small-world networks

introduction to *network analysis* (*ina*)

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small-world *documentary*

connected

the power of six degrees

documentary on small-world and scale-free networks

letters to nature

Collective dynamics of 'small-world' networks

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Networks of coupled dynamical systems have been used to model biological oscillators[1–4], Josephson junction arrays[5], excitable media[6], neural networks[7–9], spatial games[10], genetic control networks[11] and many other self-organizing systems. Ordinarily, the connection topology is assumed to be either completely regular or completely random. But many biological, technological and social networks lie somewhere between these two extremes. Here we explore simple models of networks that can be tuned through this middle ground: regular networks 'rewired' to introduce increasing amounts of disorder. We find that these systems can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. We call them 'small-world' networks, by analogy with the small-world phenomenon[12,13] (popularly known as six degrees of separation[14]). The neural network of the worm Caenorhabditis elegans, the power grid of the western United States, and the collaboration graph of film actors are shown to be small-world networks. Models of dynamical systems with small-world coupling display enhanced signal-propagation speed, computational power, and synchronizability. In particular, infectious diseases spread more easily in small-world networks than in regular lattices.

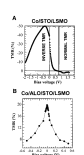

Fig. 2 Rise dependence of the TMR ratio in (A) Co/STO/LSMO and (B) Co/AlO/STO/LSMO tunnel junctions.

REPORTS

Emergence of Scaling in Random Networks

Albert-László Barabási* and Réka Albert

Systems as diverse as genetic networks or the World Wide Web are best described as networks with complex topology. A common property of many large networks is that the vertex connectivities follow a scale-free power-law distribution. This feature was found to be a consequence of two generic mechanisms: (i) networks expand continuously by the addition of new vertices, and (ii) new vertices attach preferentially to sites that are already well connected. A model based on these two ingredients reproduces the observed stationary scale-free distributions, which indicates that the development of large networks is governed by robust self-organizing phenomena that go beyond the particulars of the individual systems.

letters to nature

Error and attack tolerance of complex networks

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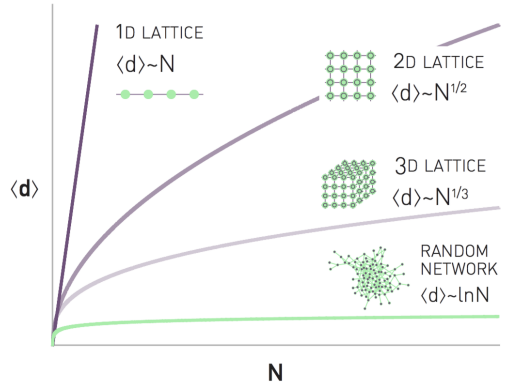
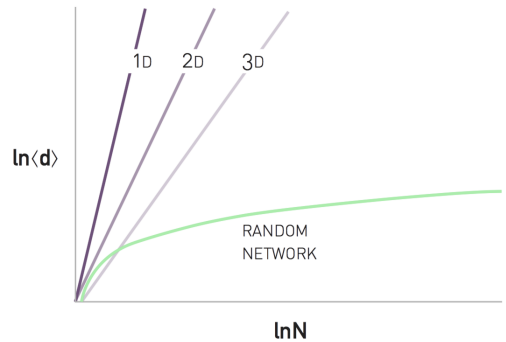
Many complex systems display a surprising degree of tolerance against errors. For example, relatively simple organisms grow, persist and reproduce despite drastic pharmaceutical or environmental interventions, an error tolerance attributed to the robustness of the underlying metabolic network[1]. Complex communication networks[2] display a surprising degree of robustness: although key components regularly malfunction, local failures rarely lead to the loss of the global information-carrying ability. The stability of these and other complex systems[3,4] is often attributed to the redundant wiring of the functional web defined by the systems' components. Here we demonstrate that error tolerance is not shared by all redundant systems: it is displayed only by a class of inhomogeneously wired networks,

