

Organizational Networks: Information Exchange and Robustness

Last updated: 2024/11/06, 17:10:59 MST

Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 6701, 6713, & a pretend number, 2024–2025

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Santa Fe Institute | University of Vermont



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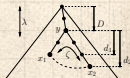
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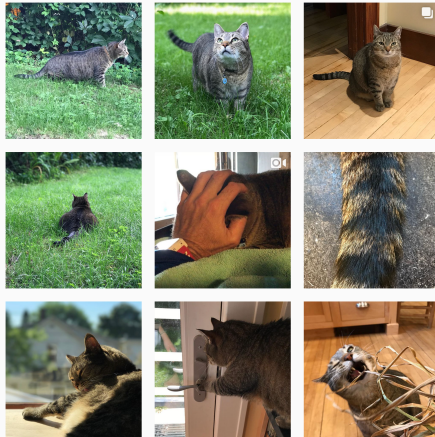
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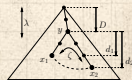
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The basic idea/problem/motivation/history:

 Organizations as information exchange entities.

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The basic idea/problem/motivation/history:

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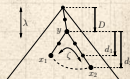
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A model of organizational networks:

-  Network construction algorithm.

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-  Task specification.



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The basic idea/problem/motivation/history:

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- Solving ambiguous, ill-defined problems.
- Robustness as 'optimal' design feature.

A model of organizational networks:

- Network construction algorithm.
- Task specification.
- Message routing algorithm.

Results:

- Performance measures.



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February, 1997:

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

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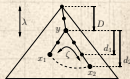
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6 months before new machines would arrive.



February, 1997:

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- 4 hours supply (“just in time”).
- 14,000 cars per day \rightarrow 0 cars per day.
- 6 months before new machines would arrive.
- Recovered in 5 days.



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4 hours supply (“just in time”).



14,000 cars per day → 0 cars per day.



6 months before new machines would arrive.

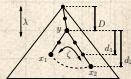


Recovered in 5 days.




Case study performed by Nishiguchi and Beaudet ^[4]

“Fractal Design: Self-organizing Links in Supply Chain”
in “Knowledge Creation: A New Source of Value”



February, 1997:

Some details:

 36 suppliers, 150 subcontractors

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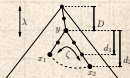
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February, 1997:

Some details:

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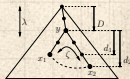
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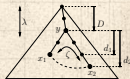
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 Sewing machine maker with no experience in car parts spent about 500 man hours refitting a milling machine to produce 40 valves a day.



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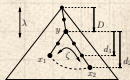
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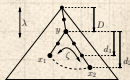
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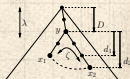
 36 suppliers, 150 subcontractors

 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:

1. robustness
2. searchability



Some things fall apart:



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LEHMAN BROTHERS



Rebirth:

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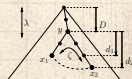
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Motivation

Recovery from catastrophe involves solving problems that are:

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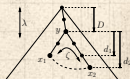
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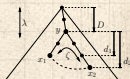
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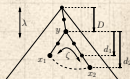
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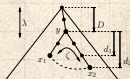
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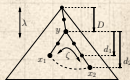
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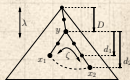
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Recovery from catastrophe involves solving problems that are:

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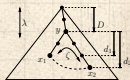
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Recovery from catastrophe involves solving problems that are:

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- Ambiguous (nothing is obvious),
- Distributed (knowledge/people/resources),
- Limited by existing resources,
- Critical for survival.

Frame:

- Collective solving of ambiguous problems



Motivation

Ambiguity:





Question much less answer is not well understood.



Motivation

Ambiguity:

 Question much less answer is not well understood.

 Back and forth search process rephrases question.



Motivation

Ambiguity:

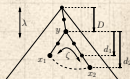
- ❏ Question much less answer is not well understood.
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- ❏ Leads to iterative process of query reformulation.



Motivation

Ambiguity:

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- ❏ Back and forth search process rephrases question.
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- ❏ Ambiguous tasks are inherently not decomposable.



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?



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.
- How do individuals collectively work on an ambiguous organization-scale problem?
- How do we define ambiguity?



Let's modelify:

Modeling ambiguous problems is hard...

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Let's modelify:

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 Model response instead...



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Model response instead...



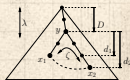
Individuals need novel information and must communicate with others outside of their usual contacts.



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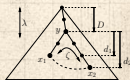


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Focus on robustness:



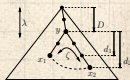
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Focus on robustness:

- Avoidance of individual failures.



