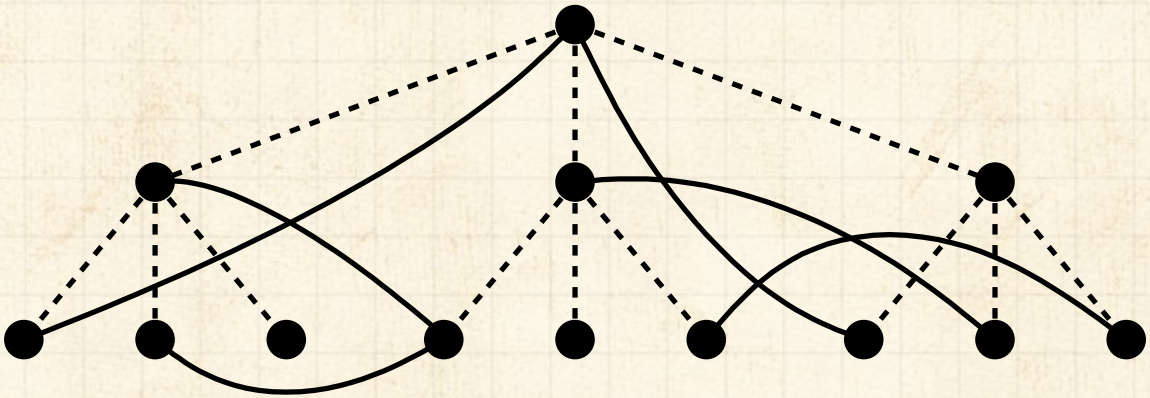
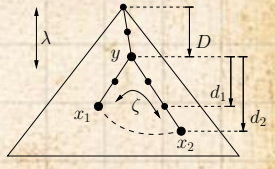
Random interdivisional networks ($m = 6$):





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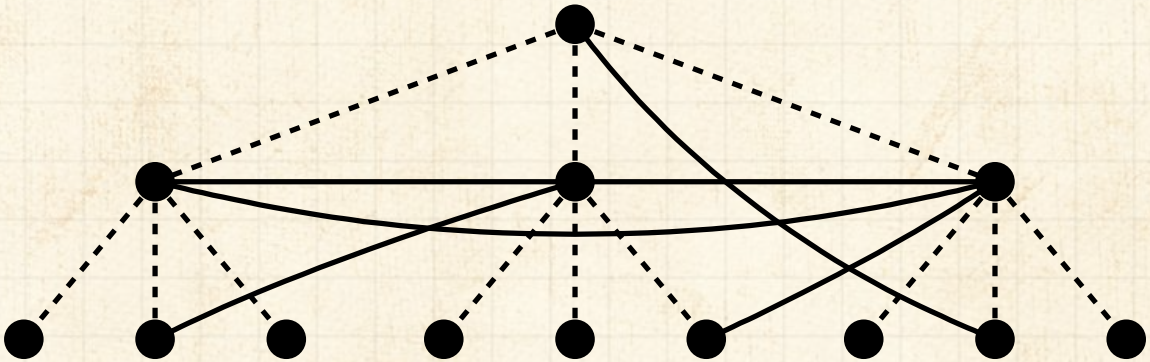
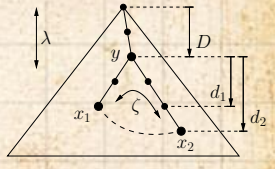
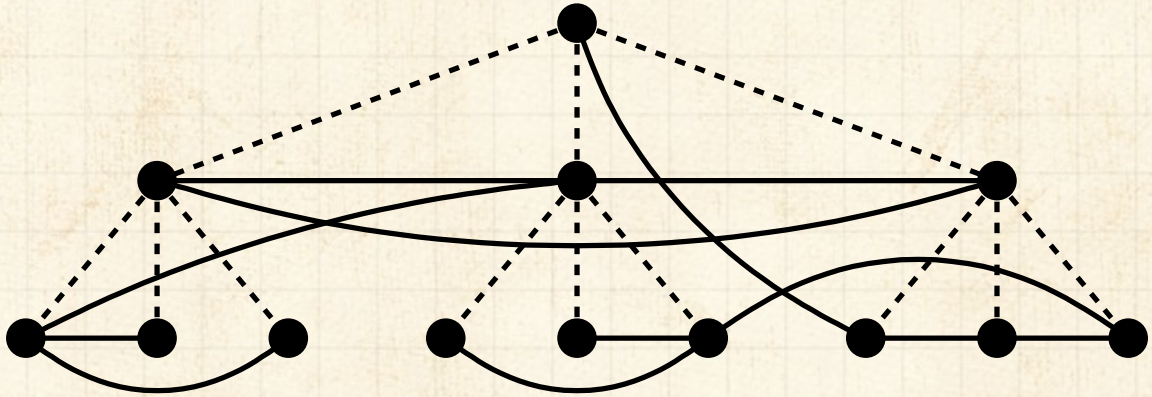
Core-periphery networks ($m = 6$):

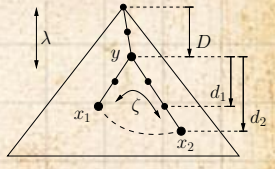




Model—addition of links

Multiscale networks $(m = 12)$:





Model—construction

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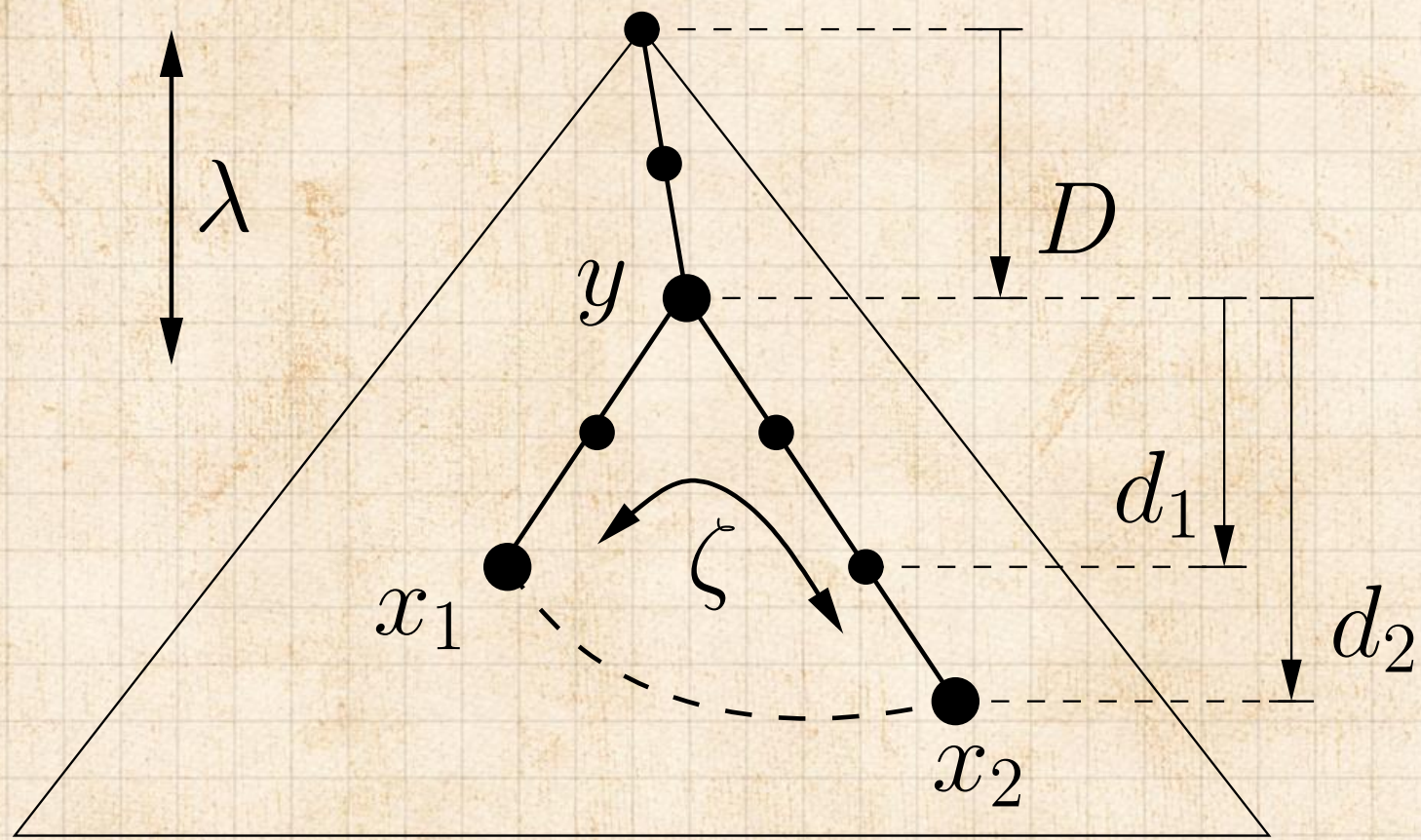

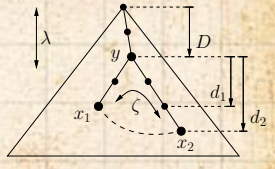

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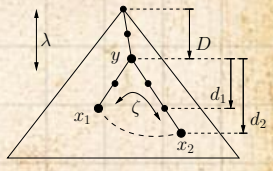
- Link addition probability:

$$P(D, d_1, d_2) \propto e^{-D/\lambda} e^{-f(d_1, d_2)/\zeta}$$

- First choose (D, d_1, d_2).
- Randomly choose (y, x_1, x_2) given (D, d_1, d_2).
- Choose links without replacement.



Model—construction

Requirements for $f(d_1, d_2)$:

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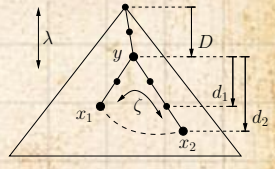

Model—construction

Requirements for $f(d_1, d_2)$:

1. $f \geq 0$ for $d_1 + d_2 \geq 2$

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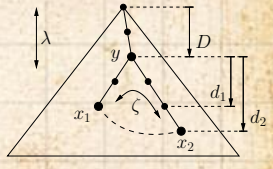

Model—construction

Requirements for $f(d_1, d_2)$:

1. $f \geq 0$ for $d_1 + d_2 \geq 2$
2. f increases monotonically with d_1, d_2.

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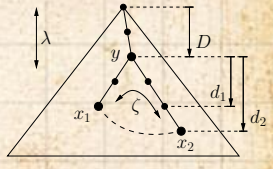

Model—construction

Requirements for $f(d_1, d_2)$:

1. $f \geq 0$ for $d_1 + d_2 \geq 2$
2. f increases monotonically with d_1, d_2.
3. $f(d_1, d_2) = f(d_2, d_1)$.

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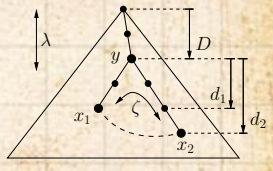

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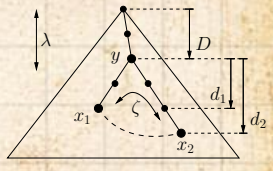

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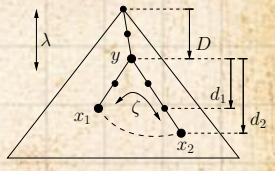
3. $f(d_1, d_2) = f(d_2, d_1)$.
4. f is maximized when $d_1 = d_2$.