[WS98] [BA99] [AJB00]

small-world *phenomenon*

- for *regular lattices*
  - *high clustering* $\langle C \rangle \gg 0$
  - long distances $\langle d \rangle \simeq n^{1/D}$
- in *random graphs* [ER59]
  - low clustering $\langle C \rangle = \frac{\langle k \rangle}{n-1}$
  - *short distances* $\langle d \rangle \simeq \frac{\ln n}{\ln \langle k \rangle}$
- real *small-world networks* [WS98]
  - *high clustering* $\langle C \rangle \gg 0$
  - *short distances* $\langle d \rangle \simeq \frac{\ln n}{\ln \langle k \rangle}$





- $\langle d \rangle = 4.74$ for *Facebook* friendships [BBR+12] while $\frac{\ln n}{\ln \langle k \rangle} = 3.98$
- $\langle C \rangle = 0.61$ for *Facebook* social circles [NL12] while $\rho < 10^{-6}$

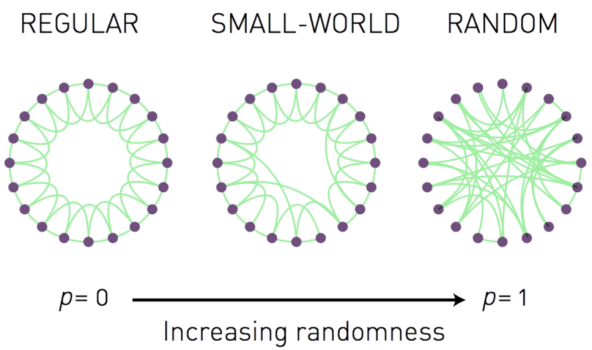
small-world *model*

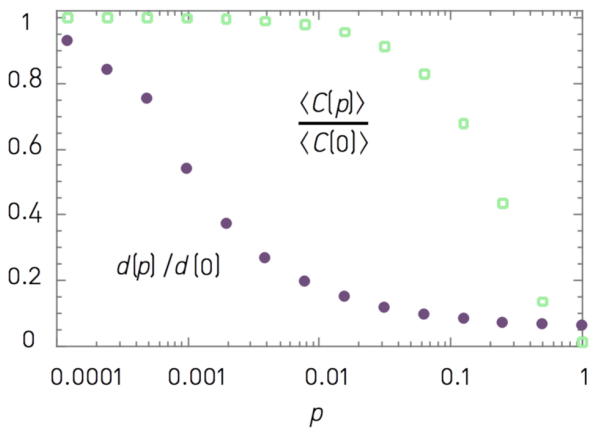
— $G(n, k, p)$ *small-world* model [WS98]

— *randomly rewire* $pnk/2$ *links* of *regular lattice*

— *conceptually interesting* but *practically inapplicable*

- for *some* p *small-world* with $\langle d \rangle \simeq \frac{\ln n}{\ln \langle k \rangle}$ and $\langle C \rangle \gg 0$
- for $p = 1$ *random graph* with $\langle d \rangle \simeq \frac{\ln n}{\ln \langle k \rangle}$
- for $p = 0$ *regular lattice* with $C = \frac{3(k-2)}{4(k-1)}$