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Modeling ambiguous problems is hard...

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- Individuals need novel information and must communicate with others outside of their usual contacts.
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Focus on robustness:

- Avoidance of individual failures.
- Survival of organization even when failures do occur.



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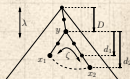
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New Series, 4, 386–405, 1937. ^[1]




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Notion of Transaction Costs .




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Notion of Transaction Costs .



More efficient for individuals to cooperate outside of the market.



Why organizations exist:



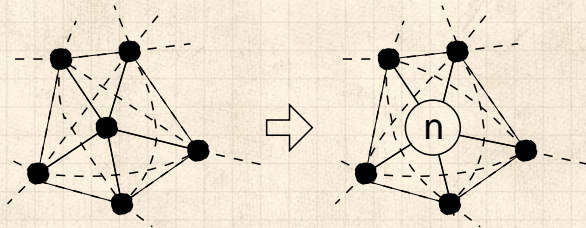
“The Nature of the Firm” [↗](#), Ronald H. Coase, *Economica*,
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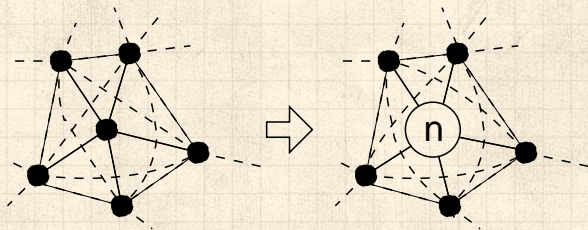
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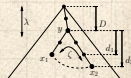
“The Nature of the Firm” [↗](#), Ronald H. Coase, *Economica*,
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 Notion of Transaction Costs [↗](#).

 More efficient for individuals to cooperate outside of the market.






 Coase [↗](#) had a solid career [↗](#).



Real organizations—Extremes




Hierarchy:

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






Real organizations—Extremes

Hierarchy:


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


Market:


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

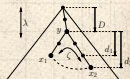


Organizations as efficient hierarchies

 Economics: Organizations \equiv Hierarchies.

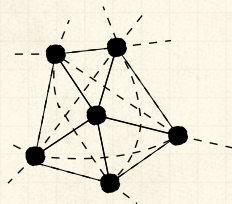
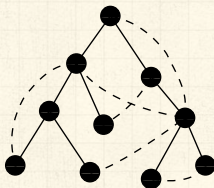
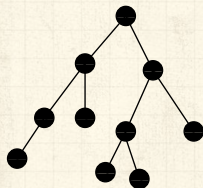
 e.g., Radner (1993) [5], Van Zandt (1998) [7]


 Hierarchies performing associative operations:



Real organizations...

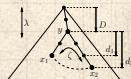
But real, complex organizations are in the middle...



“Heterarchy” 

David Stark,

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



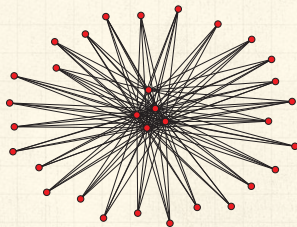
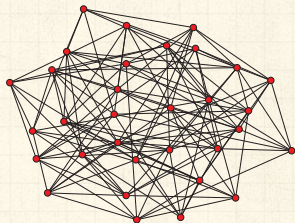
Optimal network topologies for local search



“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.

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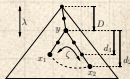
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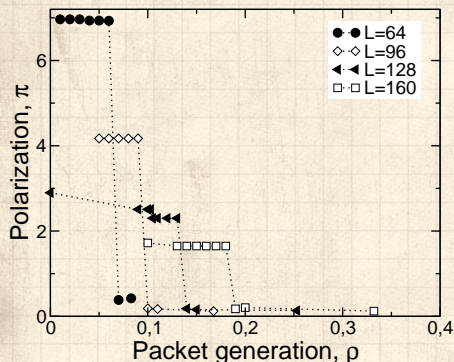
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Optimal network topologies for local search





 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).

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Desirable organizational qualities:

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



Desirable organizational qualities:

1. Low cost (requiring few links).
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3. Ease of construction—existence is plausible.



Desirable organizational qualities:

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4. Searchability.



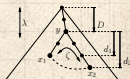
Desirable organizational qualities:

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5. **'Ultra-robustness'**:



Desirable organizational qualities:

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 - I Congestion robustness
(Resilience to failure due to information exchange);



Desirable organizational qualities:

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5. **'Ultra-robustness'**:
 - I Congestion robustness
(Resilience to failure due to information exchange);
 - II Connectivity robustness
(Recoverability in the event of failure).