Simple function satisfying 1–4:

$$f(d_1, d_2) = (d_1^2 + d_2^2 - 2)^{1/2}$$

$$\Rightarrow P(y, x_1, x_2) \propto e^{-D/\lambda} e^{-(d_1^2+d_2^2-2)^{1/2}/\zeta}$$



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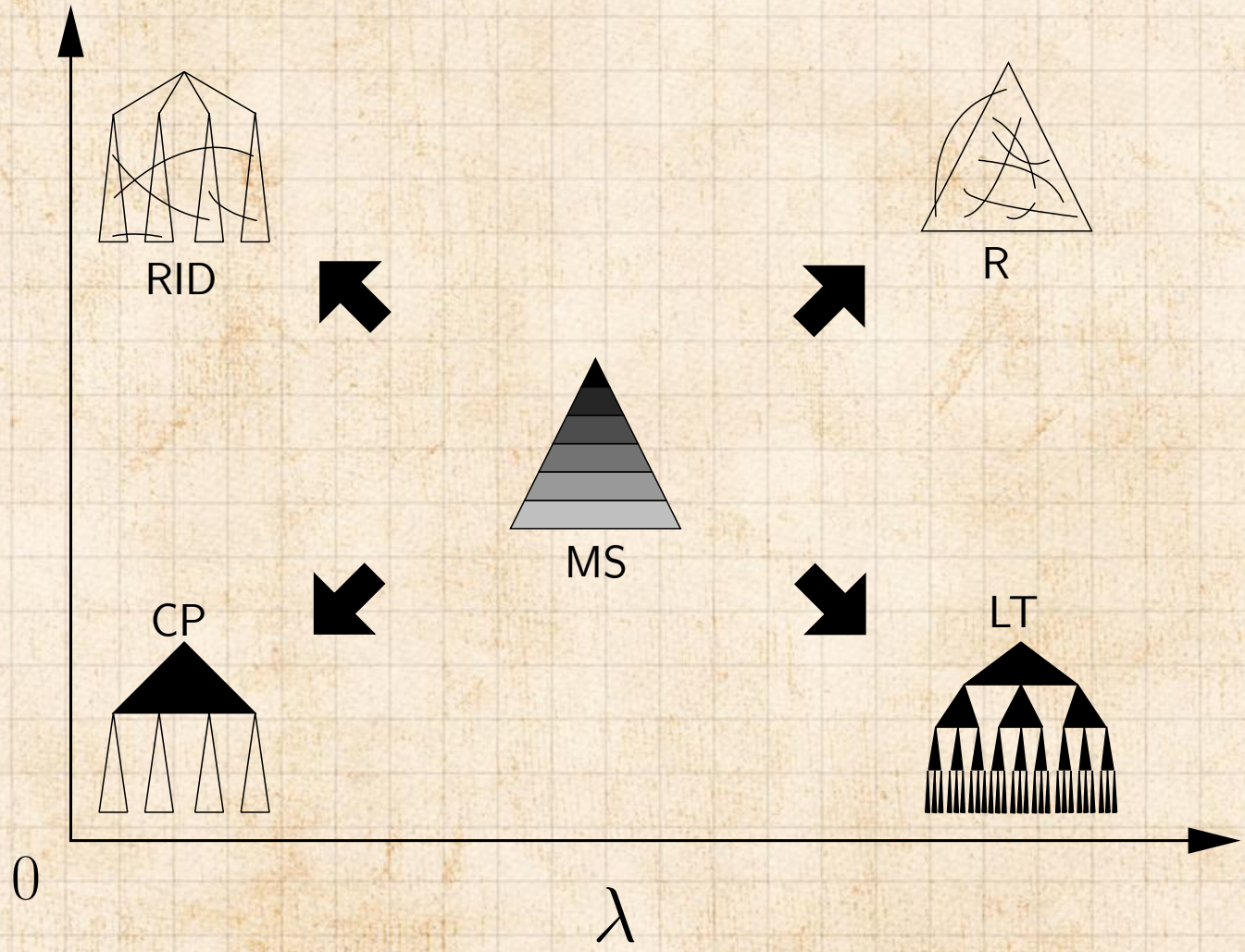
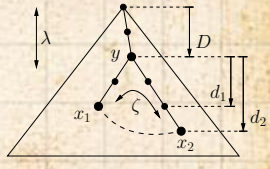
Model—limiting cases





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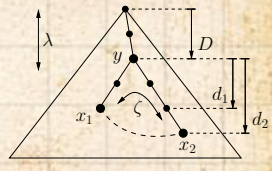

Message passing pattern

- Each of T time steps, each node generates a message with probability μ.

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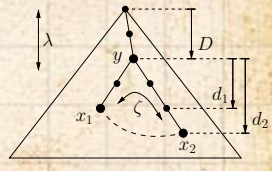

Message passing pattern

- Each of T time steps, each node generates a message with probability μ.
- Recipient of message chosen based on distance from sender.

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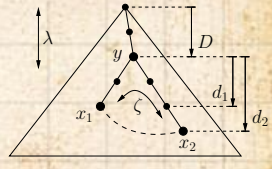

Message passing pattern

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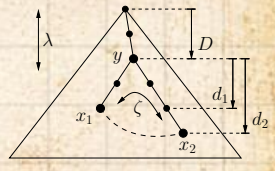
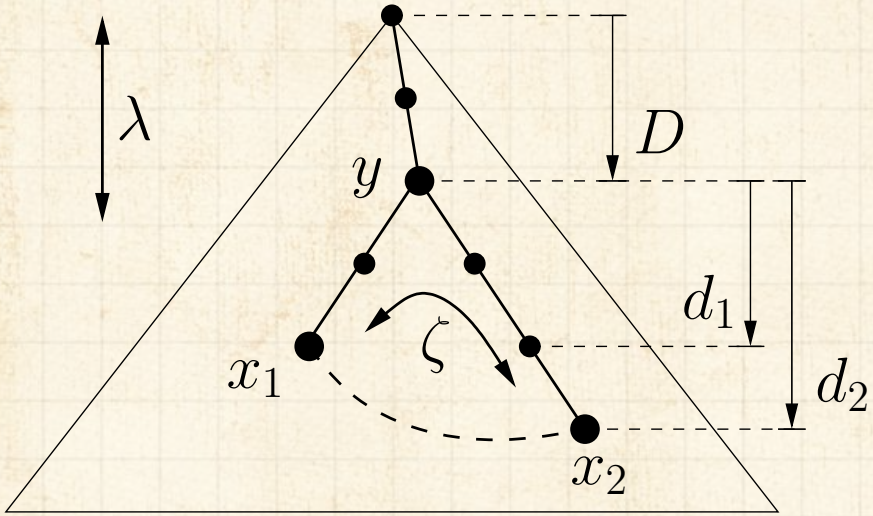
- Each of T time steps, each node generates a message with probability μ.
- Recipient of message chosen based on distance from sender.
- $$P(\text{recipient at distance } d) \propto e^{-d/\xi}.$$