see small-world model NetLogo demo

small-world *networks*

— *clustering coefficient* $\langle C \rangle$ in *real small-world* networks

— *average distance* $\langle d \rangle$ in *real small-world* networks

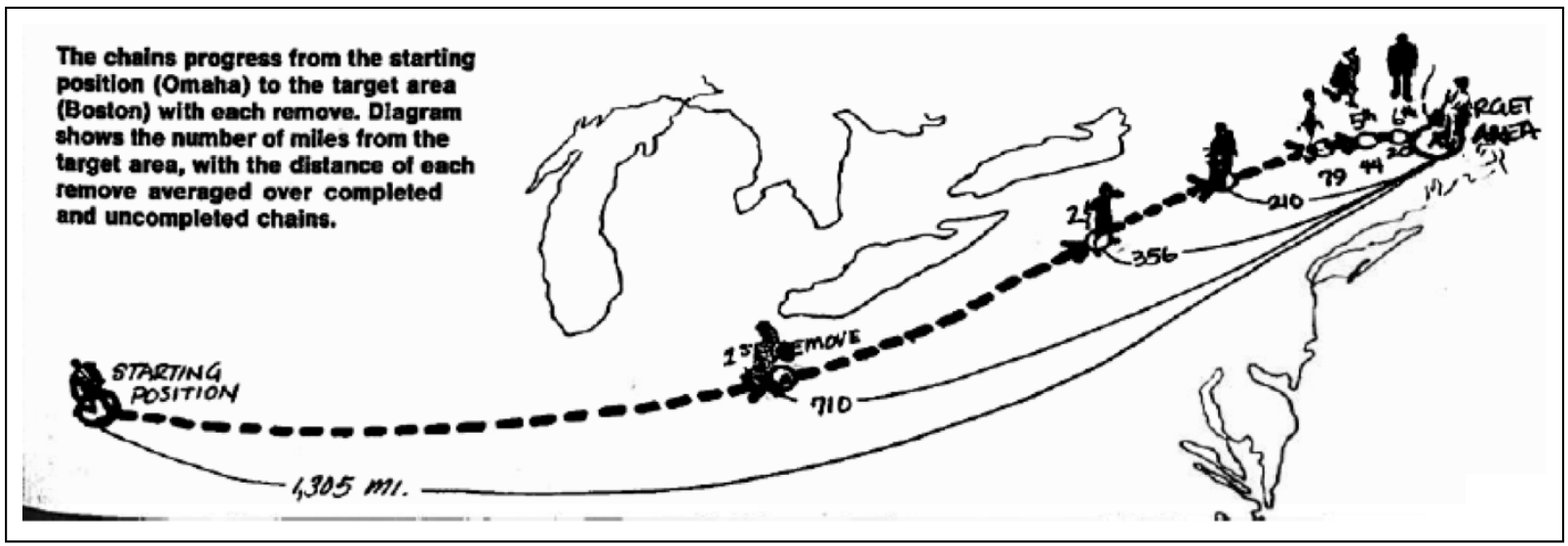
network	n	$\langle C \rangle$	$\gg \frac{\langle k \rangle}{n-1}$	$\langle d \rangle$	$\approx \frac{\ln n}{\ln \langle k \rangle}$
southern women [DGG41]	32	0.000	0.179	2.31	2.02
karate club [Zac77]	34	0.571	0.139	2.41	2.31
American football [GN02]	115	0.403	0.094	2.51	2.00
Java dependencies [ŠB11]	1368	0.497	0.012	2.21	2.59
Facebook circles [ML12]	4039	0.606	0.011	3.69	2.20
physics collaboration [New01]	36 458	0.657	0.000	5.50	4.68
Enron e-mails [LLDM09]	36 692	0.497	0.001	3.39	3.51
Internet map [HJJ+03]	75 885	0.160	0.000	5.83	5.01
actors collaboration [BA99]	382 219	0.780	0.000	≈ 3.6	2.94
physics citation [ŠFB14]	438 943	0.227	0.000	≈ 5.0	4.23
patent citation [HJT01]	3 774 768	0.076	0.000	≈ 8.1	6.98
Facebook snowball [Fer12]	8 217 272	0.019	0.000	≈ 6.8	14.23

small-world *experiments*

— 6 *degrees of separation* in *letter* passing as $\langle d \rangle = 6.2$ [Mil67]

— 4/7 *degrees of separation* in *e-mail* communication [DMW03]

— 4 *degrees of separation* on *Facebook* as $\langle d \rangle = 4.74$ [BBR+12]