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
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Dodds, Watts, and Sabel,

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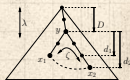
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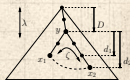
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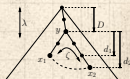
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 branching ratio b

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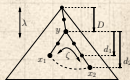
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Formal organizational structure:

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 branching ratio b

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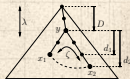
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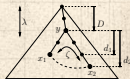
Formal organizational structure:

 Underlying hierarchy:

 branching ratio b

 depth L

 $N = (b^L - 1)/(b - 1)$ nodes



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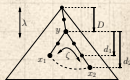
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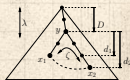
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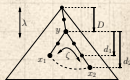
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 Choose m links according to a two parameter probability
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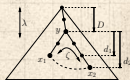
Formal organizational structure:

 Underlying hierarchy:

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

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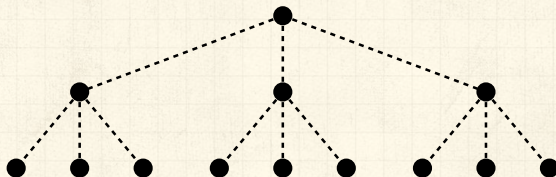
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Model—formal structure:



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



Model—addition of links

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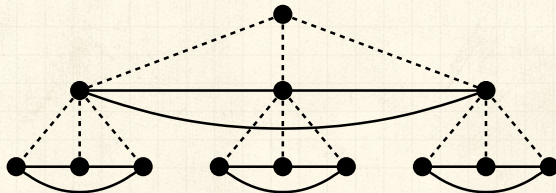
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Team-based networks ($m = 12$):



Model—addition of links

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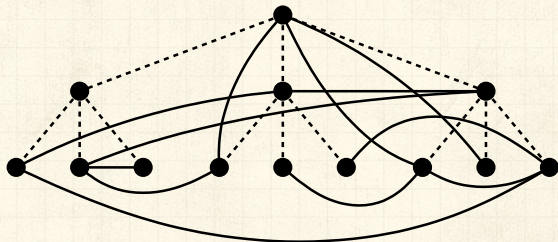
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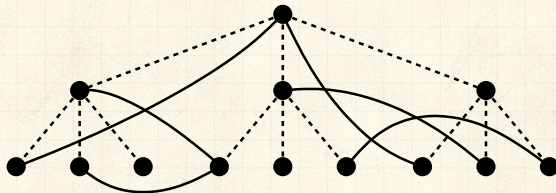
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Random networks ($m = 12$):



Model—addition of links

Random interdivisional networks ($m = 6$):



Model—addition of links

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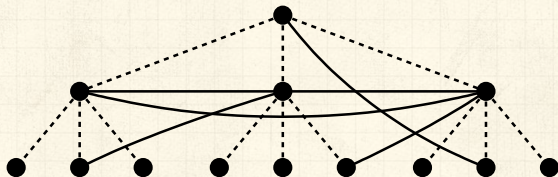
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Core-periphery networks ($m = 6$):



Model—addition of links

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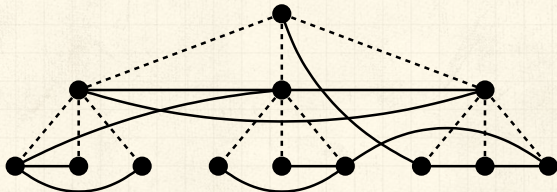
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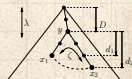
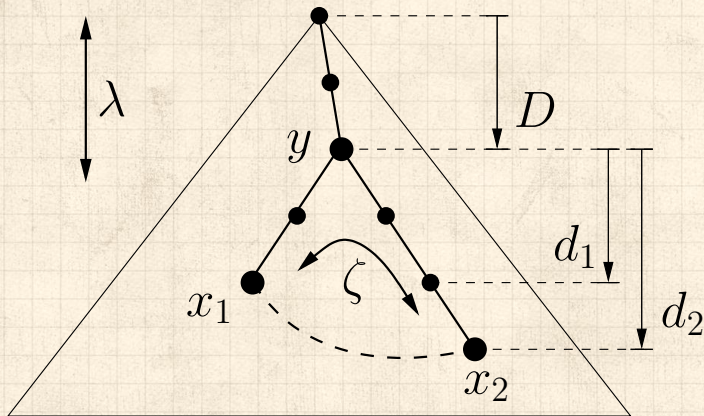
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Multiscale networks ($m = 12$):





Model—construction




 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

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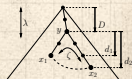
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Requirements for $f(d_1, d_2)$:



Model—construction

Requirements for $f(d_1, d_2)$:

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



Model—construction

Requirements for $f(d_1, d_2)$:

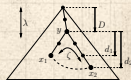
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2. f increases monotonically with d_1, d_2 .