1. ξ = measure of uncertainty;
2. $\xi = 0$: local message passing;
3. $\xi = \infty$: random message passing.



Message passing pattern:

Distance d_{12} between two nodes x_1 and x_2:



$$d_{12} = \max(d_1, d_2) = 3$$

- Measure unchanged with presence of informal ties.

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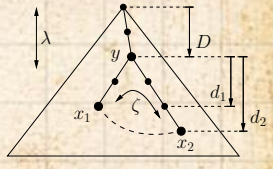
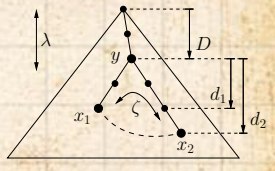


Message passing pattern

Simple message routing algorithm:

- Look ahead one step: always choose neighbor closest to recipient node.



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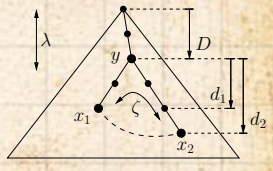
Simple message routing algorithm:

- Look ahead one step: always choose neighbor closest to recipient node.
- Pseudo-global knowledge:
  1. Nodes understand hierarchy.
  2. Nodes know only local informal ties.



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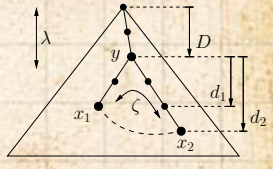
Interpretations:

1. Sender knows specific recipient.



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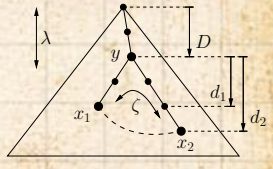
Interpretations:

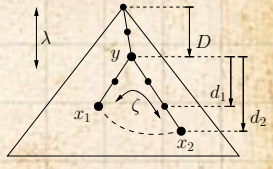
1. Sender knows specific recipient.
2. Sender requires certain kind of recipient.



Message passing pattern

Interpretations:

1. Sender knows specific recipient.
2. Sender requires certain kind of recipient.
3. Sender seeks specific information but recipient unknown.



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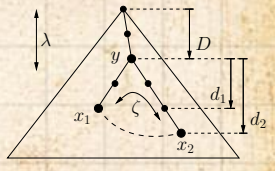
Interpretations:

1. Sender knows specific recipient.
2. Sender requires certain kind of recipient.
3. Sender seeks specific information but recipient unknown.
4. Sender has a problem but information/recipient unknown.



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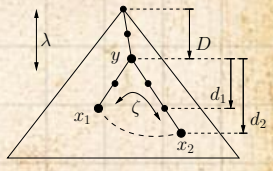
Performance:

- Measure Congestion Centrality ρ_i, fraction of messages passing through node i.



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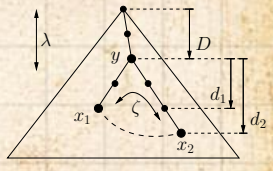
Performance:

- Measure Congestion Centrality ρ_i, fraction of messages passing through node i.
- Similar to betweenness centrality.



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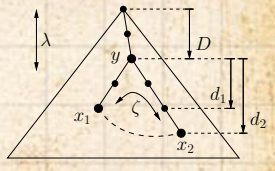
- Measure Congestion Centrality ρ_i, fraction of messages passing through node i.
- Similar to betweenness centrality.
- However: depends on
  1. Search algorithm;



Message passing pattern

Performance:

- Measure Congestion Centrality ρ_i, fraction of messages passing through node i.
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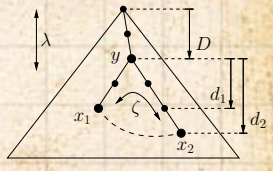
- However: depends on
  1. Search algorithm;
  2. Task specification (μ, ξ).



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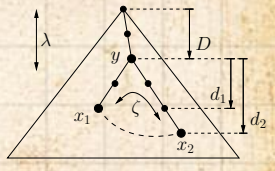
Performance:

- Measure Congestion Centrality ρ_i, fraction of messages passing through node i.
- Similar to betweenness centrality.
- However: depends on
  1. Search algorithm;
  2. Task specification (μ, ξ).
- Congestion robustness comes from minimizing $\rho_{\max}$.



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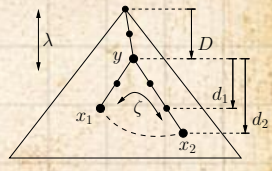

Performance testing:

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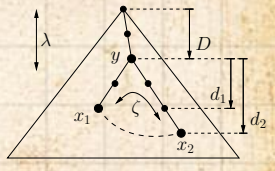
Parameter settings (unless varying):

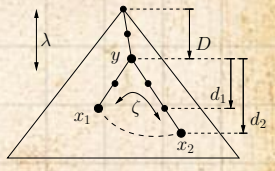
- Underlying hierarchy: $b = 5$, $L = 6$, $N = 3096$;



Performance testing:

Parameter settings (unless varying):

- Underlying hierarchy: $b = 5$, $L = 6$, $N = 3096$;
- Number of informal ties: $m = N$.



