

Small-world networks

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Principles of Complex Systems, Vols. 1 & 2
CSYS/MATH 300 and 303, 2021-2022 | @pocsvox

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Vermont Advanced Computing Core | University of Vermont



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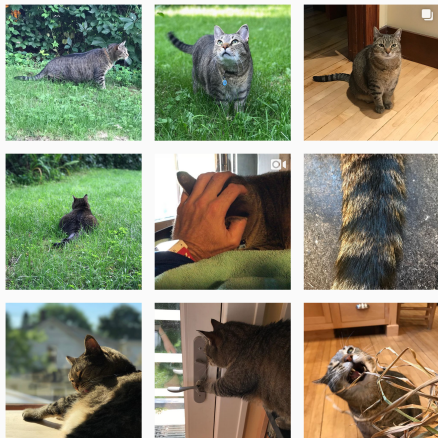
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People thinking about people:

How are social networks structured?

- How do we define and measure connections?
- Methods/issues of self-report and remote sensing.

What about the dynamics of social networks?


- How do social networks/movements begin & evolve?
- How does collective problem solving work?
- How does information move through social networks?
- Which rules give the best 'game of society'?


Sociotechnical phenomena and algorithms:

- What can people and computers do together? (google)
- Use Play + Crunch to solve problems. Which problems?



A small slice of the pie:

 **Q.** Can people pass messages between distant individuals using only their existing social connections?

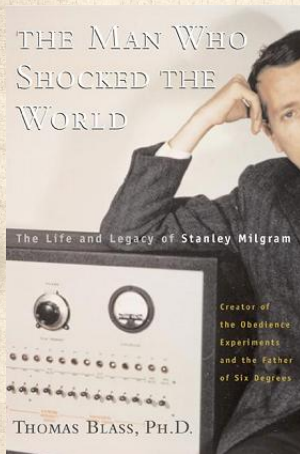
 **A.** Apparently yes ...



Milgram's social search experiment (1960s)

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<http://www.stanleymilgram.com>

- Target person = Boston stockbroker.
- 296 senders from Boston and Omaha.
- 20% of senders reached target.
- chain length ≈ 6.5 .

Popular terms:

- The Small World Phenomenon;
- “Six Degrees of Separation.”

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From Frigyes Karinthy's "Chain-links" in "Everything is Different", 1929:

'A fascinating game grew out of this discussion. One of us suggested performing the following experiment to prove that the population of the Earth is closer together now than they have ever been before. We should select any person from the 1.5 billion inhabitants of the Earth—anyone, anywhere at all. He bet us that, using no more than five individuals, one of whom is a personal acquaintance, he could contact the selected individual using nothing except the network of personal acquaintances. For example, "Look, you know Mr. X.Y., please ask him to contact his friend Mr. Q.Z., whom he knows, and so forth."



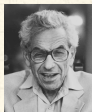
Six Degrees of Kevin Bacon:



It's a game: "Kevin Bacon is the Center of the Universe"

The Oracle of Bacon

Six Degrees of Paul Erdős:



Academic papers.

Erdős Number

Erdős Number Project

So naturally we must have the Erdős-Bacon Number.

One Story Lab alum has $EB\# < \infty$.

Natalie Hershlag's (Portman's) $EB\# = 5 + 2 = 7$.

The EBS# is also a thing: erdosbaconsabbath.com.

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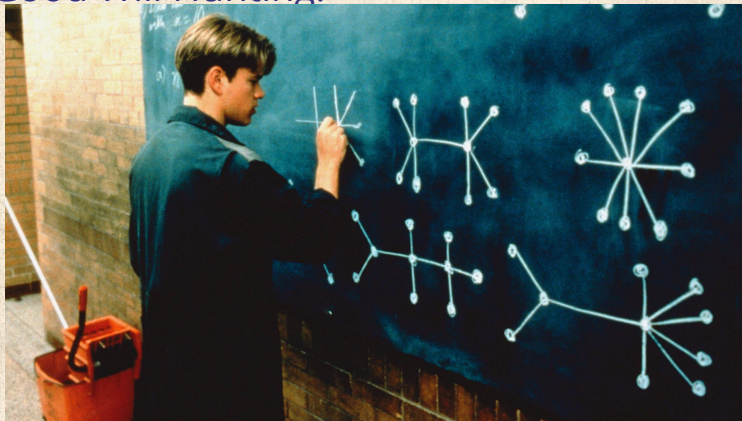
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Good Will Hunting:



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 Boardwork by Dan Kleitman ,
 $EB\# = 1 + 2 = 3$.

