Epidemics, Erdős Numbers, and the Internet: The Form and Function of Networks

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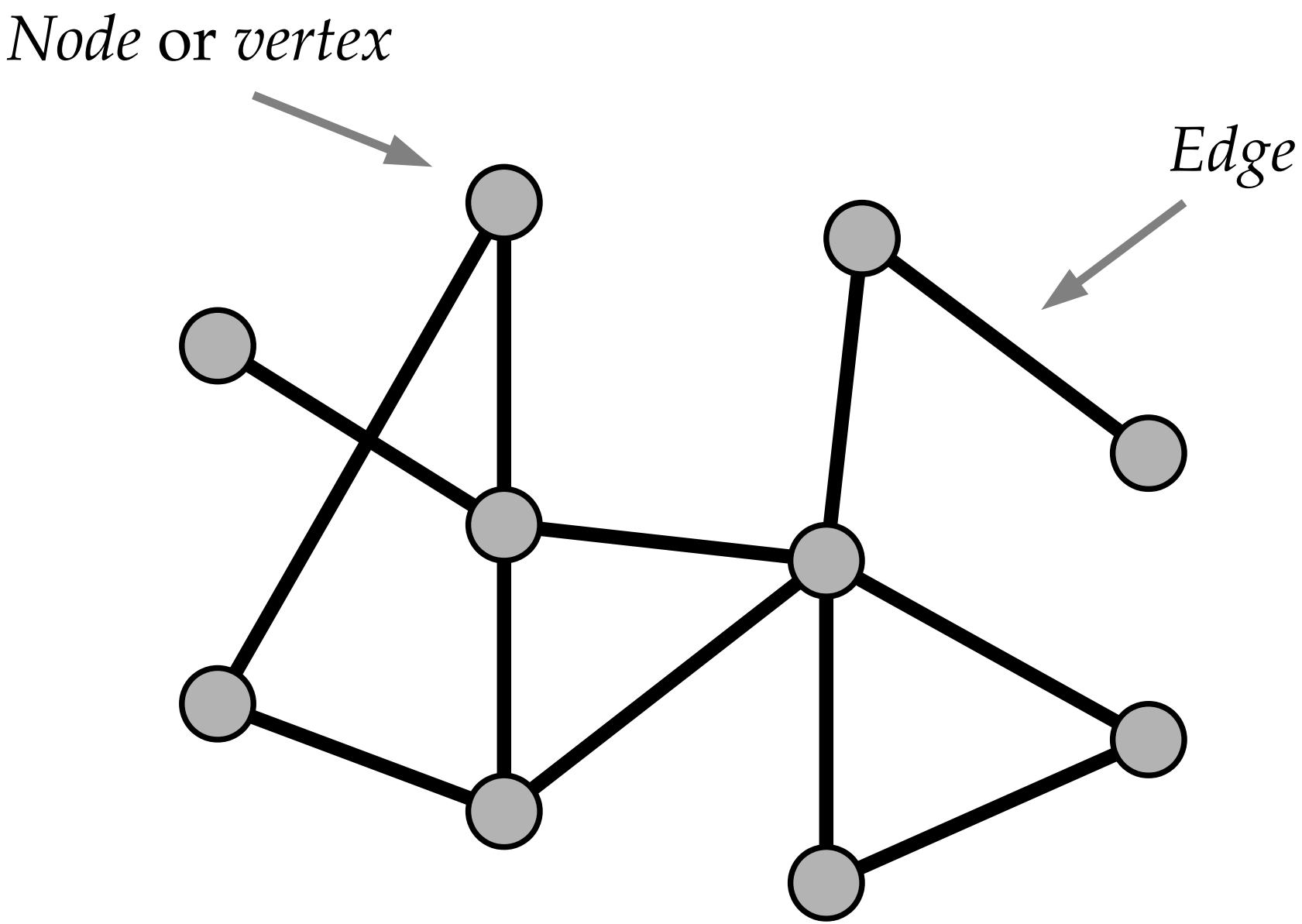

Node or *vertex*
Edge

Milgram's “small-world” experiment

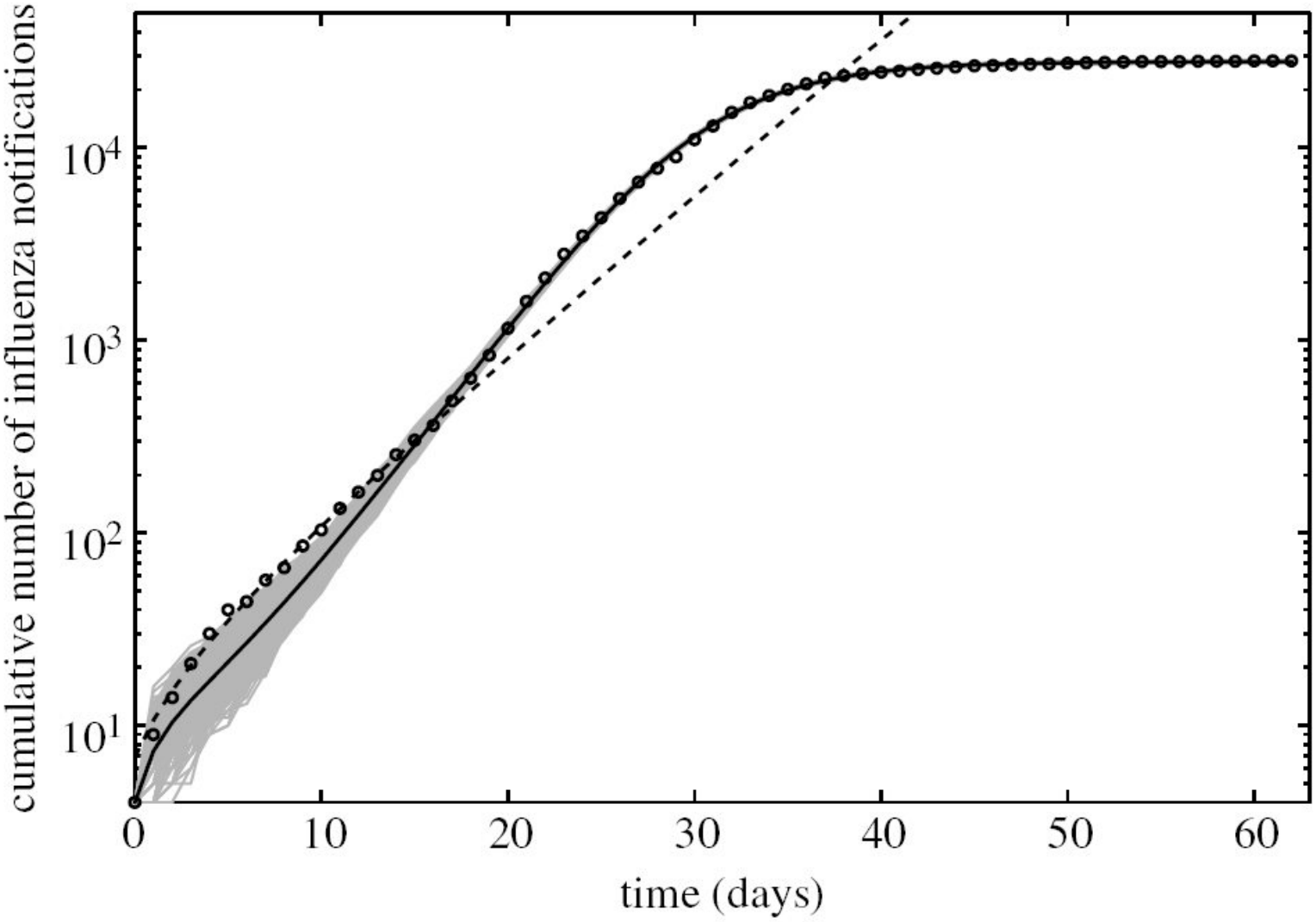
- Stanley Milgram's 1967 experiment
  - 296 people were asked to get a letter to a target person in Boston (196 from Nebraska and 100 from Boston)
  - Letters could only be passed along a chain of first-name acquaintances
  - 64 letters arrived (29%)
  - They took an average of 6.2 steps to get there