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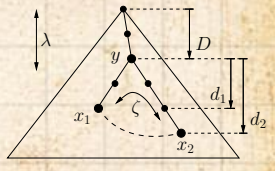
Parameter settings (unless varying):

- Underlying hierarchy: $b = 5$, $L = 6$, $N = 3096$;
- Number of informal ties: $m = N$.
- Link addition algorithm: $\lambda = \zeta = 0.5$.



Performance testing:

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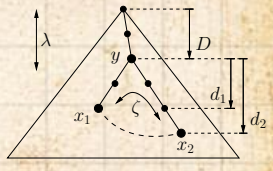
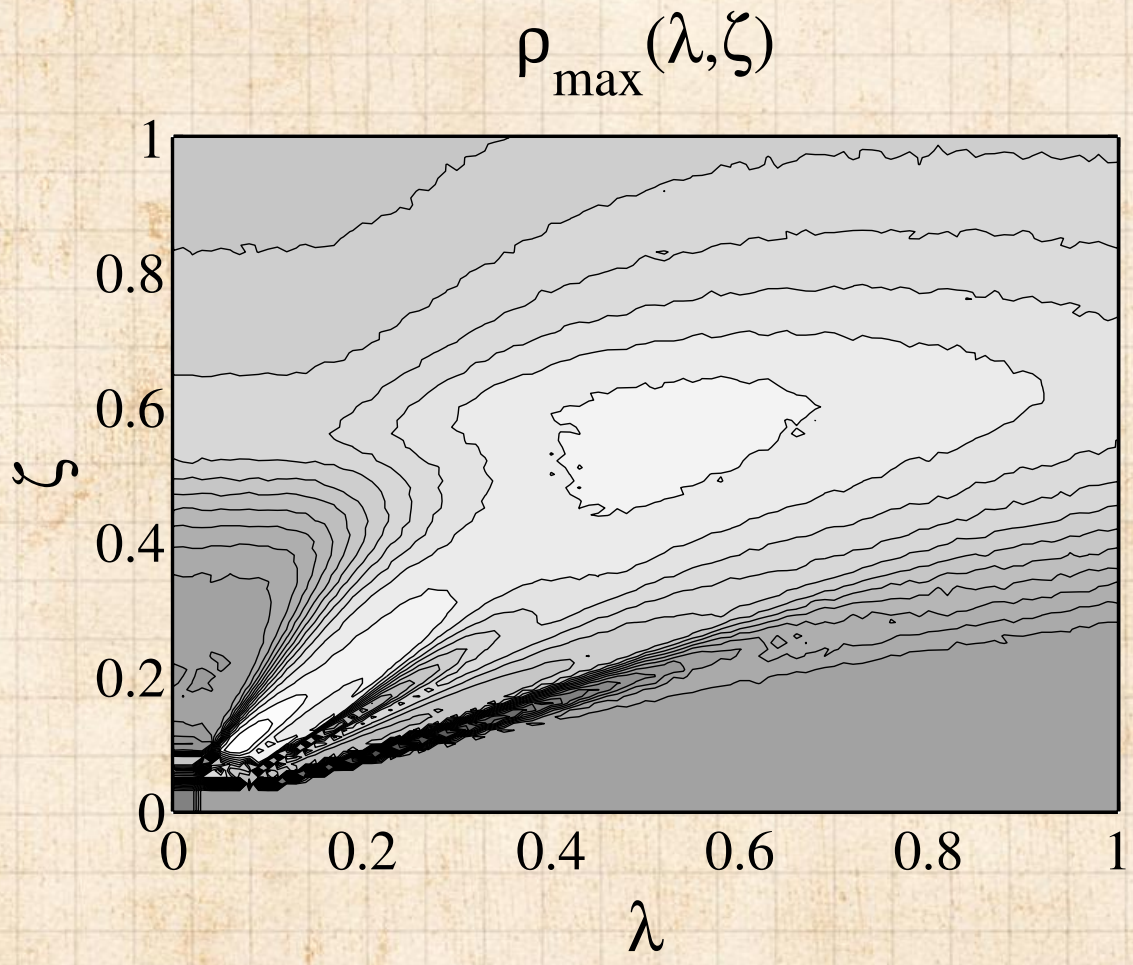
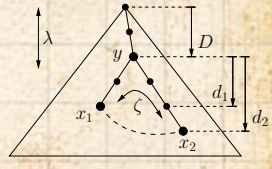
Parameter settings (unless varying):

- Underlying hierarchy: $b = 5$, $L = 6$, $N = 3096$;
- Number of informal ties: $m = N$.
- Link addition algorithm: $\lambda = \zeta = 0.5$.
- Message passing: $\xi = 1$, $\mu = 10/N$, $T = 1000$.