 See Kleitman's sidebar in
Mark Saul's Movie Review 
(Notices of the AMS, Vol. 45,
1998.)



You may already be a winner in NSA's "three-degrees" surveillance sweepstakes!



NSA's probes could cover hundreds of millions of Americans. Thanks, Kevin Bacon.

by Sean Gallagher - July 18 2013, 4:00pm EDT

BIG DATA 109



Aurich Lawson

 Many people  are within three degrees from a random person ...

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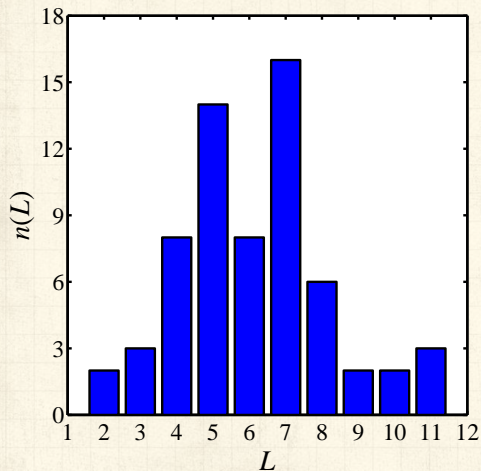


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Lengths of successful chains:



From Travers and
Milgram (1969) in
Sociometry: ^[9]
"An Experimental
Study of the Small
World Problem."

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Two features characterize a social 'Small World':

1. Short paths exist, (= Geometric piece)
and
2. People are good at finding them. (= Algorithmic piece)



Social Search

Milgram's small world experiment with email:

Events and News
Duncan J. Watts's new book is out now!

Project Information
In the Press
Description
Procedures
Security and Privacy
Articles/References
Results

Research Team
Duncan J. Watts
Peter Dodds
Roby Muhamad
Peter Haisul

Web Development
Peter Haisul

Vijay (Delhi, India) worked at an engineering firm with...

Sareer (Kolkata, India) whose daughter...

Prima (Berkeley, USA) goes to school in California and plays soccer with...

Christie (Sanctuary, USA) whose best friend from high school...

Alice (New York, USA)

William (New York, NY) is studying medicine with...

home
my small world
chat
FAQ
related links

login
sign up

The **SMALL WORLD** project is an online experiment to test the idea that any two people in the world can be connected via "six degrees of separation".

Your objective is to get a message to a "target person", somewhere in the world, by forwarding the message to a friend of yours—someone who is "closer" to the target than you are. (If you happen know the target, you can of course send it to them)

If we have asked you to participate (you would have received a message from a friend of yours), you should **CONTINUE** the chain.

If you are just visiting us, sign up to start a new chain.

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"An Experimental Study of Search in Global Social Networks" 

Dodds, Muhamad, and Watts, Science, **301**, 827–829, 2003. ^[4]



Social search—the Columbia experiment

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- 60,000+ participants in 166 countries
- 18 targets in 13 countries including
 - a professor at an Ivy League university,
 - an archival inspector in Estonia,
 - a technology consultant in India,
 - a policeman in Australia,
 - and
 - a veterinarian in the Norwegian army.
- 24,000+ chains

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We were lucky and contagious (more later):

[“Using E-Mail to Count Connections”](#) ↗, Sarah Milstein,
New York Times, Circuits Section (December, 2001)



All targets:

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Table S1

Target	City	Country	Occupation	Gender	N	N_c (%)	r (ro)	<L>
1	Novosibirsk	Russia	PhD student	F	8234	20(0.24)	64 (76)	4.05
2	New York	USA	Writer	F	6044	31 (0.51)	65 (73)	3.61
3	Bandung	Indonesia	Unemployed	M	8151	0	66 (76)	n/a
4	New York	USA	Journalist	F	5690	44 (0.77)	60 (72)	3.9
5	Ithaca	USA	Professor	M	5855	168 (2.87)	54 (71)	3.84
6	Melbourne	Australia	Travel Consultant	F	5597	20 (0.36)	60 (71)	5.2
7	Bardufoss	Norway	Army veterinarian	M	4343	16 (0.37)	63 (76)	4.25
8	Perth	Australia	Police Officer	M	4485	4 (0.09)	64 (75)	4.5
9	Omaha	USA	Life Insurance Agent	F	4562	2 (0.04)	66 (79)	4.5
10	Welwyn Garden City	UK	Retired	M	6593	1 (0.02)	68 (74)	4
11	Paris	France	Librarian	F	4198	3 (0.07)	65 (75)	5
12	Tallinn	Estonia	Archival Inspector	M	4530	8 (0.18)	63(79)	4
13	Munich	Germany	Journalist	M	4350	32 (0.74)	62 (74)	4.66
14	Split	Croatia	Student	M	6629	0	63 (77)	n/a
15	Gurgaon	India	Technology Consultant	M	4510	12 (0.27)	67 (78)	3.67
16	Managua	Nicaragua	Computer analyst	M	6547	2 (0.03)	68 (78)	5.5
17	Katikati	New Zealand	Potter	M	4091	12 (0.3)	62 (74)	4.33
18	Elderton	USA	Lutheran Pastor	M	4438	9 (0.21)	68 (76)	4.33
Totals					98,847	384 (0.4)	63 (75)	4.05

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- ☰ Milgram's participation rate was roughly 75%
- ☰ Email version: Approximately 37% participation rate.
- ☰ Probability of a chain of length 10 getting through:

$$.37^{10} \simeq 5 \times 10^{-5}$$

- ☰ \Rightarrow 384 completed chains (1.6% of all chains).

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 Motivation/Incentives/Perception matter.

 If target *seems* reachable
⇒ participation more likely.

 Small changes in attrition rates
⇒ large changes in completion rates

 e.g., ↘ 15% in attrition rate
⇒ ↗ 800% in completion rate

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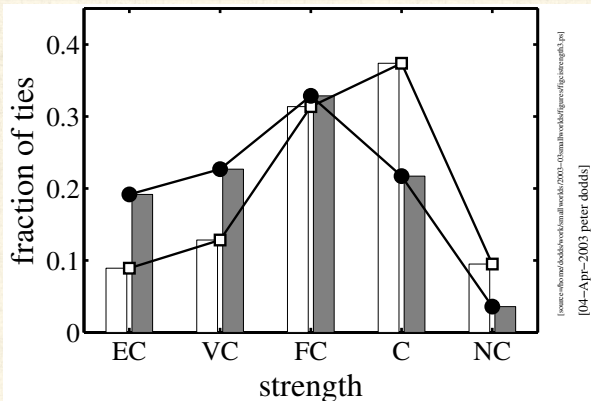
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Comparing successful to unsuccessful chains:

 Successful chains used relatively weaker ties:



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Successful chains disproportionately used:

-  Weak ties, Granovetter ^[5]
-  Professional ties (34% vs. 13%)
-  Ties originating at work/college
-  Target's work (65% vs. 40%)

...and disproportionately avoided

-  hubs (8% vs. 1%) (+ no evidence of funnels)
-  family/friendship ties (60% vs. 83%)

Geography → Work

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Senders of successful messages showed
little absolute dependency on

-  age, gender
-  country of residence
-  income
-  religion
-  relationship to recipient

Range of completion rates for subpopulations:

30% to 40%

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Mildly bad for continuing chain:

choosing recipients because “they have lots of friends”
or because they will “likely continue the chain.”

Why:

-  Specificity important
-  Successful links used relevant information.
(e.g. connecting to someone who shares same profession as target.)