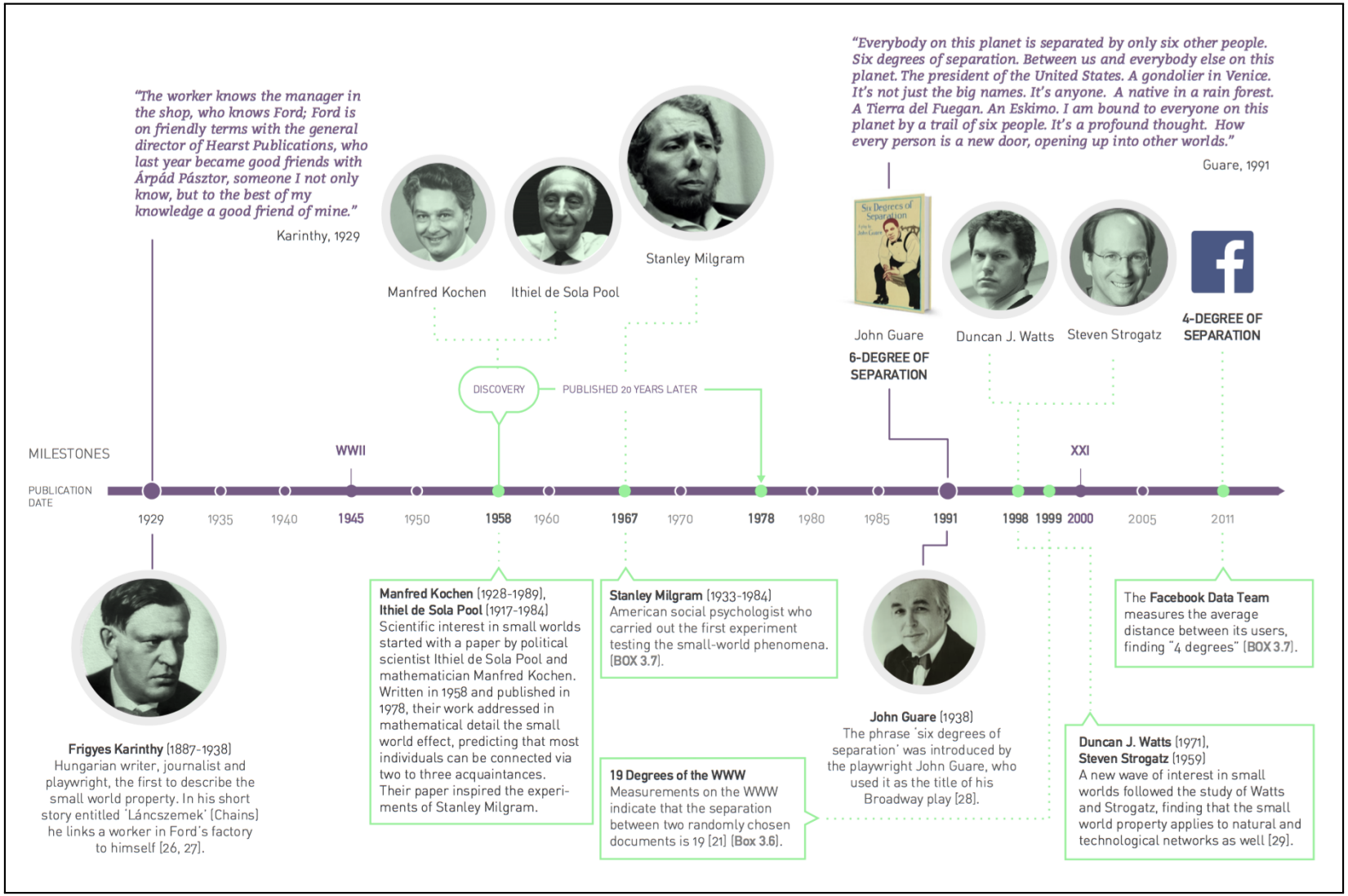
— the *strength* (*weakness*) of *weak* (*strong*) *ties* [Gra73]

small-world *navigation*

does existence of short paths imply

navigable small-world by *decentralized search*? [Kle00]

small-world *history*



small-world *references*

Reka Albert, Hawoong Jeong, and Albert Laszlo Barabasi.
Error and attack tolerance of complex networks.
Nature, 406(6794):378–382, 2000.