Model—construction

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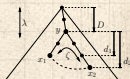
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Model—construction

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4. f is maximized when $d_1 = d_2$.



Model—construction

Requirements for $f(d_1, d_2)$:

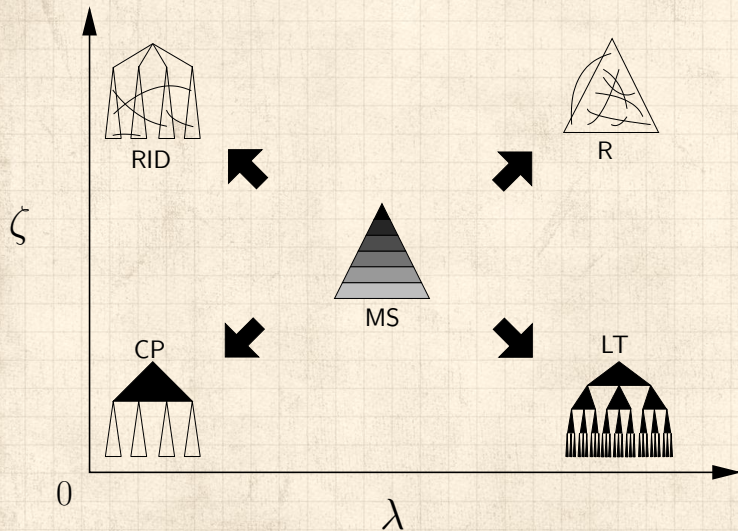
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2. f increases monotonically with d_1, d_2 .
3. $f(d_1, d_2) = f(d_2, d_1)$.
4. f is maximized when $d_1 = d_2$.

Simple function satisfying 1–4:

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



Model—limiting cases



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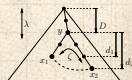
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Message passing pattern

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





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.



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.



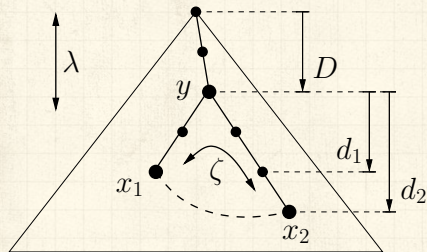
$$P(\text{recipient at distance } d) \propto e^{-d/\xi}.$$

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.



Message passing pattern


Simple message routing algorithm:

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



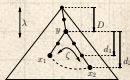
Message passing pattern

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.



Message passing pattern

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Interpretations:

1. Sender knows specific recipient.



Message passing pattern

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.



Message passing pattern

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.



Message passing pattern

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Performance:

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



Message passing pattern

Performance:

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



Message passing pattern

Performance:

🧱 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 .

🧱 Similar to betweenness centrality.

🧱 However: depends on

1. Search algorithm;
2. Task specification (μ, ξ) .



Message passing pattern

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 ρ_{\max} .



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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: $m = N$.




Performance testing:

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:

Parameter settings (unless varying):

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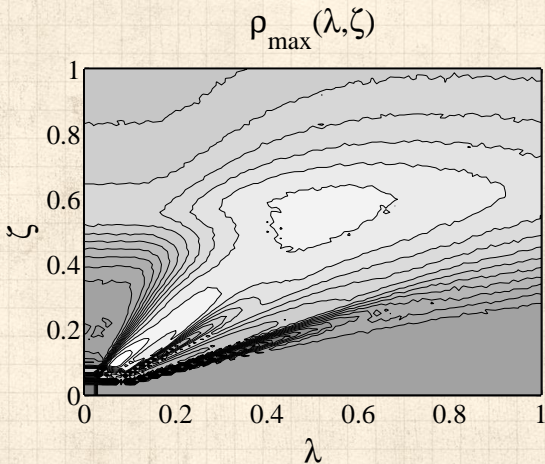
 Number of informal ties: $m = N$.

 Link addition algorithm: $\lambda = \zeta = 0.5$.