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Basic results:


 $\langle L \rangle = 4.05$ for all completed chains

 L_* = Estimated 'true' median chain length (zero attrition)

 Intra-country chains: $L_* = 5$

 Inter-country chains: $L_* = 7$

 All chains: $L_* = 7$

 Milgram: $L_* \simeq 9$

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Harnessing social search:

- Can distributed social search be used for something big/good?
- What about something evil? (Good idea to check.)
- What about socio-inspired algorithms for information search? (More later.)
- For real social search, we have an incentives problem.
- Which kind of influence mechanisms/algorithms would help propagate search?
- Fun, money, prestige, ...?
- Must be 'non-gameable.'












Red balloons:

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A Grand Challenge:

-  1969: The Internet is born 
(the ARPANET —four nodes!).
-  Originally funded by DARPA who created a grand Network Challenge  for the 40th anniversary.
-  Saturday December 5, 2009: DARPA puts 10 red weather balloons up during the day.
-  Each 8 foot diameter balloon is anchored to the ground **somewhere in the United States**.
-  Challenge: Find the latitude and longitude of each balloon.
-  Prize: **\$40,000**.

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*DARPA = Defense Advanced Research Projects Agency .



Where the balloons were:

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Finding red balloons:

The winning team and strategy:

- MIT's Media Lab [↗](#) won in less than 9 hours. ^[7]
- Pickard et al. "Time-Critical Social Mobilization," ^[7] Science Magazine, 2011.
- People were virally recruited online to help out.
- Idea: Want people to both (1) find the balloons, and (2) involve more people.
- Recursive incentive structure with exponentially decaying payout:
 - \$2000 for correctly reporting the coordinates of a balloon.
 - \$1000 for recruiting a person who finds a balloon.
 - \$500 for recruiting a person who recruits the balloon finder, ...
 - (Not a Ponzi scheme.)

True victory: [Colbert interviews Riley Crane](#) [↗](#)




Finding balloons:

Clever scheme:

- Max payout = \$4000 per balloon.
- Individuals have clear incentives to both
 - involve/source more people (spread), and
 - find balloons (goal action).
- Gameable?
- Limit to how much money a set of bad actors can extract.

Extra notes:

- MIT's brand helped greatly.
- MIT group first heard about the competition a few days before. **Ouch.**
- A number of other teams did well .
- Worthwhile looking at these competing strategies. ^[7]



Collective Detective:

Finding an errant panda

Once again, social media proved to be a powerful dragnet. Around 1:15 p.m., a Washingtonian posted a picture on Twitter of Rusty in a patch of weeds in the Adams Morgan district, not far from the 163-acre zoo, which was created in 1889 by an act of Congress. "Red panda in our neighborhood," wrote Ashley Foughty, who identified herself as a singer, actress and traveler. "Please come save him!"

Another neighbor posted a [photograph](#) of two zoo workers, one in safari shorts standing on a rooftop, one holding a giant butterfly net. Soon the zoo announced: "Rusty the red panda has been recovered, crated & is headed safely back to the National Zoo!"

Nature News: "Crowdsourcing in manhunts can work: Despite mistakes over the Boston bombers, social media can help to find people quickly" by Philip Ball (April 26, 2013)

Motherboard, Vice: One Degree of Separation in the Forever War by Brian Castner (November 11, 2015)

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The social world appears to be small ...why?

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Theory: how do we understand the small world property?

 Connected random networks have short average path lengths:

$$\langle d_{AB} \rangle \sim \log(N)$$

N = population size,

d_{AB} = distance between nodes A and B .

 But: social networks aren't random ...

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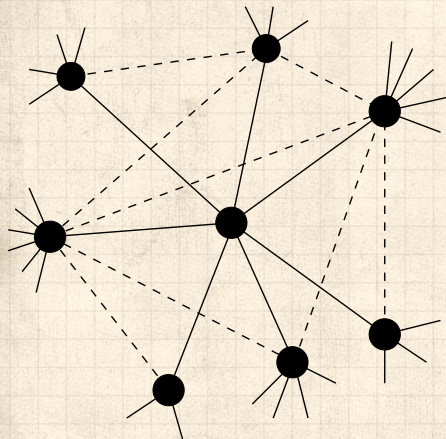
References



Simple socialness in a network:

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Need “clustering”
(your friends are
likely to know each
other):