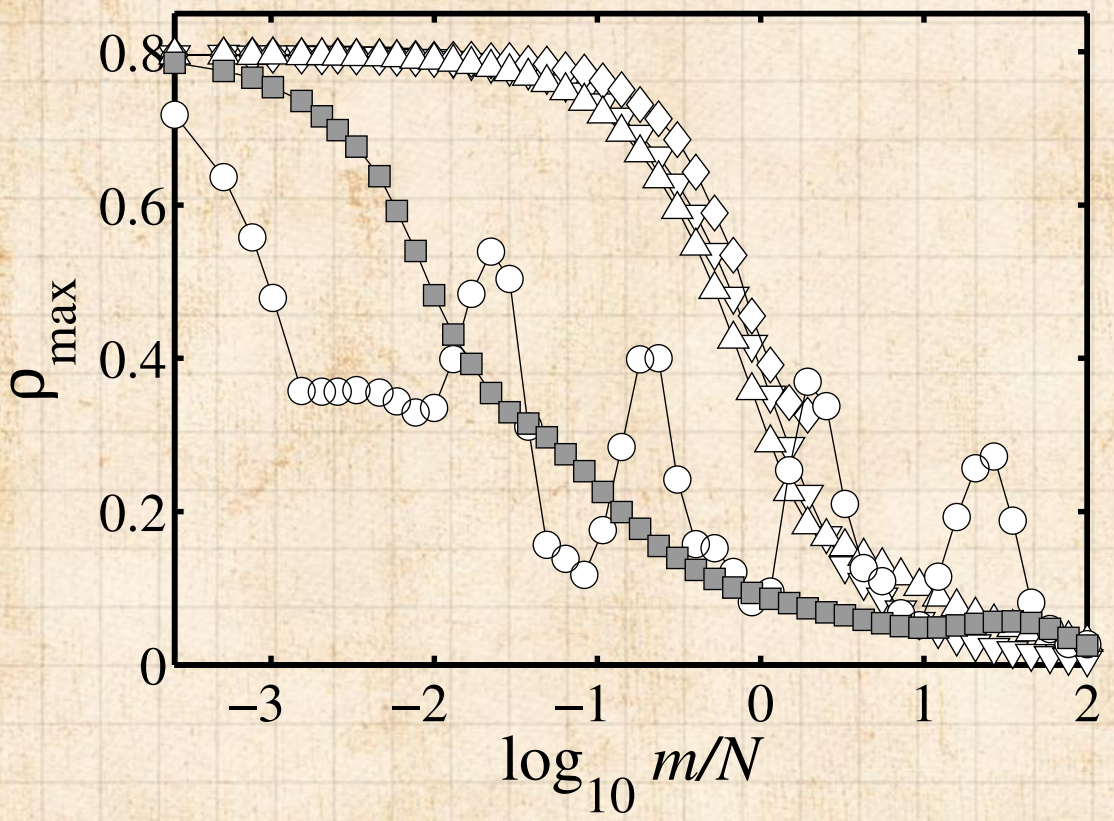


Results—congestion robustness





Results—varying number of links added:



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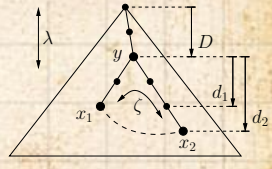
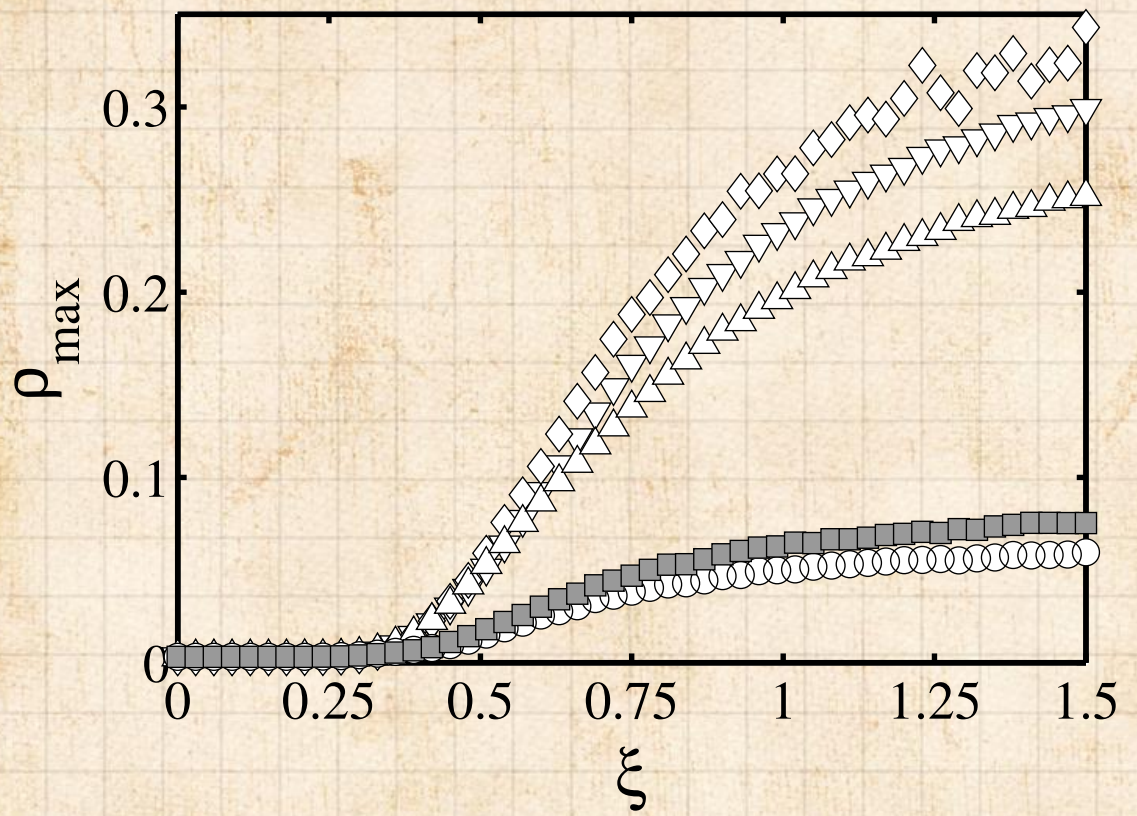


Results—varying message passing pattern



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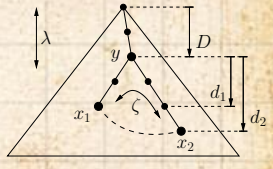
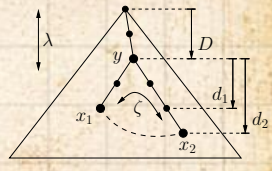


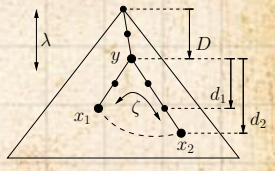
Results—Maximum firm size

- Congestion may increase with size of network.



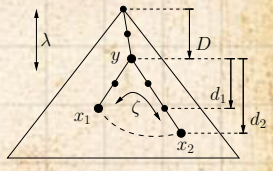
Results—Maximum firm size

- Congestion may increase with size of network.
- Fix rate of message passing (μ) and Message pattern (ξ).