New York Times

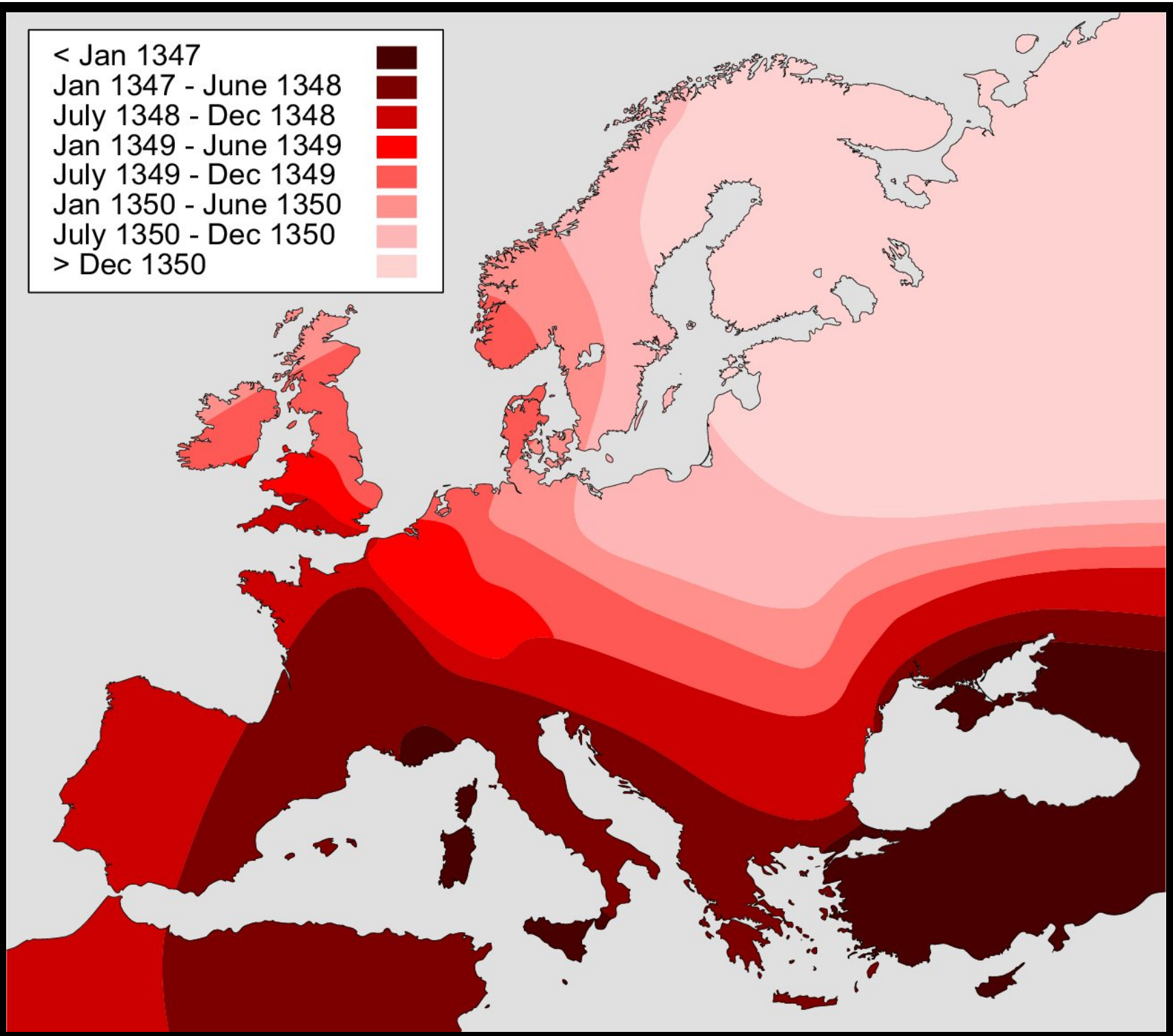
The small-world effect

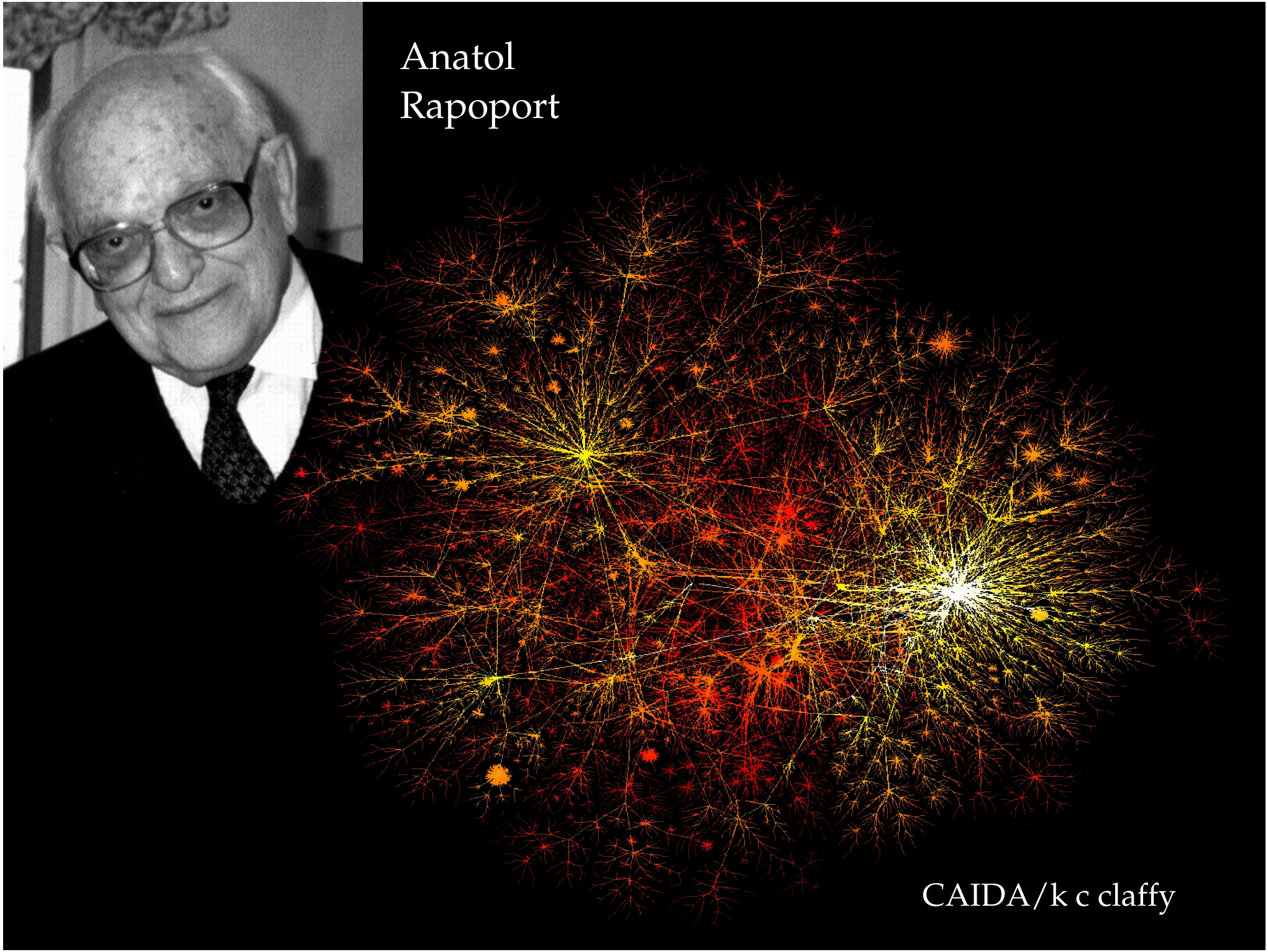
- If each person knows 100 people then:
  - Number of people 1 step away from you is 100
  - People 2 steps away is 100 x 100 = 10,000
  - People 3 steps away is 100 x 100 x 100 = 1,000,000
  - People 4 steps away is 100,000,000
  - People 5 steps away is 10,000,000,000
- But 10 billion is more than the total number of people in the world

Spanish flu, San Francisco 1918-1919

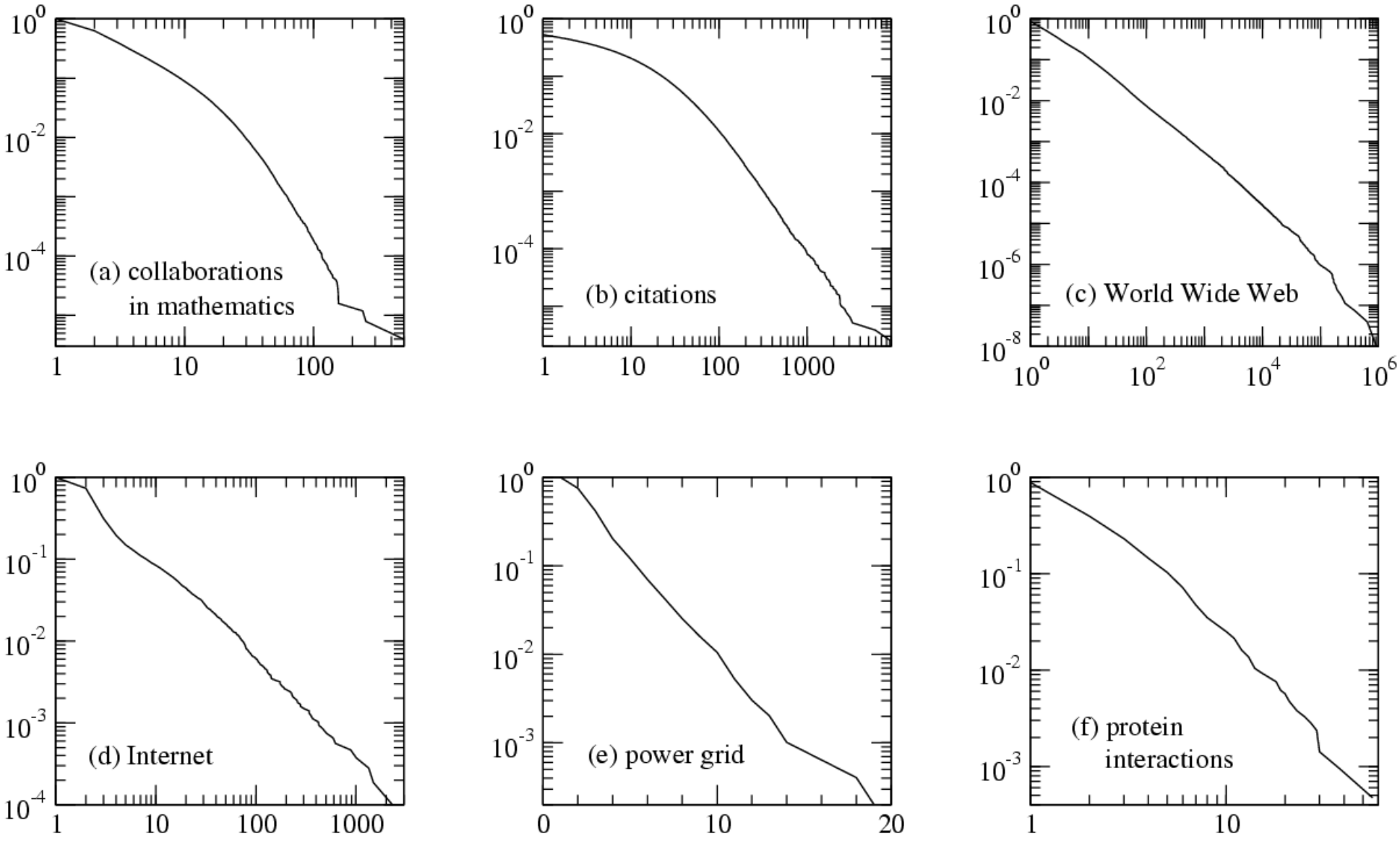


Chowell *et al*. 2007


< Jan 1347
Jan 1347 - June 1348
July 1348 - Dec 1348
Jan 1349 - June 1349
July 1349 - Dec 1349
Jan 1350 - June 1350
July 1350 - Dec 1350
> Dec 1350


Anatol
Rapoport
CAIDA/k c claffy

Degree distributions



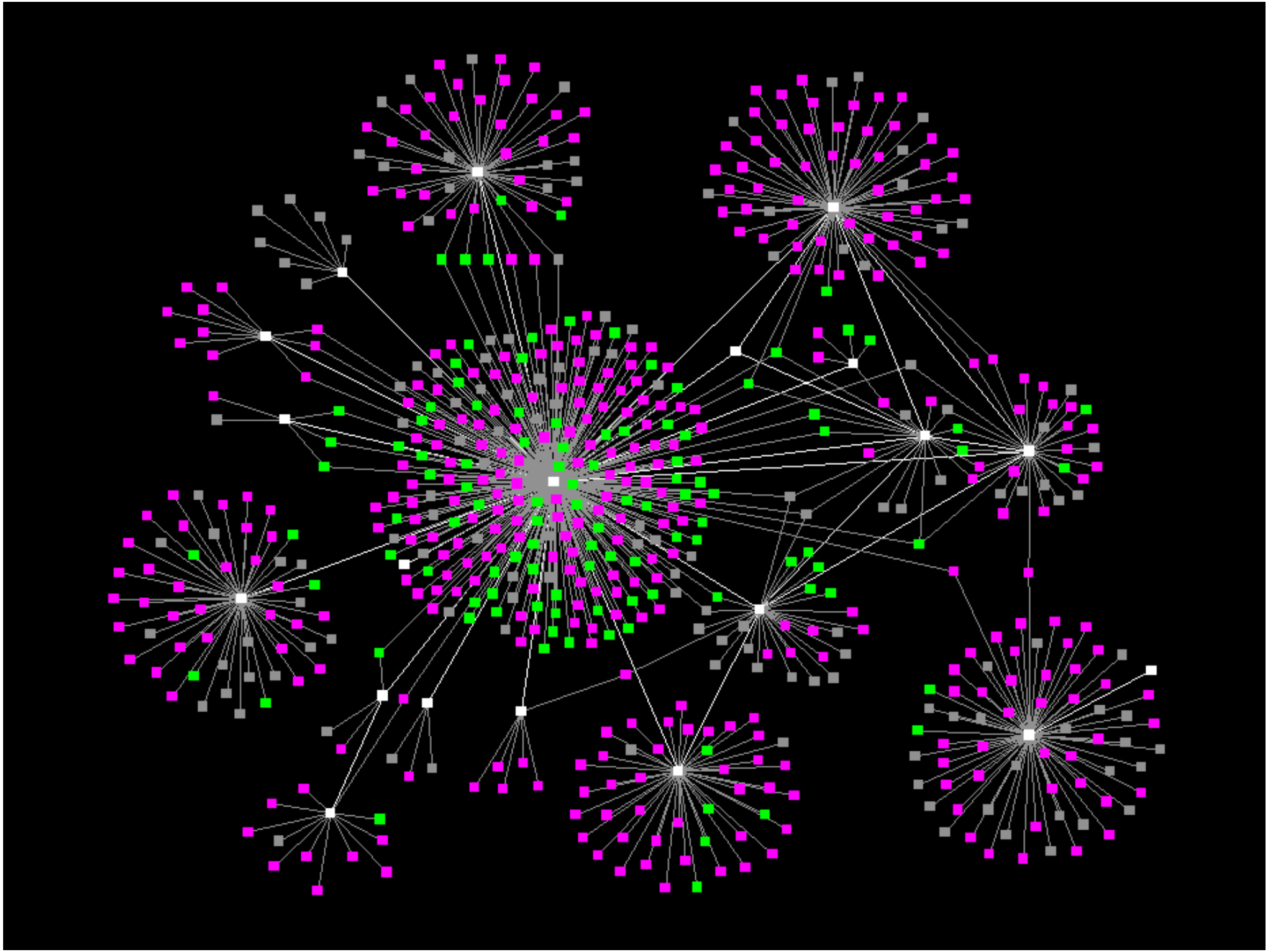
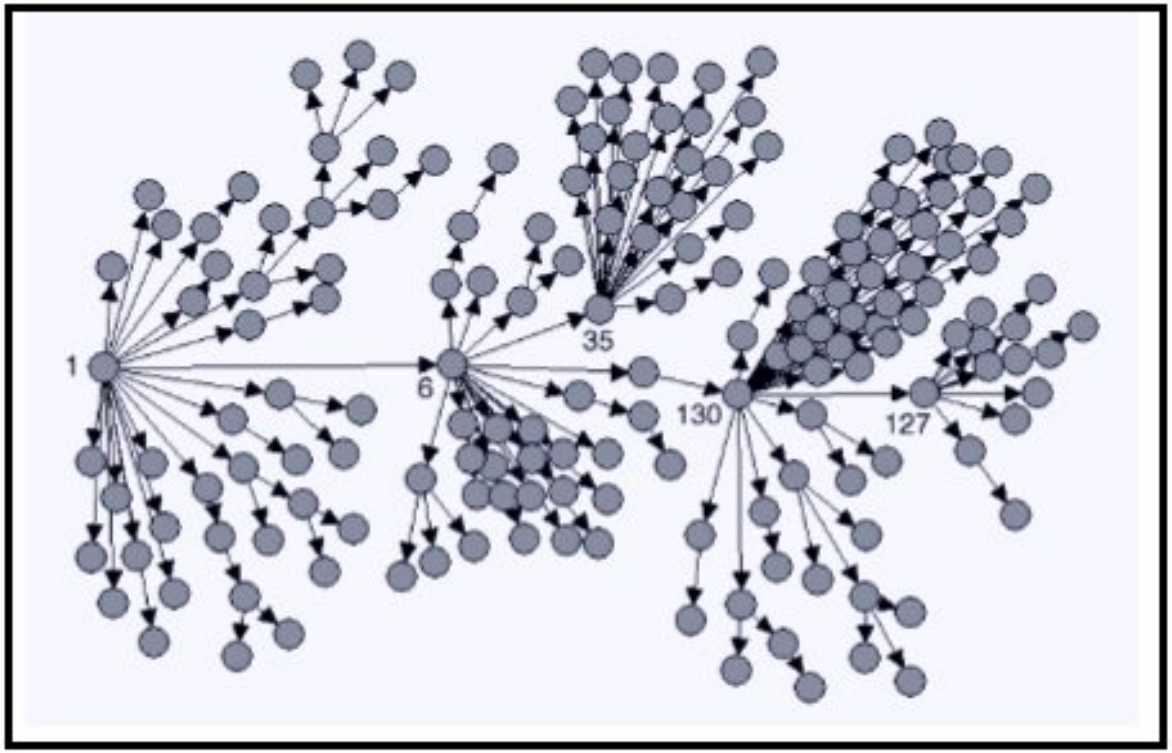


FIGURE 2. Probable cases of severe acute respiratory syndrome, by reported source of infection* — Singapore, February 25–April 30, 2003



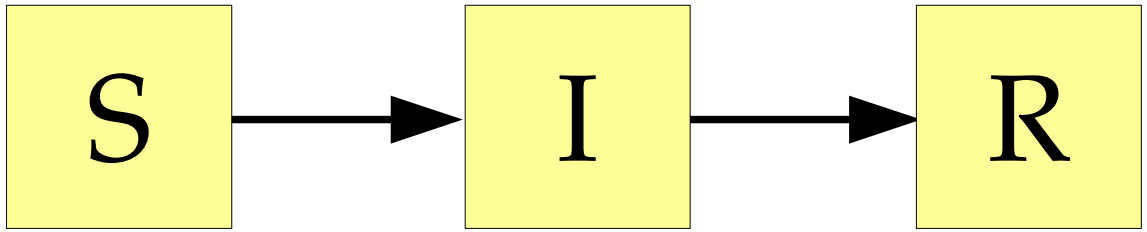
* Patient 1 represents Case 1; Patient 6, Case 2; Patient 35, Case 3; Patient 130, Case 4; and Patient 127, Case 5. Excludes 22 cases with either no or poorly defined direct contacts or who were cases translocated to Singapore and the seven contacts of one of these cases.