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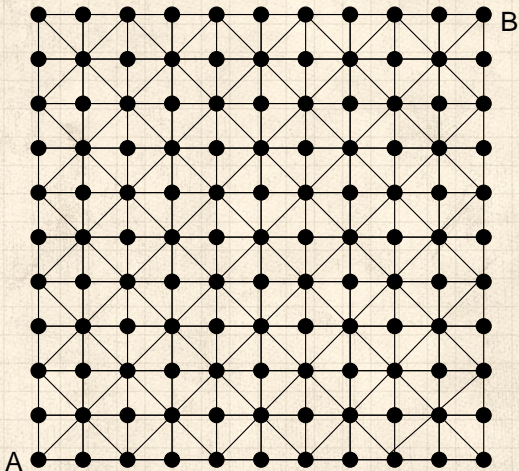
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Non-randomness gives clustering:

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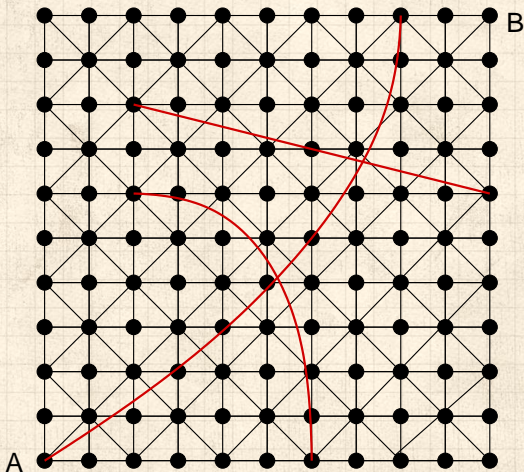
$d_{AB} = 10 \rightarrow$ too many long paths.



Randomness + regularity

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Now have $d_{AB} = 3$

$\langle d \rangle$ decreases overall



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Introduced by Watts and Strogatz (Nature, 1998)^[11]
"Collective dynamics of 'small-world' networks."

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Small-world networks were found everywhere:

-  neural network of C. elegans,
-  semantic networks of languages,
-  actor collaboration graph,
-  food webs,
-  social networks of comic book characters, ...

Very weak requirements:

-  local regularity + random short cuts



Papers should be apps:

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ALGORITHM To interpolate between regular and random networks, we consider the following random rewiring procedure.

We start with a ring of n vertices where each vertex is connected to its k nearest neighbors like so. We choose a vertex, and the edge to its nearest clockwise neighbour. With probability p , we reconnect this edge to a vertex chosen uniformly at random over the entire ring, with duplicate edges forbidden. Otherwise, we leave the edge in place. We repeat this process by moving clockwise around the ring, considering each vertex in turn until one lap is completed.

Next, we consider the edges that connect vertices to their second-nearest neighbours clockwise. As before, we randomly rewired each of these edges with probability p . We continue this process, circling around the ring and proceeding outward to more distant neighbours after each lap, until each original edge has been considered once. For $p = 0$, the ring is unchanged. As p increases, the graph becomes increasingly disordered. At $p = 1$, all edges are rewired randomly.

As there are $nk/2$ edges in the entire graph, the rewiring process stops after $k/2$ laps. This construction allows us to "tune" the graph between regularity ($p = 0$) and disorder ($p = 1$), and thereby to probe the intermediate region $0 < p < 1$, about which little is known.

METRICS We quantify the structural properties of these graphs by their **characteristic path length $L(p)$** and **clustering coefficient $C(p)$** . $L(p)$ measures the typical separation between two vertices (a global property). $C(p)$ measures the cliquishness of a typical neighbourhood (a local property).

L is defined as the number of edges in the shortest path between two vertices averaged over all pairs of vertices. C is defined as follows. Suppose that a vertex v has k_v neighbours. Then at most $k_v(k_v - 1)/2$ edges can exist between them. (This occurs when every neighbor of v is connected to every other neighbour of v .) Let C_v denote the fraction of these allowable edges that actually exist. Define C as the average of C_v over all vertices.