A.-L. Barabási and R. Albert.
Emergence of scaling in random networks.
Science, 286(5439):509–512, 1999.

A.-L. Barabási.
Network Science.
Cambridge University Press, Cambridge, 2016.

Lars Backstrom, Paolo Boldi, Marco Rosa, Johan Ugander, and Sebastiano Vigna.
Four degrees of separation.
In *Proceedings of the ACM International Conference on Web Science*, pages 45–54, Evanston, IL, USA, 2012.

A. Davis, B. B. Gardner, and M. R. Gardner.
Deep South.
Chicago University Press, Chicago, 1941.

Peter Sheridan Dodds, Roby Muhamad, and Duncan J. Watts.
An experimental study of search in clobal social networks.
Science, 301(5634):827–829, 2003.

Wouter de Nooy, Andrej Mrvar, and Vladimir Batagelj.
Exploratory Social Network Analysis with Pajek: Expanded and Revised Second Edition.
Cambridge University Press, Cambridge, 2011.

David Easley and Jon Kleinberg.
Networks, Crowds, and Markets: Reasoning About a Highly Connected World.
Cambridge University Press, Cambridge, 2010.

small-world *references*

Ernesto Estrada and Philip A. Knight.
A First Course in Network Theory.
Oxford University Press, 2015.

P. Erdős and A. Rényi.
On random graphs I.
Publ. Math. Debrecen, 6:290–297, 1959.

Stefano Ferretti.
On the degree distribution of faulty peer-to-peer overlays.
ICST Transactions on Complex Systems, 2012.

M. Girvan and M. E. J Newman.
Community structure in social and biological networks.
P. Natl. Acad. Sci. USA, 99(12):7821–7826, 2002.

Mark S. Granovetter.
The strength of weak ties.
Am. J. Sociol., 78(6):1360–1380, 1973.

M Hoerdt, M Jaeger, A James, D Magoni, J Maillard, D Malka, and P Merindol.
Internet {IP}v4 overlay map produced by network cartographer (nec), 2003.

B. H. Hall, A. B. Jaffe, and M. Tratjenberg.
The NBER patent citation data file: Lessons, insights and methodological tools.
Technical report, National Bureau of Economic Research, 2001.

Jon M. Kleinberg.
Navigation in a small world.
Nature, 406(6798):845, 2000.

small-world *references*

Jure Leskovec, Kevin J Lang, Anirban Dasgupta, and Michael W Mahoney.

Community structure in large networks: Natural cluster sizes and the absence of large well-defined clusters.
Internet Math., 6(1):29–123, 2009.

Stanley Milgram.

The small world problem.
Psychol. Today, 1(1):60–67, 1967.

Seth A. Myers and Jure Leskovec.

Clash of the contagions: Cooperation and competition in information diffusion.
In *Proceedings of the IEEE International Conference on Data Mining*, 2012.

M. E. J. Newman.

The structure of scientific collaboration networks.
P. Natl. Acad. Sci. USA, 98(2):404–409, 2001.

Mark E. J. Newman.

Networks.
Oxford University Press, Oxford, 2nd edition, 2018.

Azree Nazri and Pietro Lio.

Investigating meta-approaches for reconstructing gene networks in a mammalian cellular context.
PLoS ONE, 7(1):e28713, 2012.

Lovro Šubelj and Marko Bajec.

Community structure of complex software systems: Analysis and applications.
Physica A, 390(16):2968–2975, 2011.

Lovro Šubelj, Dalibor Fiala, and Marko Bajec.

Network-based statistical comparison of citation topology of bibliographic databases.
Sci. Rep., 4:6496, 2014.

small-world *references*

D. J. Watts and S. H. Strogatz.
Collective dynamics of 'small-world' networks.
Nature, 393(6684):440–442, 1998.

Wayne W. Zachary.
An information flow model for conflict and fission in small groups.
J. Anthropol. Res., 33(4):452–473, 1977.