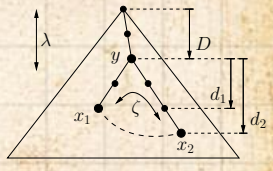
Results—Maximum firm size

- Congestion may increase with size of network.
- Fix rate of message passing (μ) and Message pattern (ξ).
- Fix branching ratio of hierarchy and add more levels.

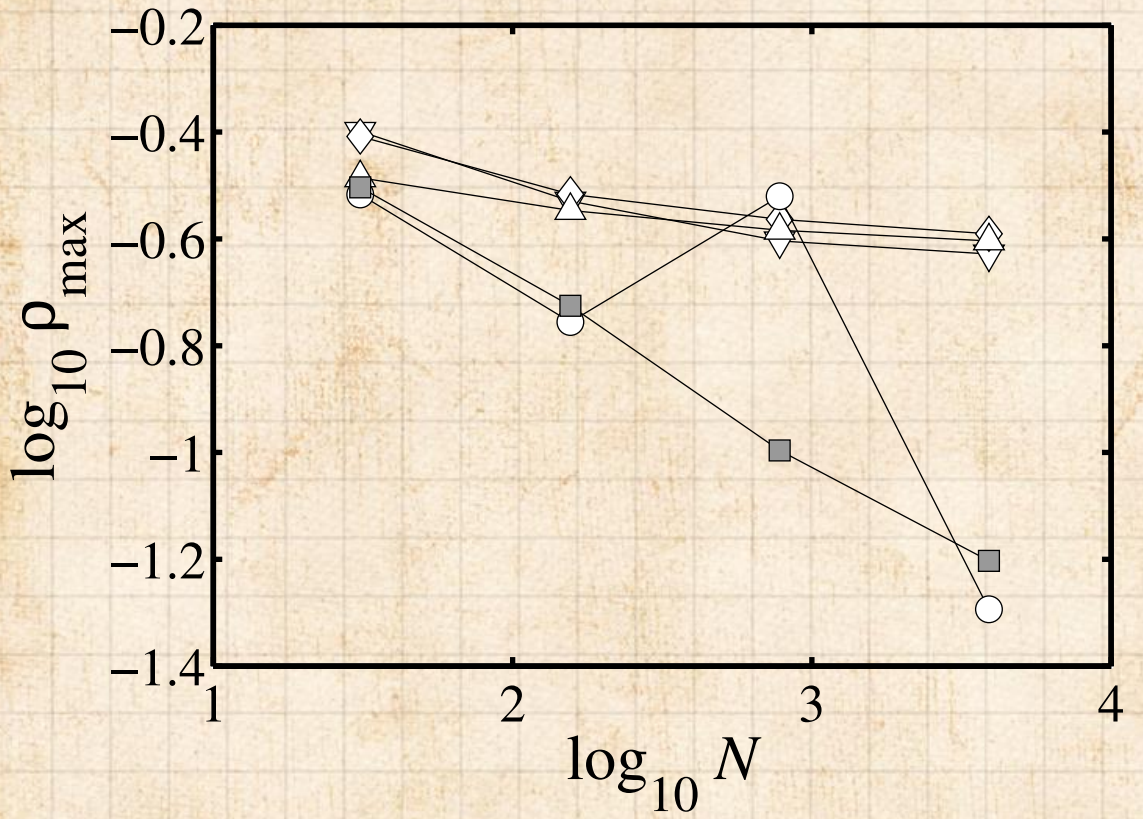


Results—Maximum firm size

- Congestion may increase with size of network.
- Fix rate of message passing (μ) and Message pattern (ξ).
- Fix branching ratio of hierarchy and add more levels.
- Individuals have limited capacity $\Rightarrow$ limit to firm size.



Scalability in complete uncertainty: $\xi = \infty$



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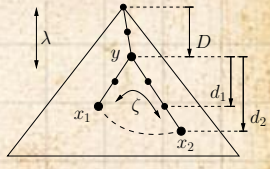

Connectivity Robustness

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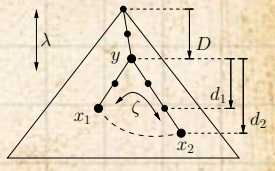
Inducing catastrophic failure:

- Remove N_r nodes and measure relative size of largest component $C = S/(N - N_r)$.



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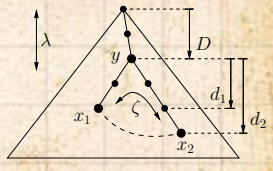
Inducing catastrophic failure:

- Remove N_r nodes and measure relative size of largest component $C = S/(N - N_r)$.
- Four deletion sequences:
  1. Top-down;
  2. Random;
  3. Hub;
  4. Cascading failure.