For friendship networks, these statistics have intuitive meanings: L is the average number of friendships in the shortest chain connecting two people. C_v reflects the extent to which friends of v are also friends of each other, and thus C measures the cliquishness of a typical friendship circle.

SMALL WORLDS The regular lattice at $p = 0$ is a highly clustered, large world where L grows linearly with n . The random network at $p = 1$ is a poorly clustered, small world where L grows only logarithmically with n . These limiting cases might lead one to suspect that large C is always associated with large L , and small C with small L . On the contrary, we find that there is a broad interval of p over which $L(p)$ is almost as small as L_{random} yet $C(p) \gg C_{\text{random}}$.



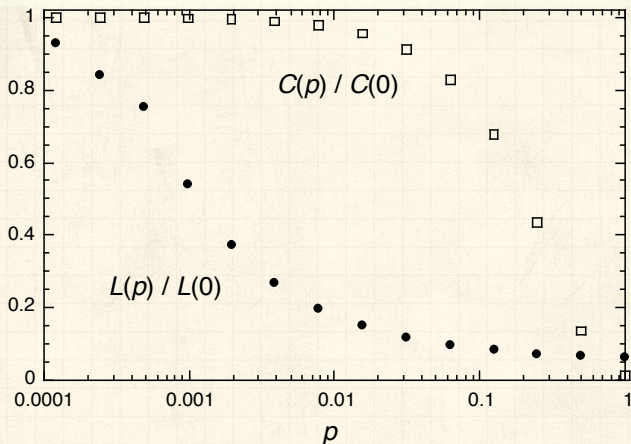
Bret Victor's Scientific Communication As Sequential Art





Interactive figures and tables = windows into large data sets (empirical or simulated).



The structural small-world property:



 $L(p)$ = average shortest path length as a function of p

 $C(p)$ = average clustering as a function of p

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Previous work—finding short paths

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But are these short cuts findable?

Nope. [6]

Nodes **cannot** find each other quickly
with **any local search method**.

Need a more sophisticated model ...

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- What can a local search method reasonably use?
- How to find things without a map?
- Need some measure of distance between friends and the target.

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Some possible knowledge:

- Target's identity
- Friends' popularity
- Friends' identities
- Where message has been



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Jon Kleinberg (Nature, 2000) [6]
“Navigation in a small world.”

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Allowed to vary:

1. local search algorithm
and
2. network structure.



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Kleinberg's Network:

1. Start with regular d -dimensional cubic lattice.
2. Add local links so nodes know all nodes within a distance q .
3. Add m short cuts per node.
4. Connect i to j with probability

$$p_{ij} \propto x_{ij}^{-\alpha}.$$



$\alpha = 0$: random connections.



α large: reinforce local connections.



$\alpha = d$: connections grow logarithmically in space.

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Theoretical optimal search:

- 🧱 “Greedy” algorithm.
- 🧱 Number of connections grow logarithmically (slowly) in space: $\alpha = d$.
- 🧱 Social golf.

Search time grows slowly with system size (like $\log^2 N$).

But: social networks aren't lattices plus links.

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- ⊞ If networks have hubs can also search well:
Adamic et al. (2001)^[1]

$$P(k_i) \propto k_i^{-\gamma}$$

where k = degree of node i (number of friends).

- ⊞ Basic idea: get to hubs first
(airline networks).
- ⊞ But: hubs in social networks are limited.

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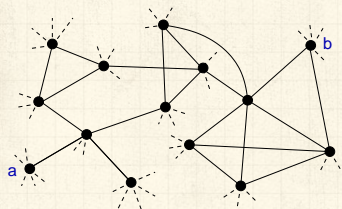


The problem

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If there are no hubs and no underlying lattice, how can search be efficient?



Which friend of **a** is closest to the target **b**?

What does 'closest' mean?

What is 'social distance'?

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One approach: incorporate **identity**.