Reference: Bogatti SP. Netdraw 1.0 Network Visualization Software. Harvard, Massachusetts: Analytic Technologies, 2002.

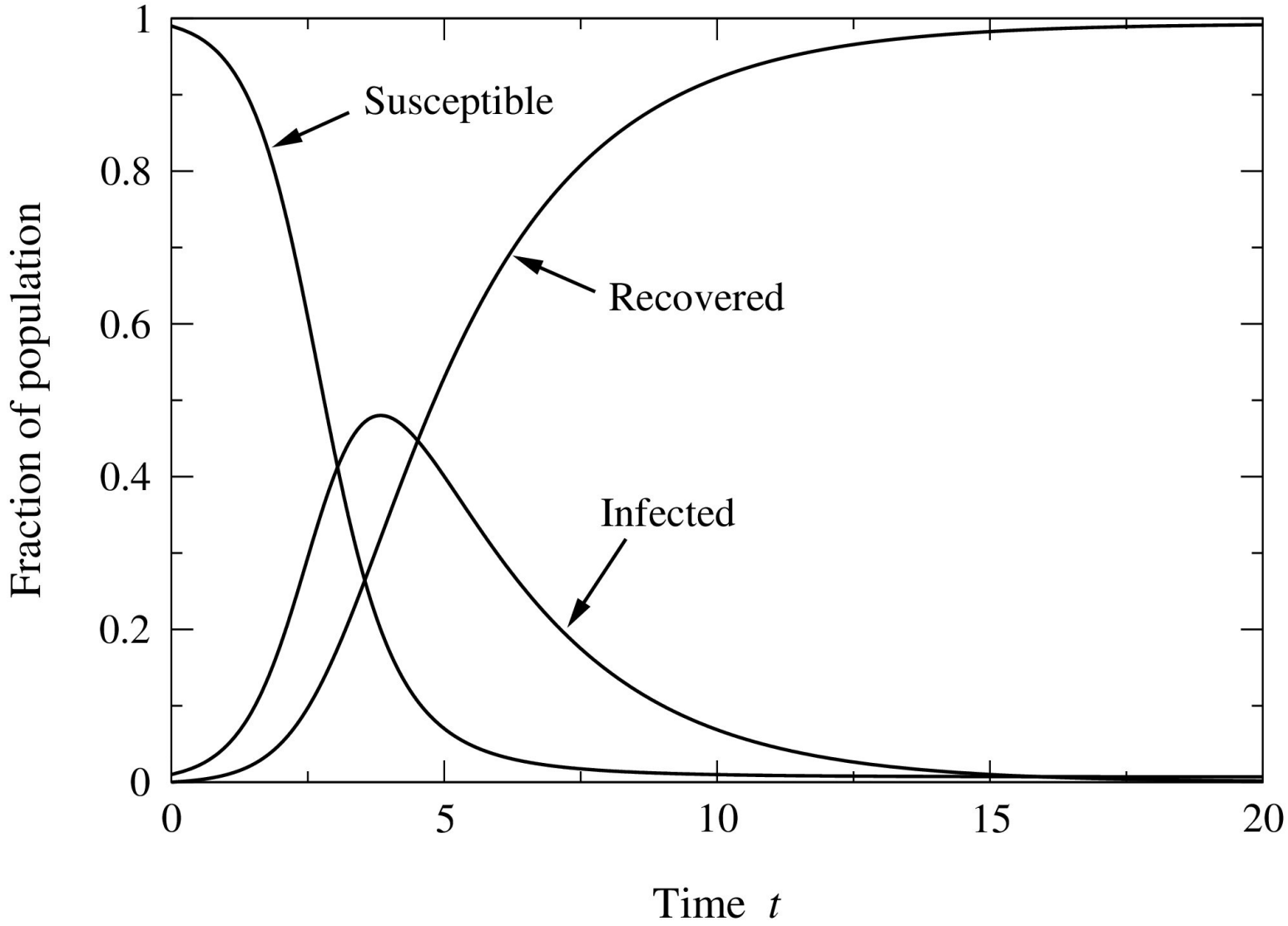
Steve Borgatti

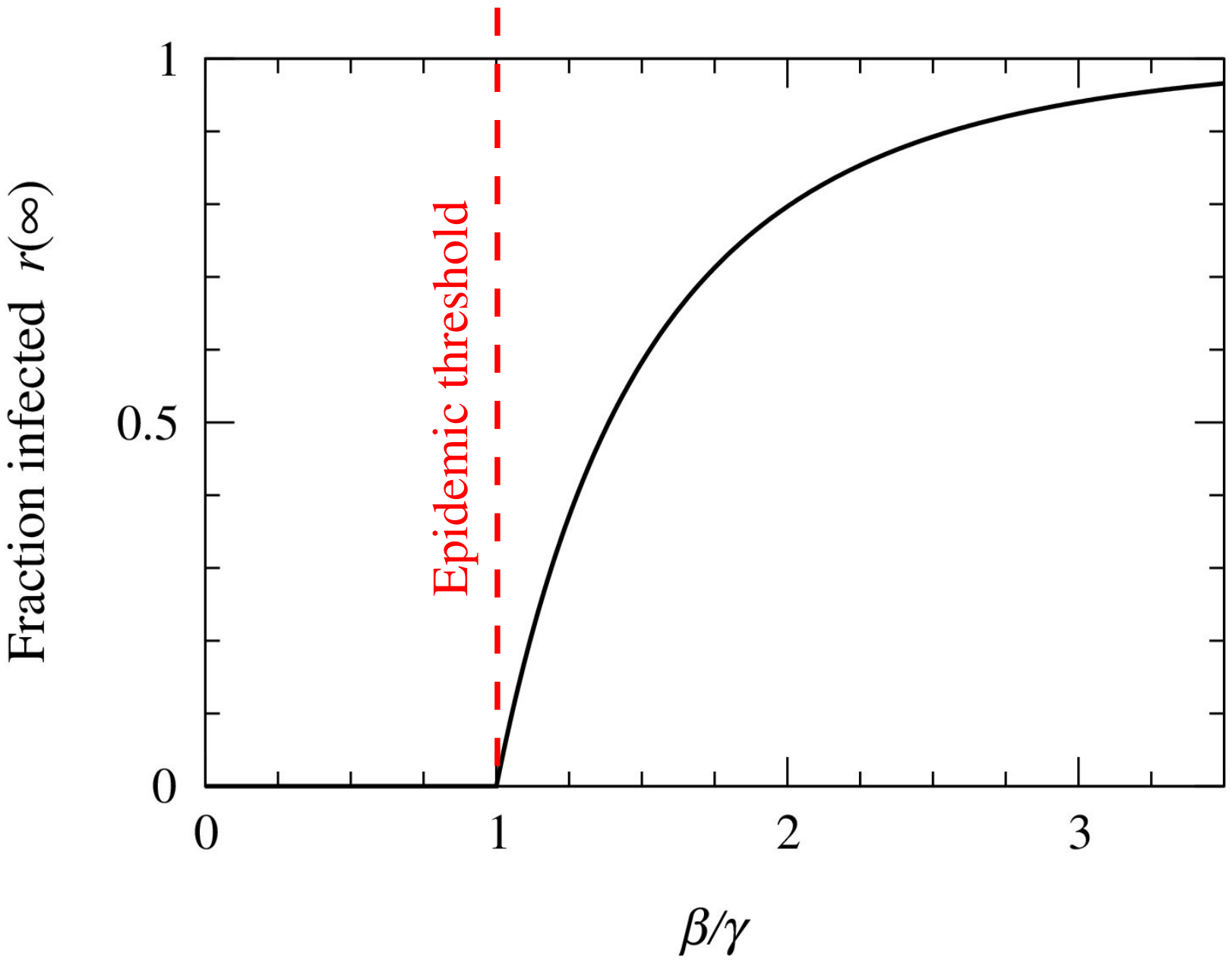
Epidemic modeling

- Population is divided into compartments
- Assuming random mixing we can write down equations that describe the changes in the number of people in each compartment

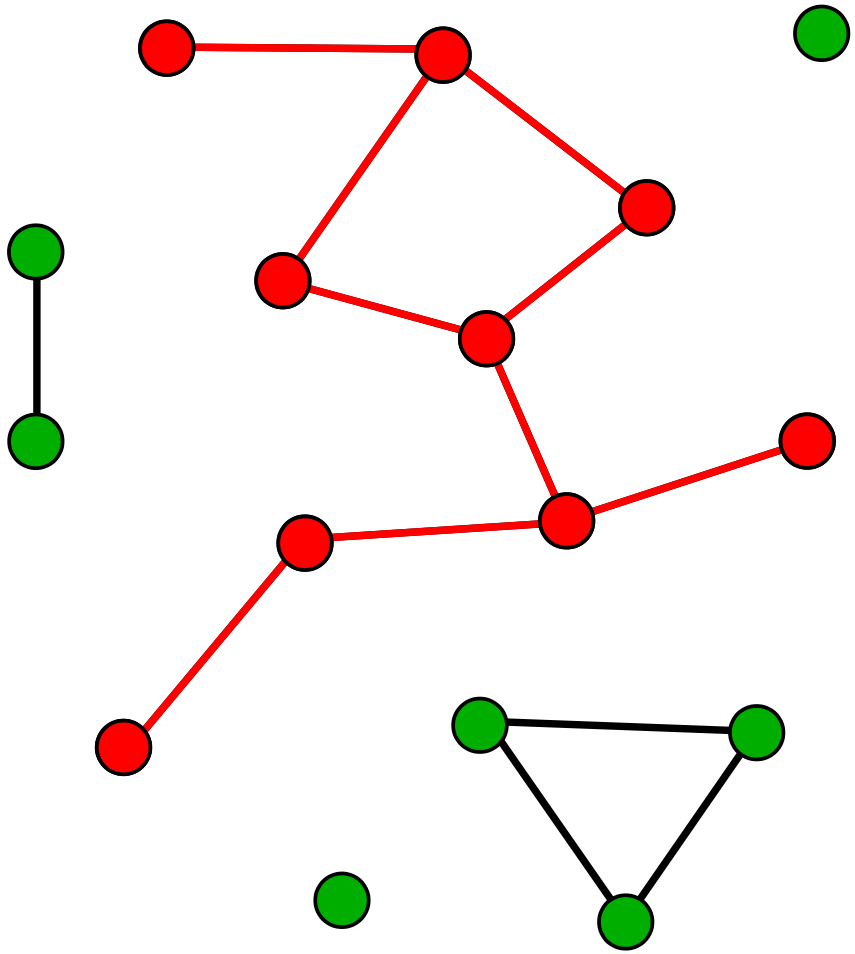


$$\frac{\mathrm{d}s}{\mathrm{d}t} = -\beta s x, \qquad \frac{\mathrm{d}x}{\mathrm{d}t} = \beta s x - \gamma x, \qquad \frac{\mathrm{d}r}{\mathrm{d}t} = \gamma x$$