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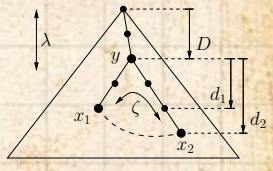
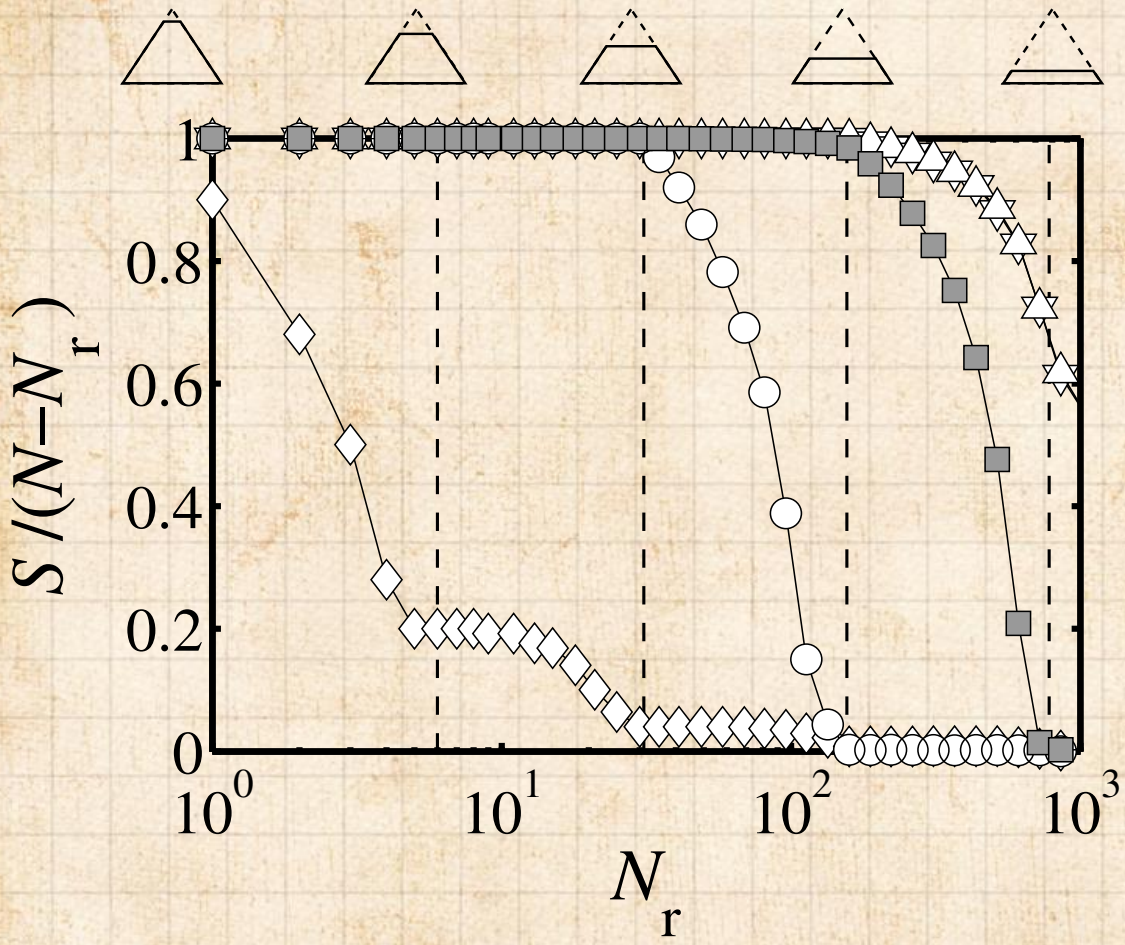
Inducing catastrophic failure:

- Remove N_r nodes and measure relative size of largest component $C = S/(N - N_r)$.
- Four deletion sequences:
  1. Top-down;
  2. Random;
  3. Hub;
  4. Cascading failure.
- Results largely independent of sequence.



Results—Connectivity Robustness



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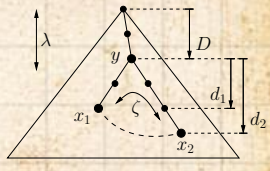

Summary of results

Feature	Congestion Robustness	Connectivity Robustness	Scalability
Core-periphery	good	average	average
Random	poor	good	poor
Rand. Interdivisional	poor	good	poor
Team-based	poor	poor	poor
Multiscale	good	good	good

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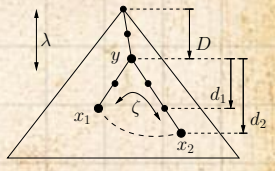

Conclusary moments

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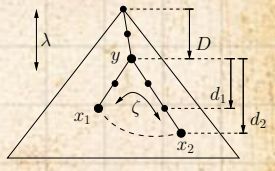
Multi-scale networks:

1. Possess good Congestion Robustness and Connectivity Robustness $\Rightarrow$ Ultra-robust;



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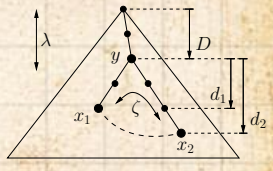

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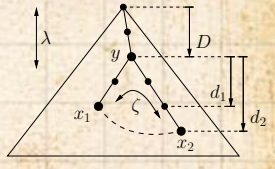

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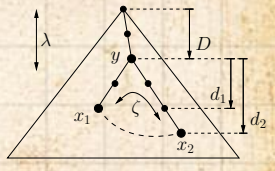
- Above suggests existence of multi-scale structure is plausible.



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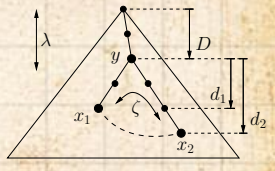
- Foregoing is an attempt to model what organizations might look like beyond simple hierarchies (2003).



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- Foregoing is an attempt to model what organizations might look like beyond simple hierarchies (2003).
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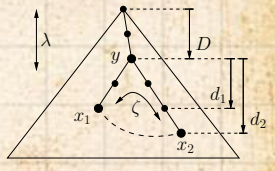

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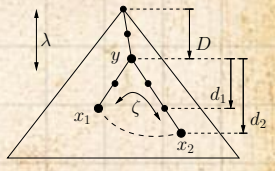

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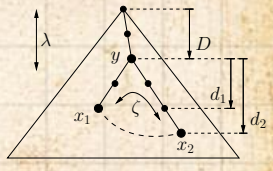
- Balance of generalists versus specialists—how many middle managers does an organization need?
- Still a need for data on real organizations...



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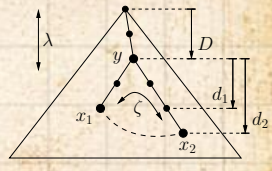

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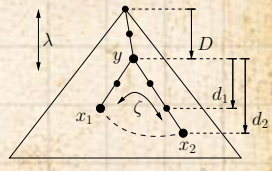

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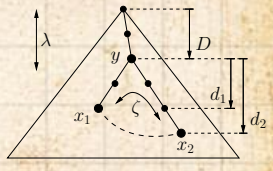
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