Identity is formed from attributes such as:

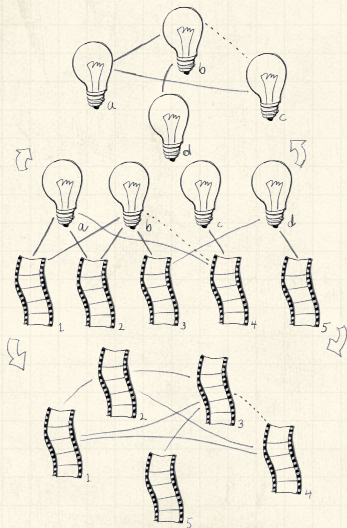
-  Geographic location
-  Type of employment
-  Religious beliefs
-  Recreational activities.

Groups are formed by people with at least one similar attribute.

Attributes \Leftrightarrow Contexts \Leftrightarrow Interactions \Leftrightarrow Networks.



Bipartite affiliation structures:



Many real-world networks have an underlying multi-partite structure.

- Stories-tropes.
- Boards and directors.
- Films-actors-directors.
- Classes-teachers-students.
- Upstairs-downstairs.



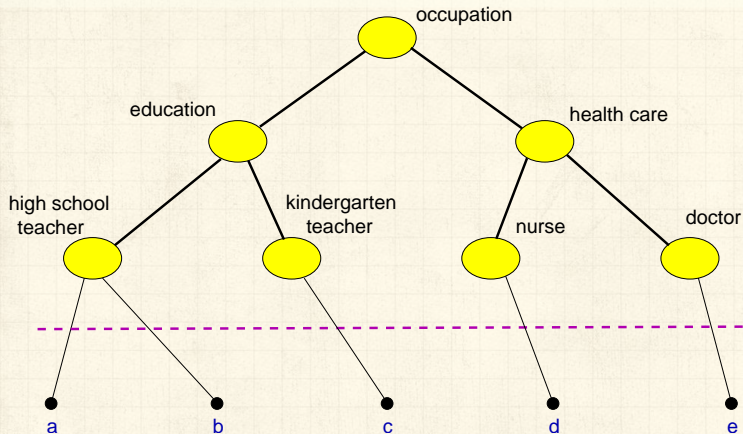
Unipartite networks may be induced or co-exist.



Social distance—Context distance

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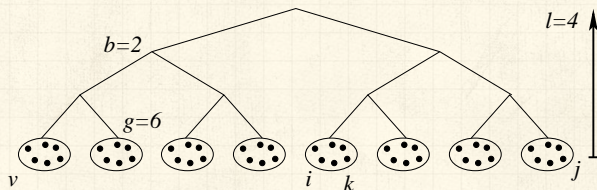
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Distance between two individuals x_{ij} is the height of lowest common ancestor.




$$x_{ij} = 3, x_{ik} = 1, x_{iv} = 4.$$




 Individuals are more likely to know each other the closer they are within a hierarchy.

 Construct z connections for each node using

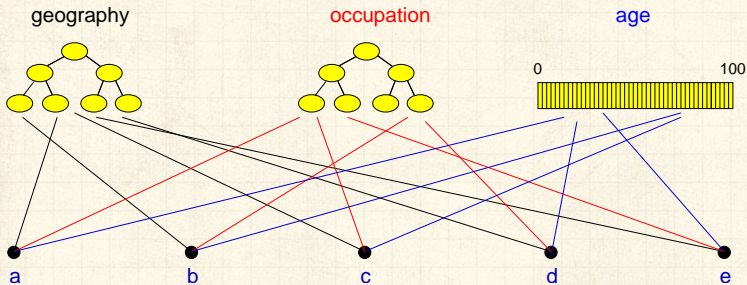
$$p_{ij} = c \exp\{-\alpha x_{ij}\}.$$

 $\alpha = 0$: random connections.

 α large: local connections.



Generalized affiliation networks



Blau & Schwartz [2], Simmel [8], Breiger [3], Watts *et al.* [10]; see also Google+ Circles.