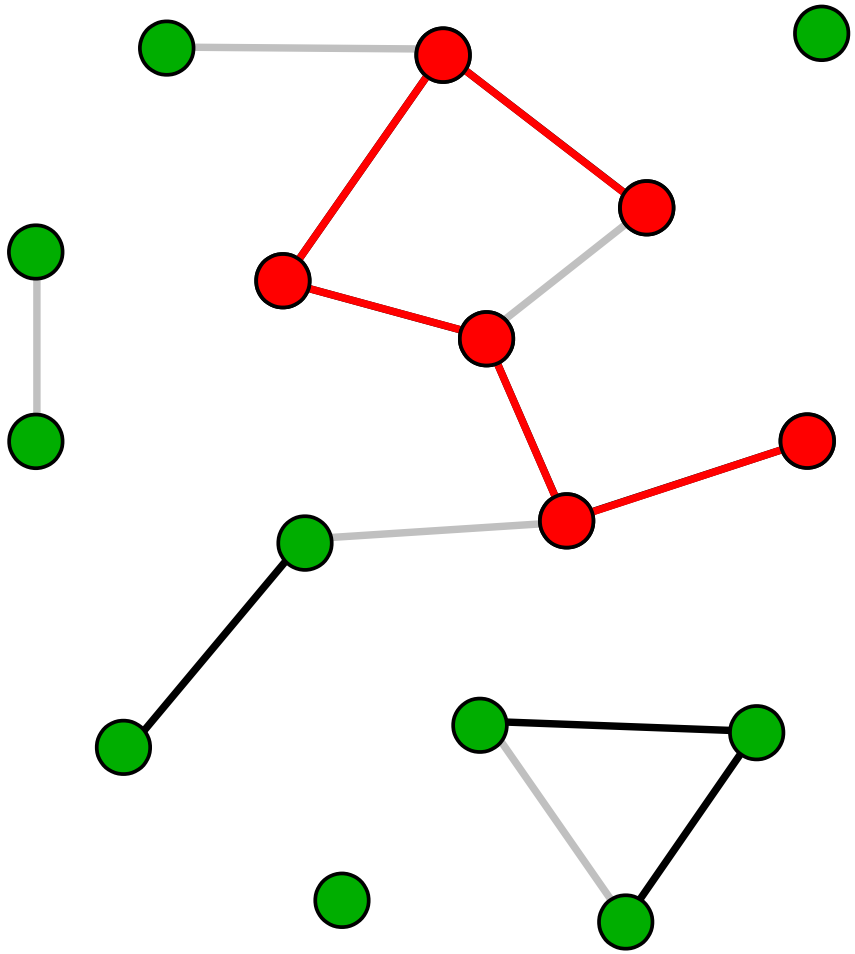



Fraction infected $r(\infty)$
1
0.5
0
0
1
2
3
β/γ
Epidemic threshold

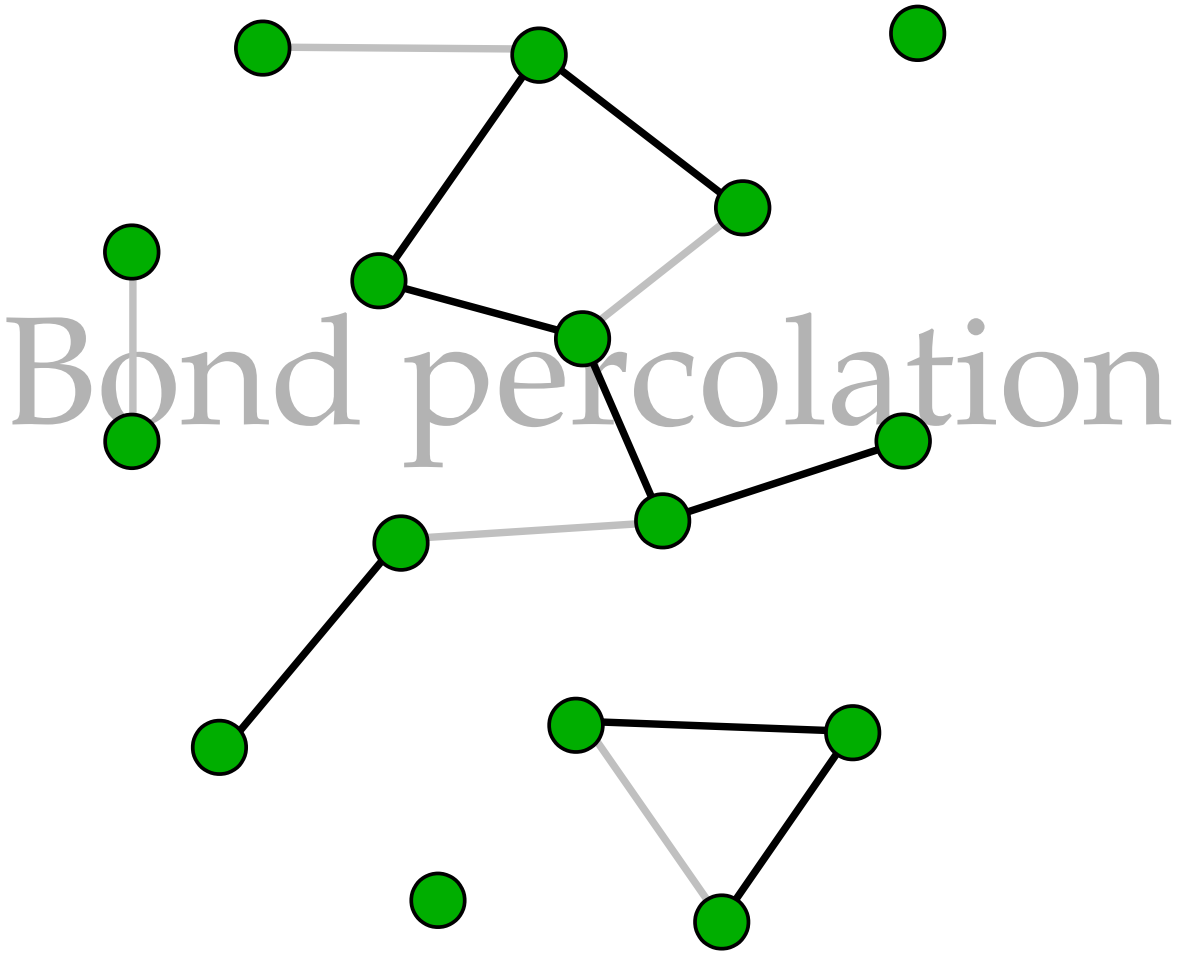
Spread of a disease



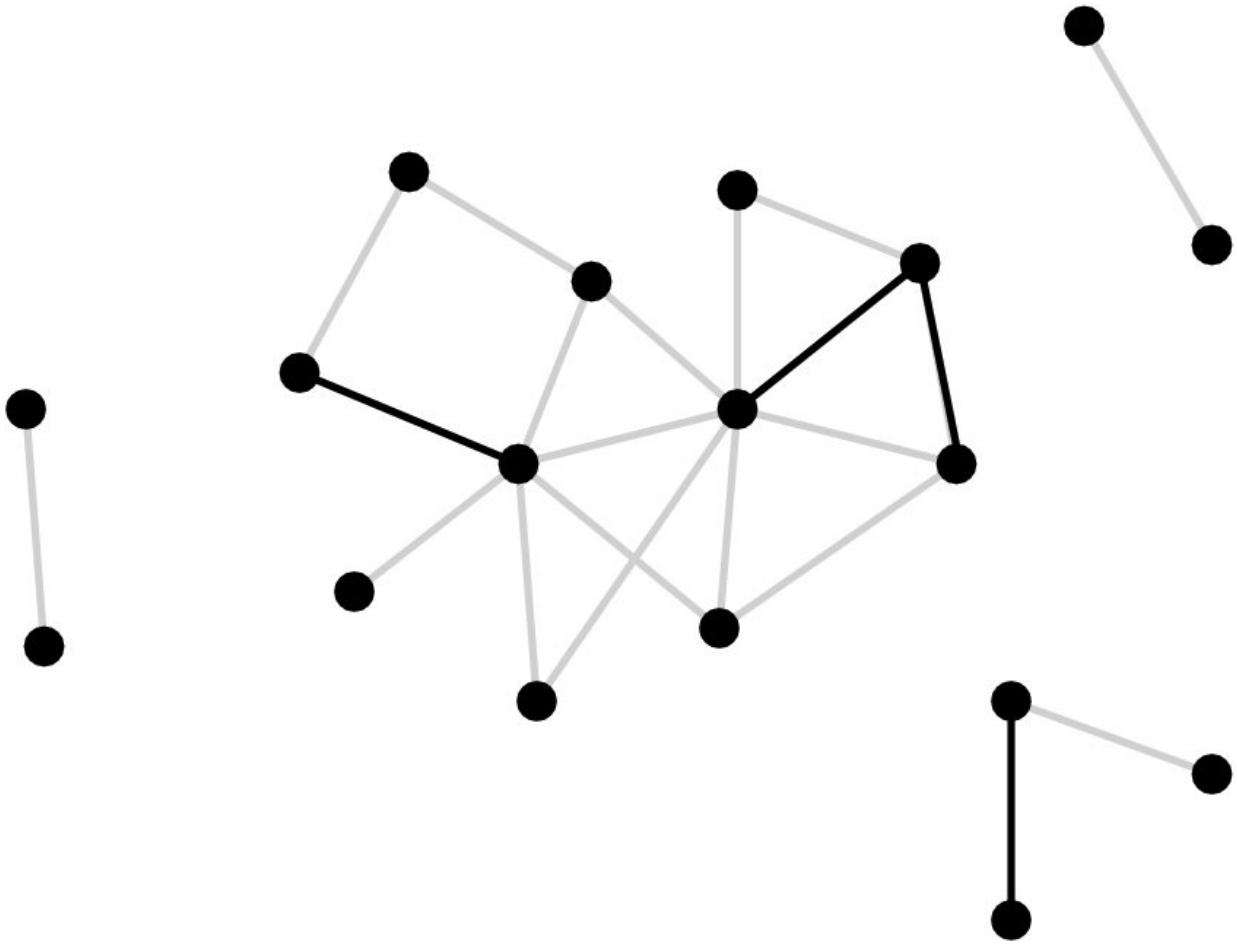
Spread of a disease



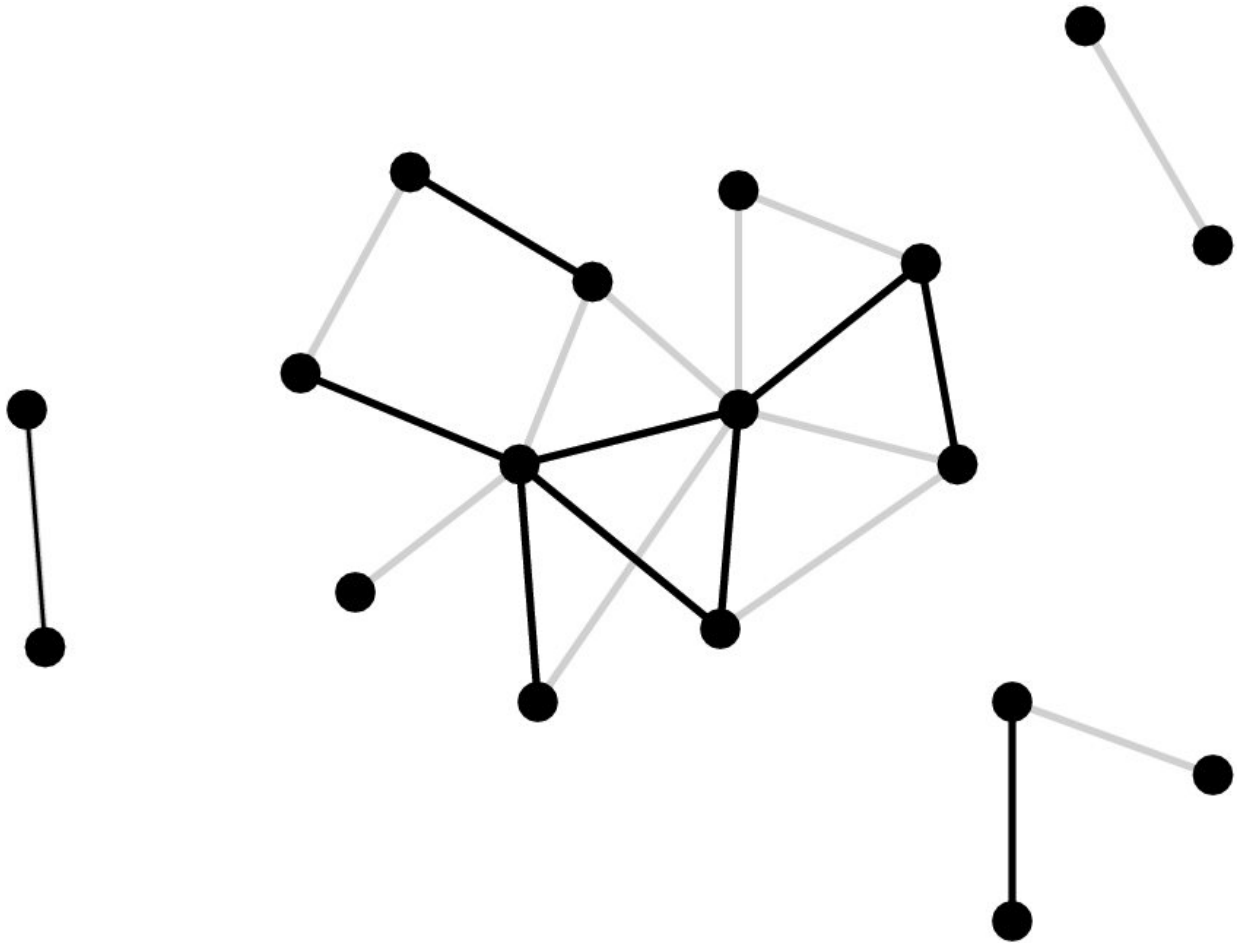
Spread of a disease