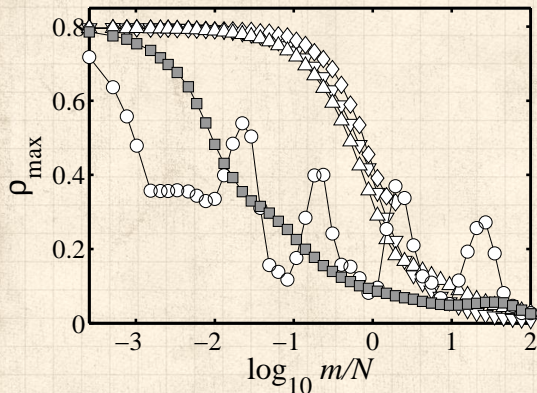
 Message passing: $\xi = 1, \mu = 10/N, T = 1000$.



Results—congestion robustness



Results—varying number of links added:



\diamond = TB

∇ = R

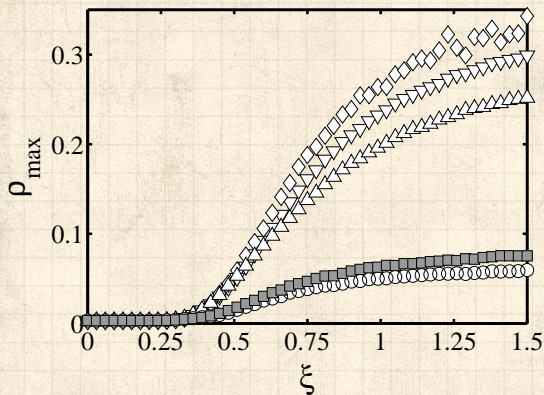
\triangle = RID

\circ = CP

\square = MS



Results—varying message passing pattern



◇=TB

▽=R

△=RID

○=CP

□=MS



Results—Maximum firm size

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Congestion may increase with size of network.



Results—Maximum firm size



Congestion may increase with size of network.

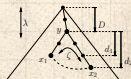


Fix rate of message passing (μ) and Message pattern (ξ).



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.

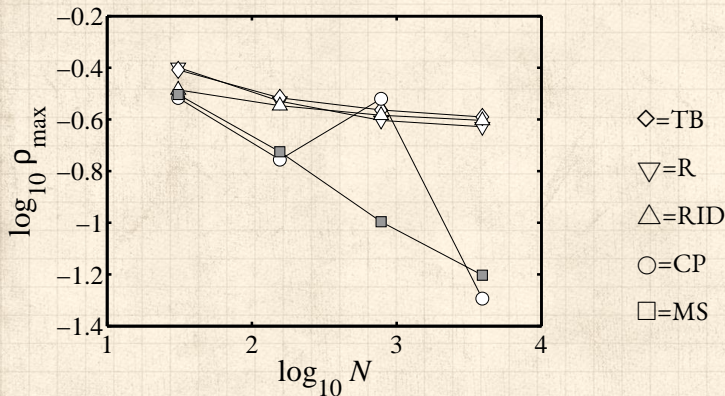


Results—Maximum firm size

- 🧱 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: $\xi = \infty$




Connectivity Robustness

Inducing catastrophic failure:


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



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.



Connectivity Robustness

Inducing catastrophic failure:

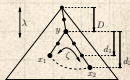
Remove N_r nodes and measure relative size of largest component

$$C = S / (N - N_r).$$

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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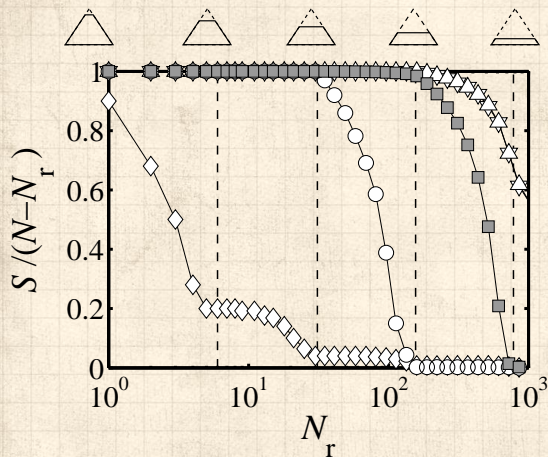
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Summary of results

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



Conclusory moments

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Multi-scale networks:

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⇒ Ultra-robust;



Conclusory moments

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 Above suggests existence of multi-scale structure is plausible.



Conclusory moments

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Overview

Toyota

Ambiguous problems

Models of organizations:

Modelification

Goals

Model

Testing

Results

Conclusion

References



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



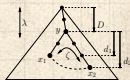
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- ⊞ Balance of **generalists versus specialists**—how many middle managers does an organization need?
- ⊞ Still a need for data on real organizations...



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