The model

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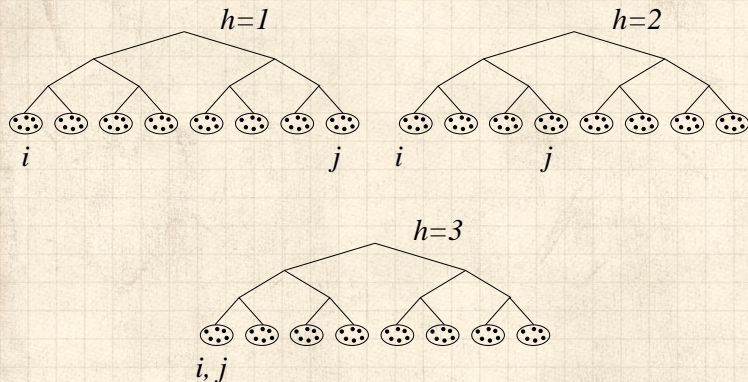
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$$\vec{v}_i = [1 \ 1 \ 1]^T, \vec{v}_j = [8 \ 4 \ 1]^T$$

$$x_{ij}^1 = 4, x_{ij}^2 = 3, x_{ij}^3 = 1.$$

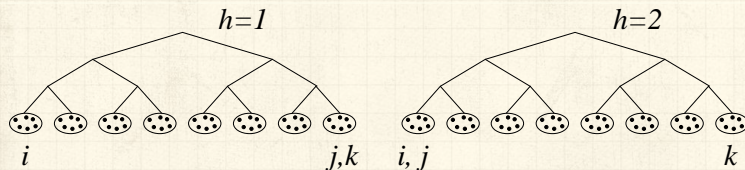
Social distance:

$$y_{ij} = \min_h x_{ij}^h.$$



The model

Triangle inequality doesn't hold:



$$y_{ik} = 4 > y_{ij} + y_{jk} = 1 + 1 = 2.$$



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Individuals know the identity vectors of

1. themselves,
2. their friends,
and
3. the target.



Individuals can estimate the social distance
between their friends and the target.



Use a greedy algorithm + allow searches to fail
randomly.

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The model-results—searchable networks

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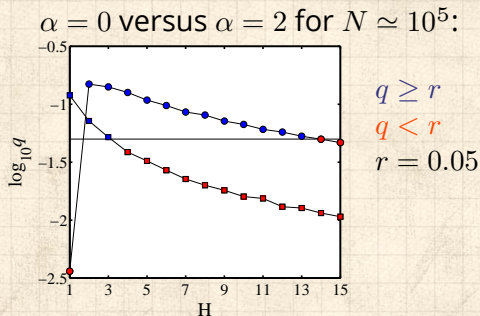
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q = probability an arbitrary message chain reaches a target.

-  A few dimensions help.
-  Searchability decreases as population increases.
-  Precise form of hierarchy largely doesn't matter.

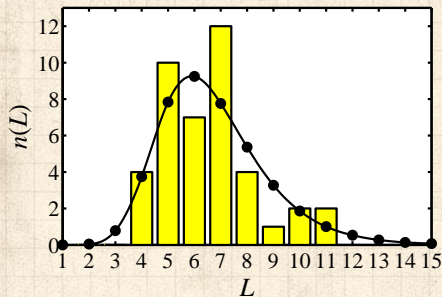


The model-results


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Milgram's Nebraska-Boston data:





Model parameters:


 $N = 10^8,$

 $z = 300, g = 100,$

 $b = 10,$

 $\alpha = 1, H = 2;$

 $\langle L_{\text{model}} \rangle \simeq 6.7$

 $L_{\text{data}} \simeq 6.5$

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Adamic and Adar (2003)


- For HP Labs, found probability of connection as function of organization distance well fit by exponential distribution.
- Probability of connection as function of real distance $\propto 1/r$.






Social Search—Real world uses



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 Tags create identities for objects

 Website tagging: bitly.com 

 (e.g., Wikipedia)

 Photo tagging: flickr.com 

 Dynamic creation of metadata plus links between information objects.

 Folksonomy: collaborative creation of metadata

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Social Search—Real world uses

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Recommender systems:

- Amazon uses people's actions to build effective connections between books.
- Conflict between 'expert judgments' and tagging of the hoi polloi.

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Nutshell for Small-World Networks:

-  Bare networks are typically unsearchable.
-  Paths are findable if nodes understand how network is formed.
-  Importance of identity (interaction contexts).
-  Improved social network models.
-  Construction of peer-to-peer networks.
-  Construction of searchable information databases.



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