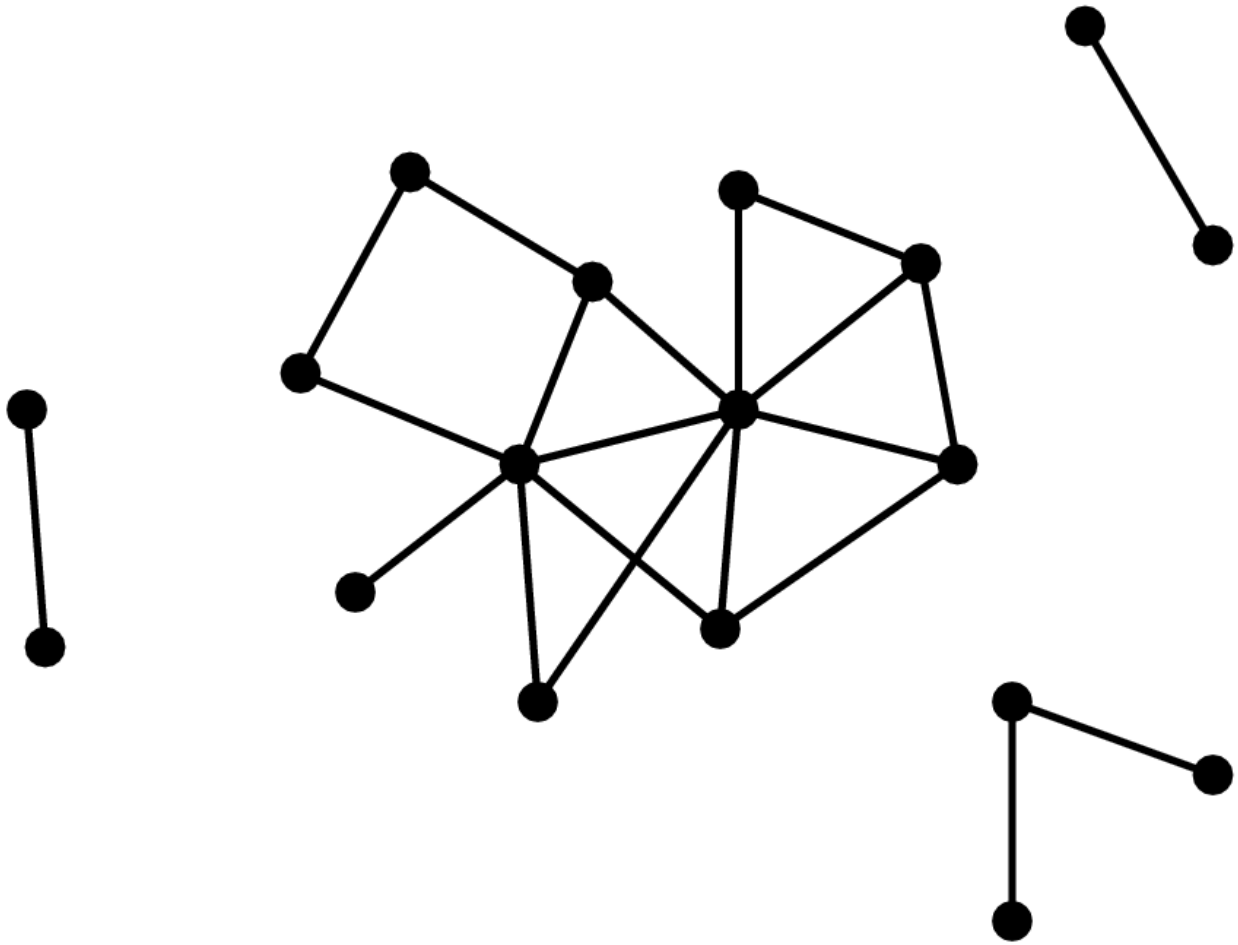
Percolation

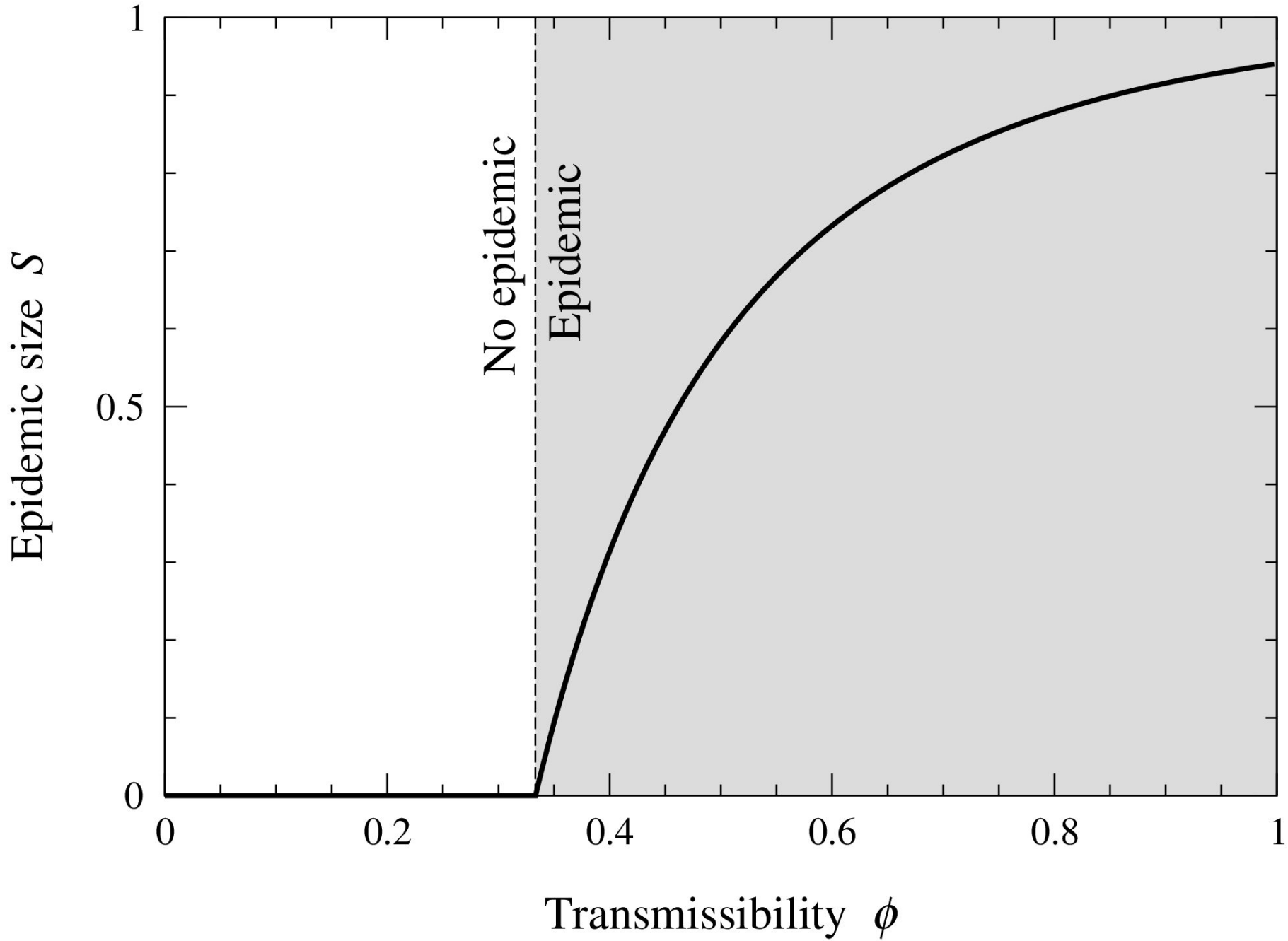


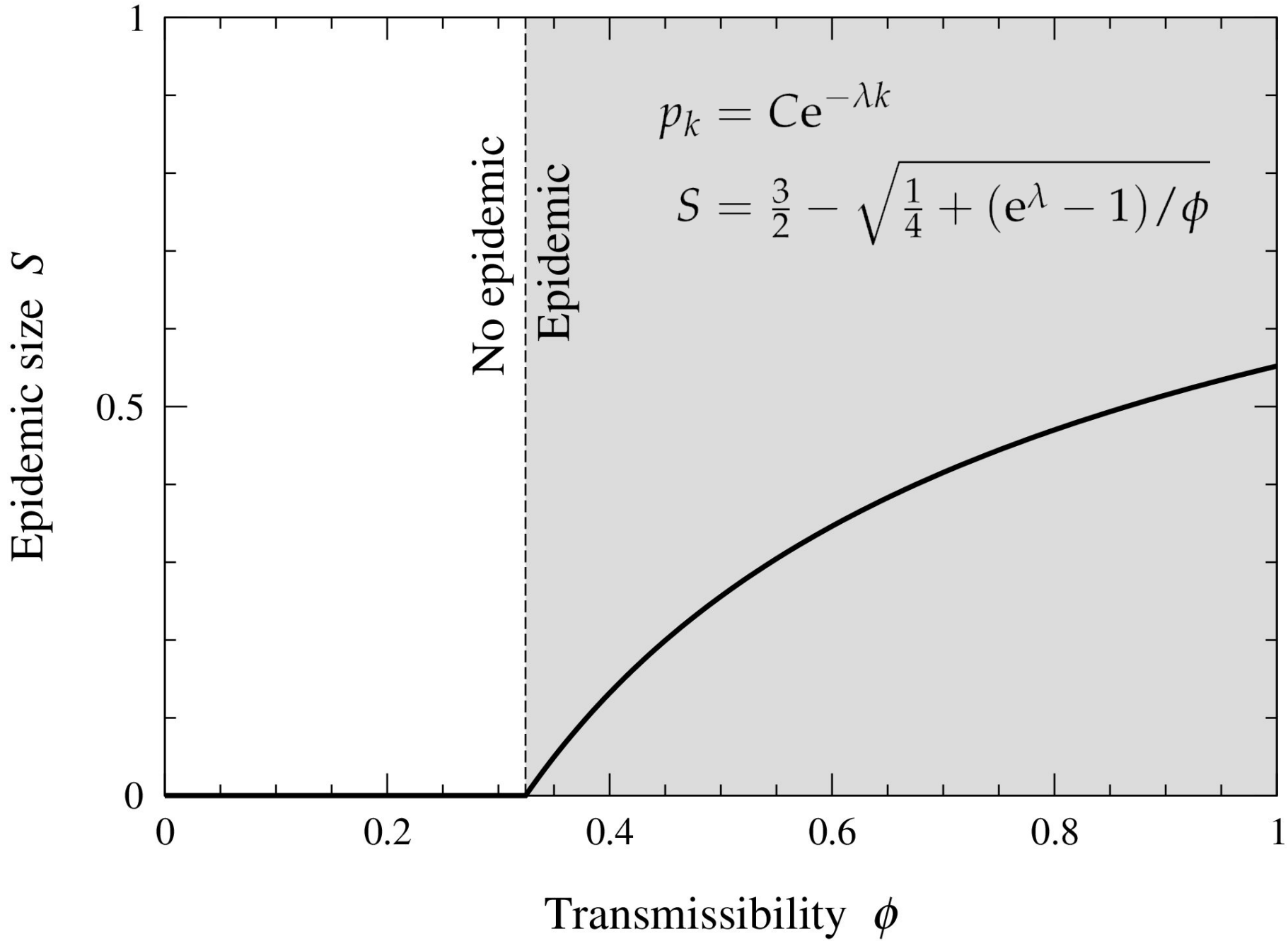
Percolation



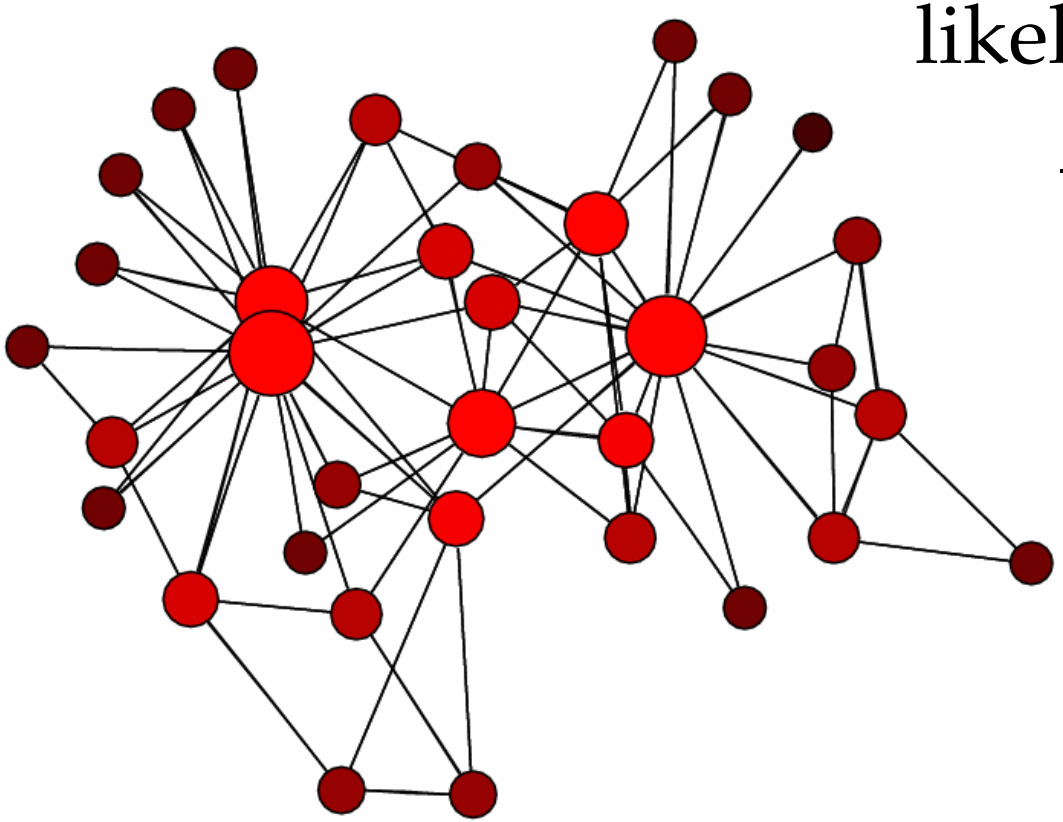
Percolation




1
0.5
0
0
0.2
0.4
0.6
0.8
1
Epidemic size S
Transmissibility ϕ
No epidemic
Epidemic


1
0.5
0
0
0.2
0.4
0.6
0.8
1
No epidemic
Epidemic
$p_k = Ce^{-\lambda k}$
$S = \frac{3}{2} - \sqrt{\frac{1}{4} + (e^{\lambda} - 1)/\phi}$
Epidemic size S
Transmissibility ϕ

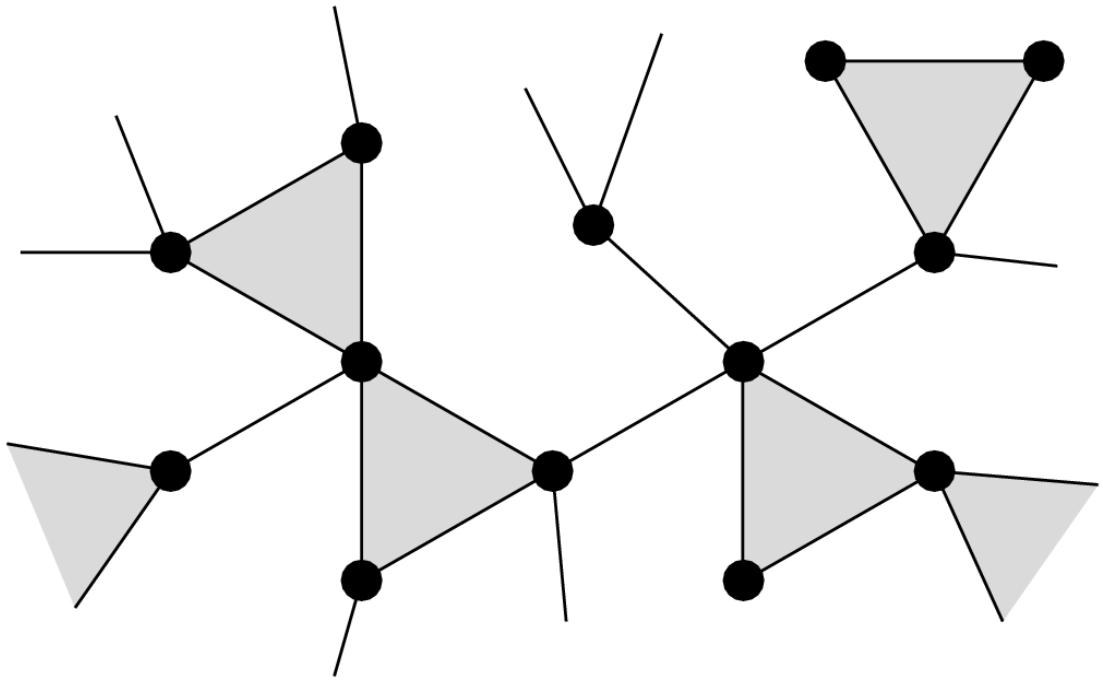
Transitivity

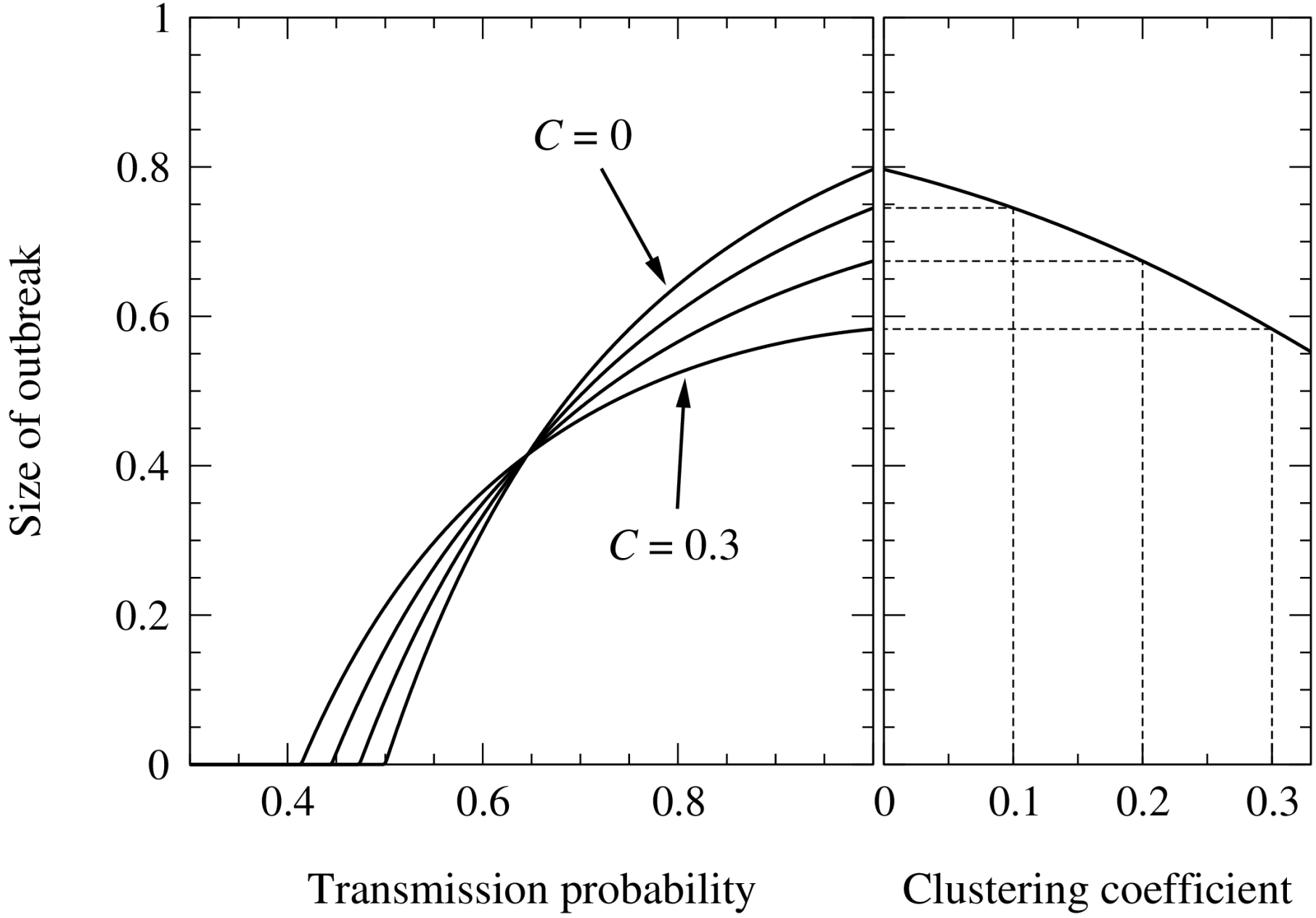


- If A knows B and B knows C, then A is likely also to know C
  - "The friend of my friend is also my friend"

Transitivity

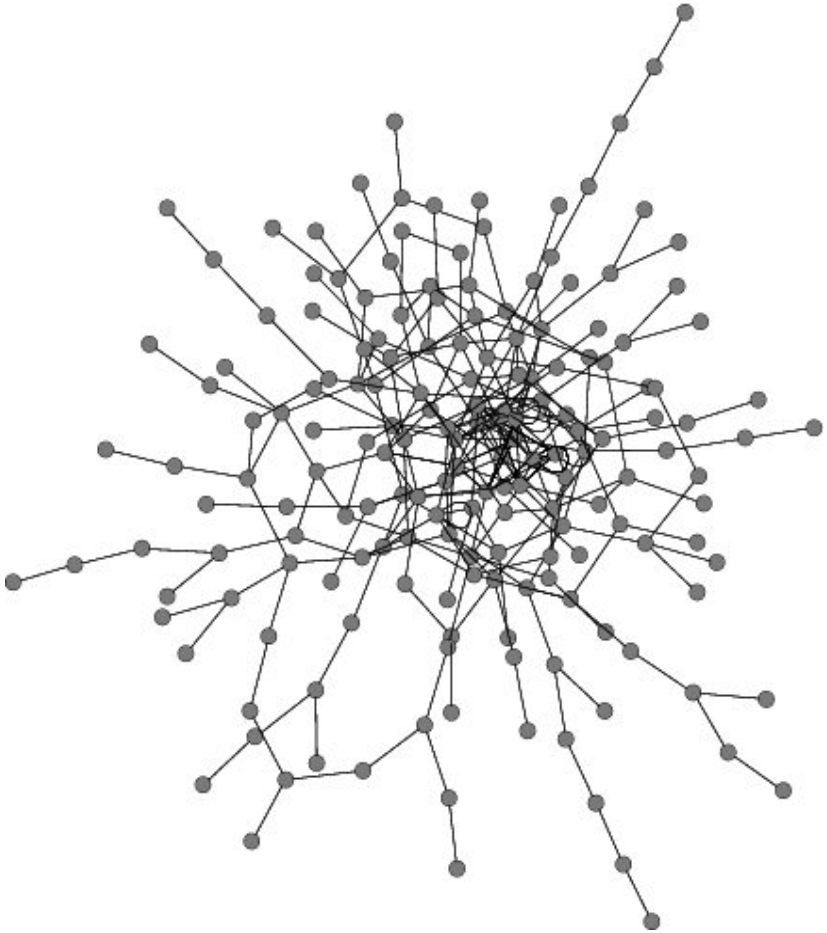
- We can make a model of a transitive network by adding triangles among the edges:



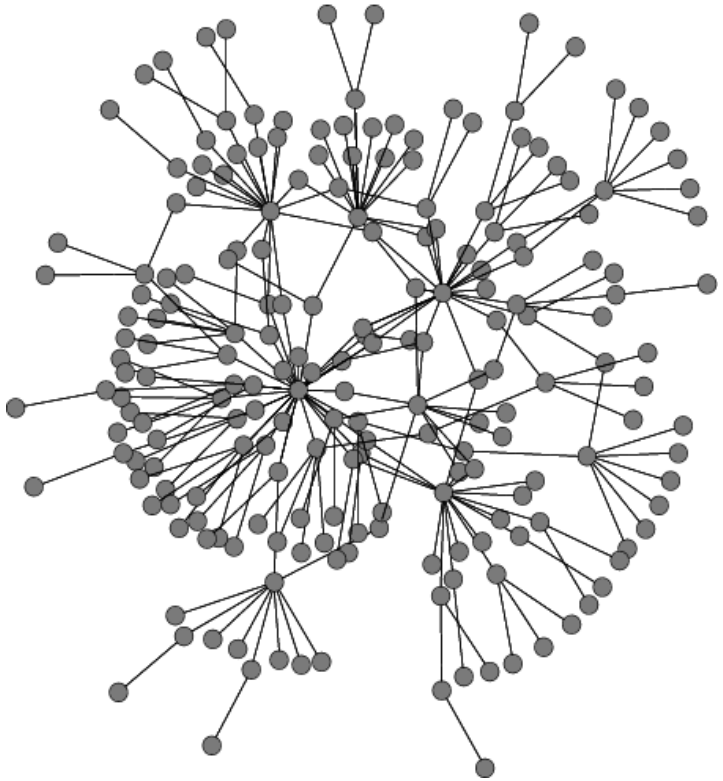


Newman, *PRL* 2009

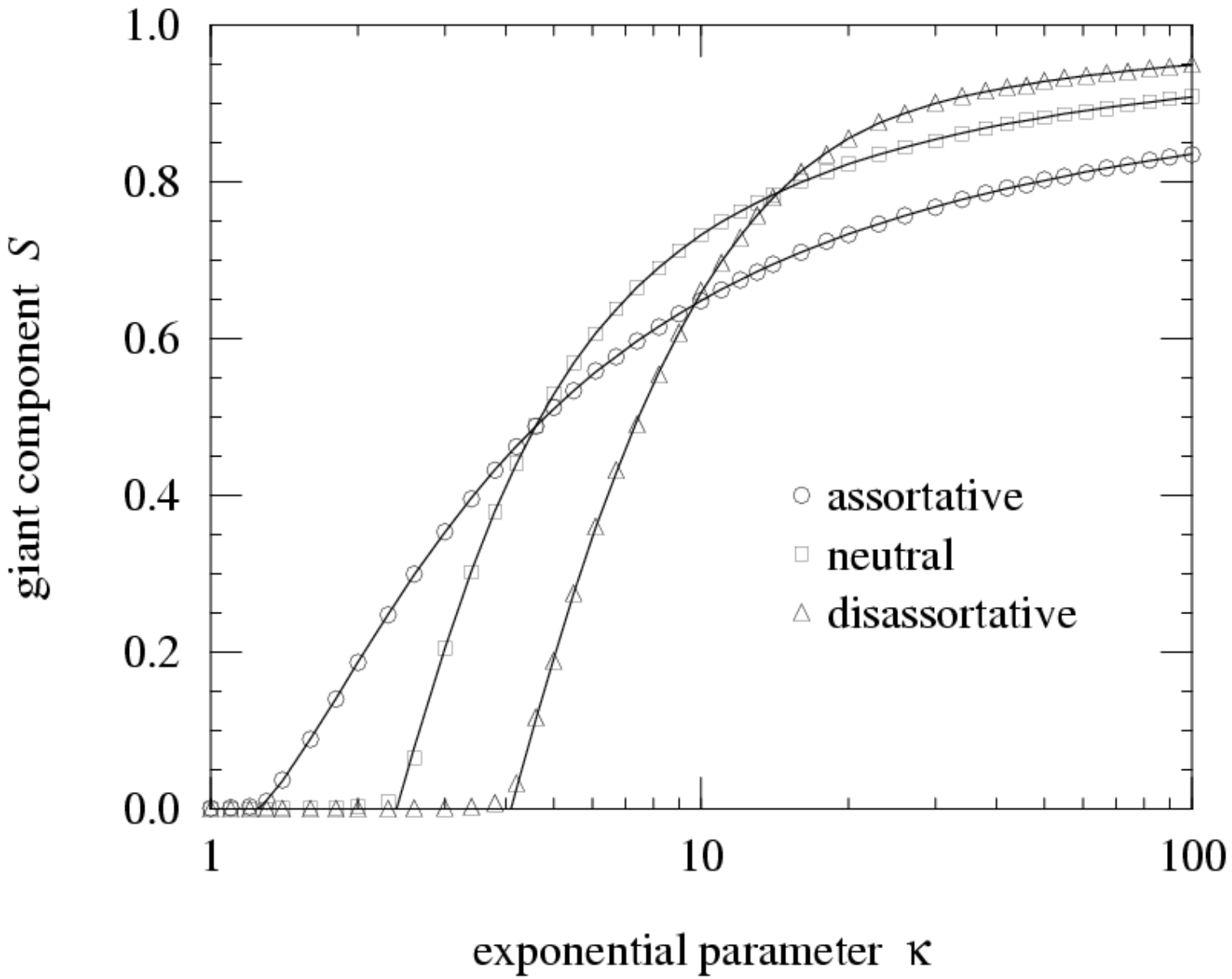
Assortative mixing



Assortative



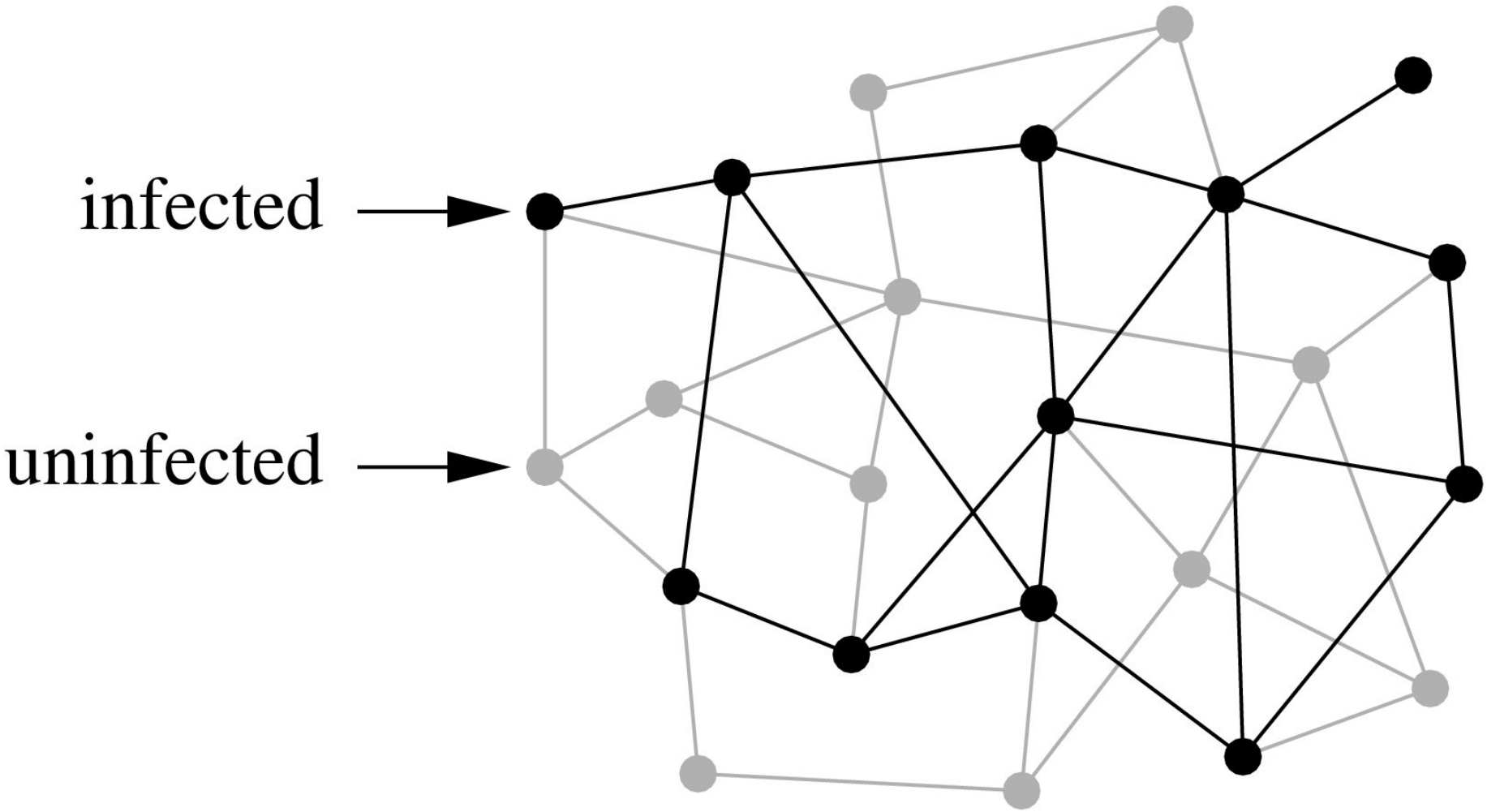
Disassortative

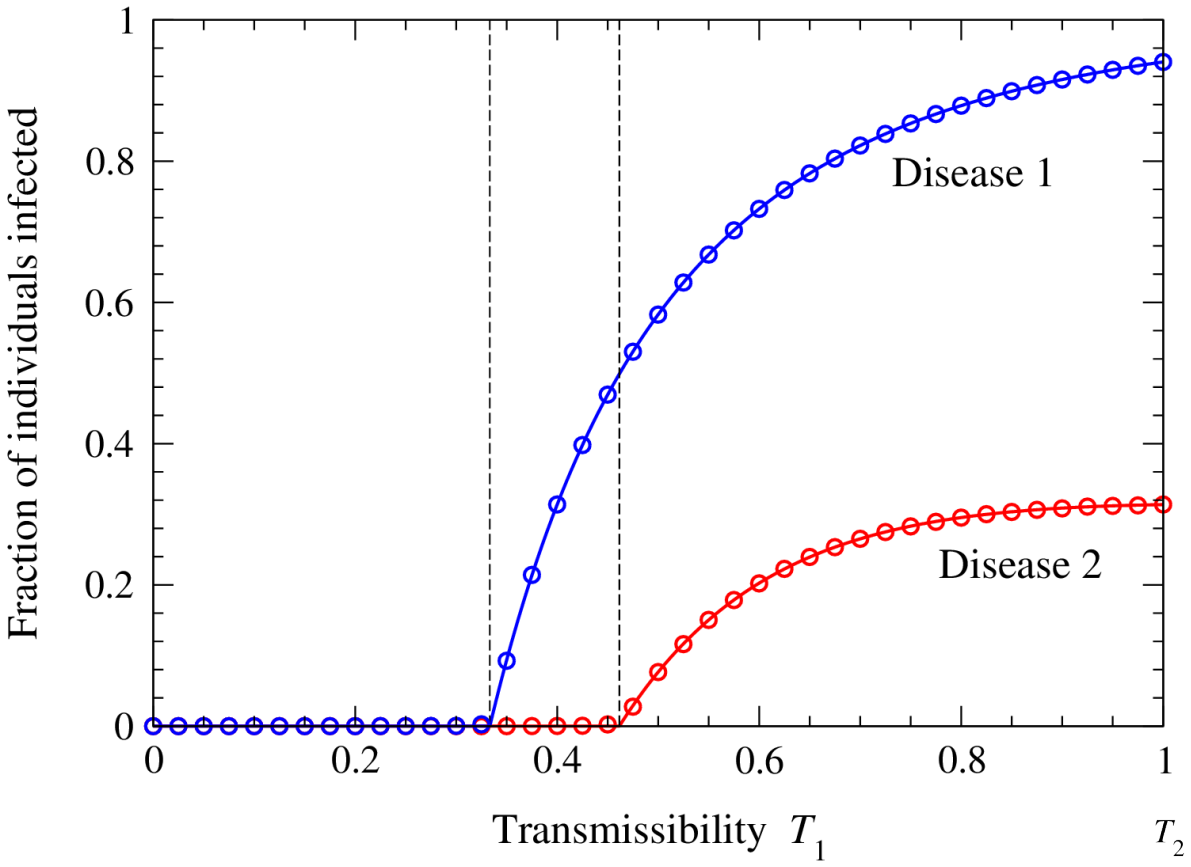


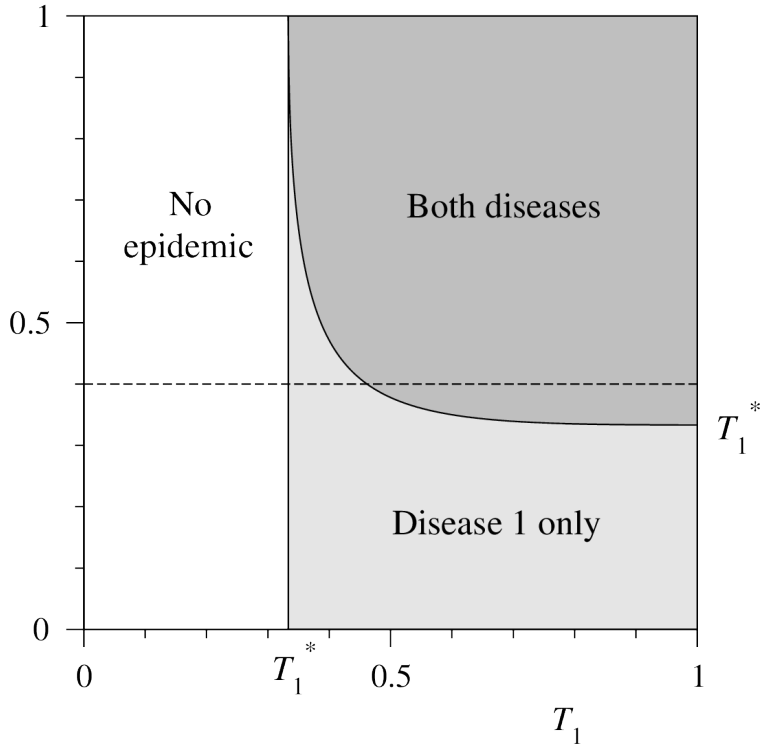
Newman, *PRE* 2004

Coinfection

- Now suppose we have *two* diseases
- And suppose that one disease *depends* on the other:
  - Infection with the first disease is necessary for infection with the second
  - Or makes the second more likely
  - Example: HIV's immunosuppressant effects increase the chances of getting certain types of infections


infected
uninfected

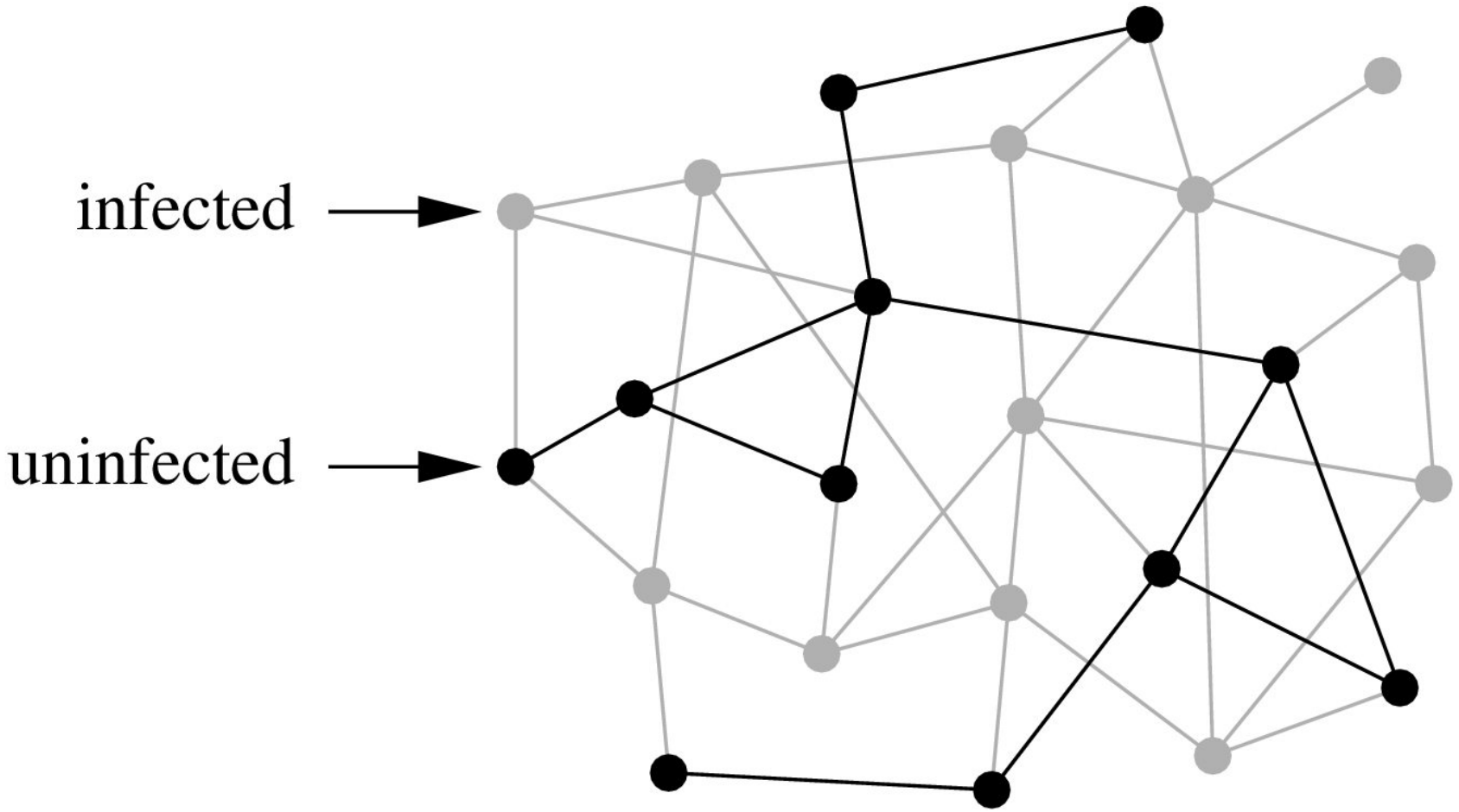


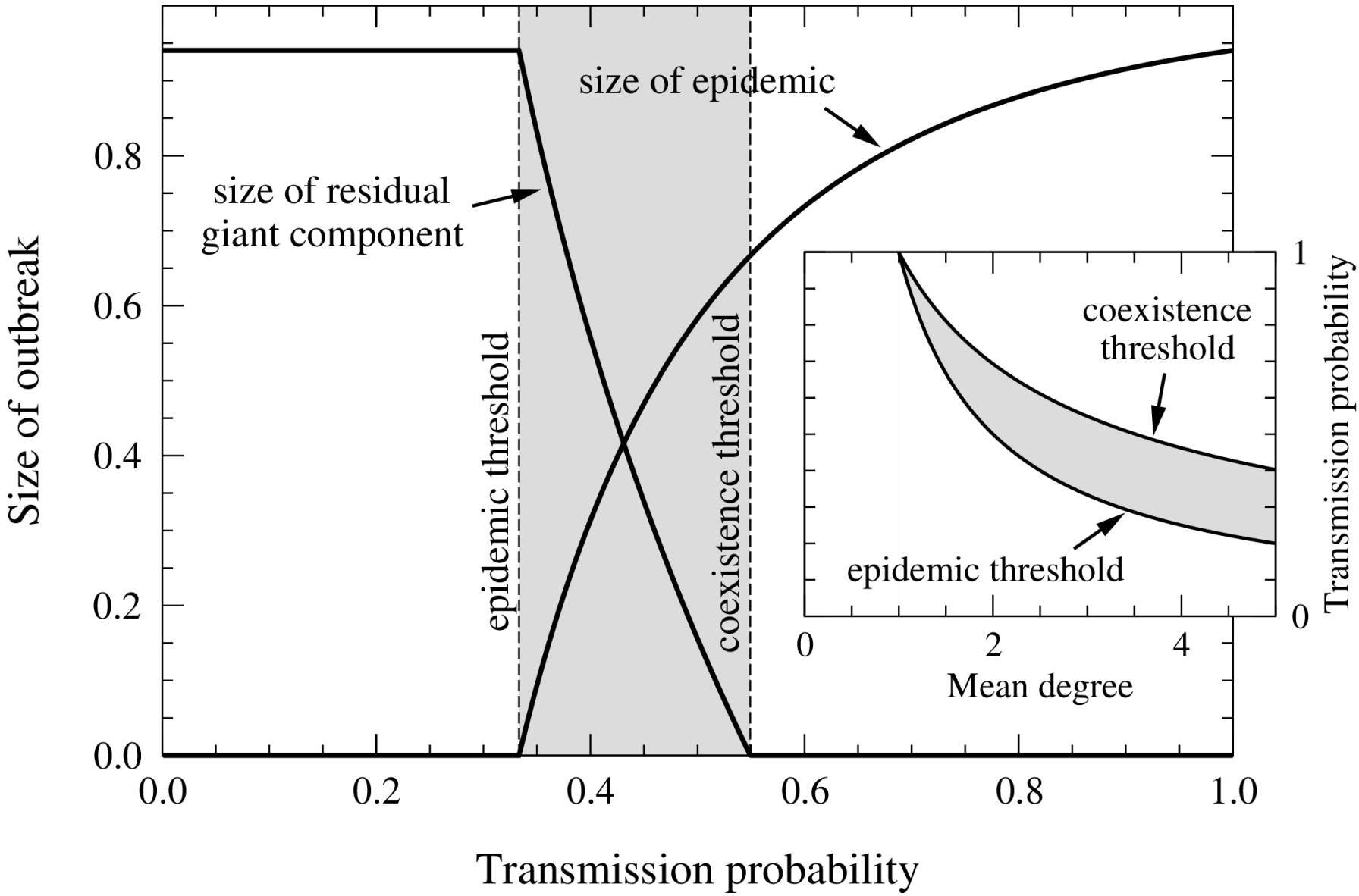


Newman and Ferrario, *PLOS One* 2013

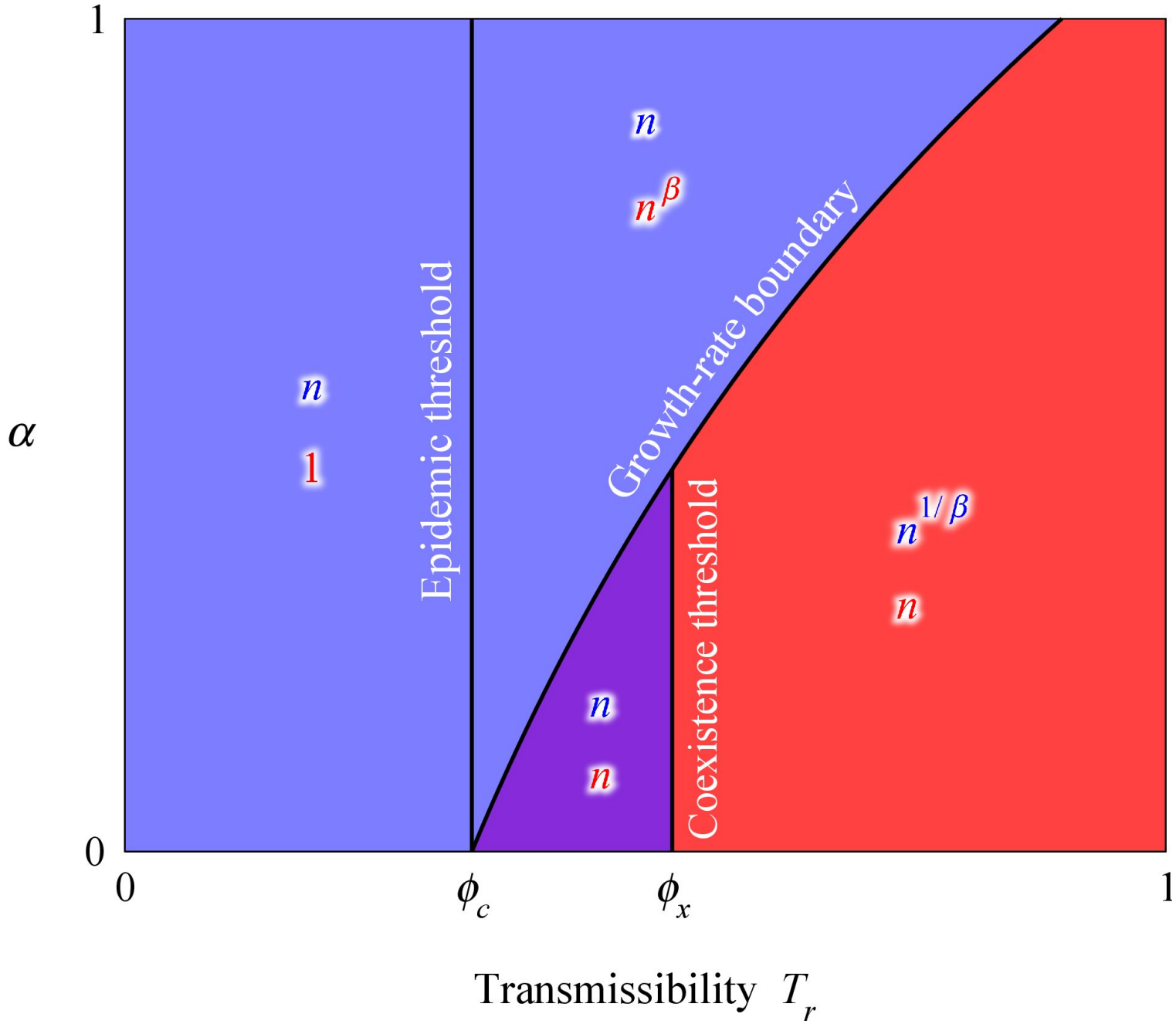
Competing pathogens

- Alternatively, the two diseases can compete:
  - One possibility is *cross-immunity*
  - Example: Different strains of the same disease, like the flu
  - Immunity to one strain gives you full or partial immunity to the other
  - The second disease can only infect those who didn't already catch the first


infected
uninfected

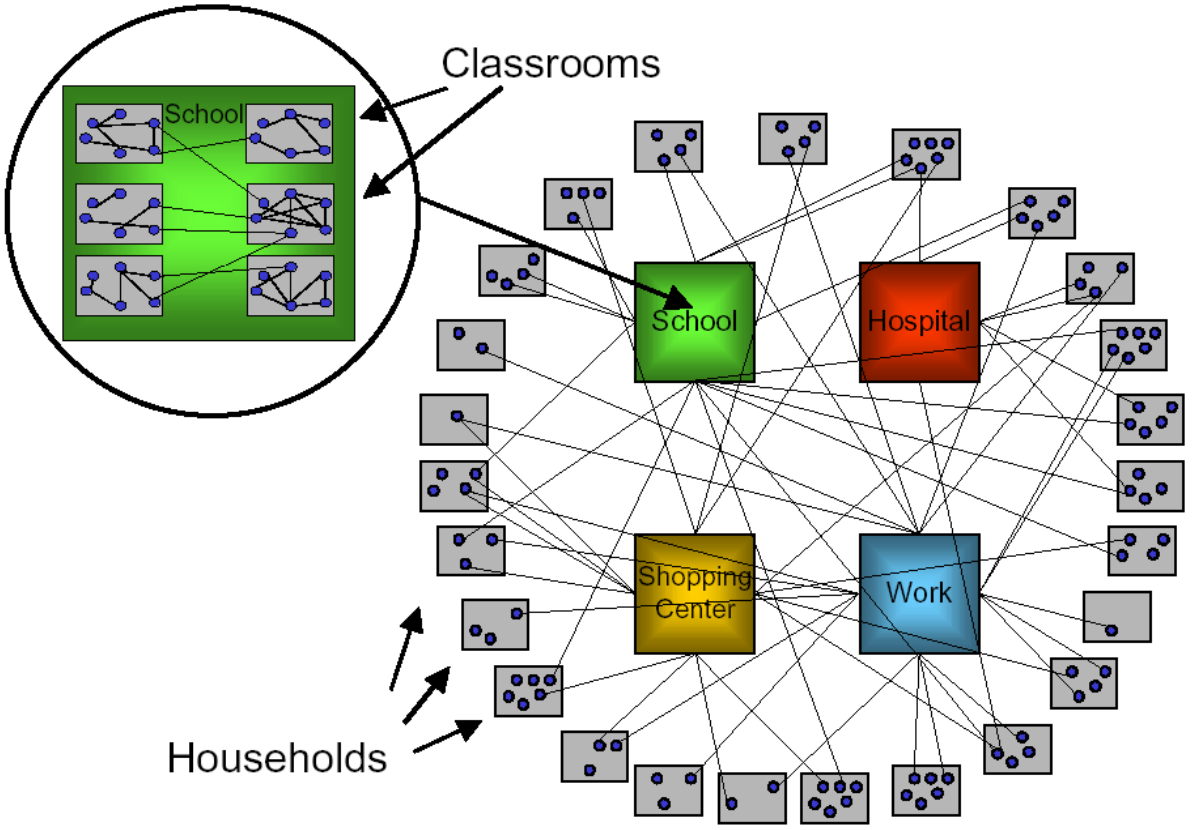


Newman, *PRL* 2005

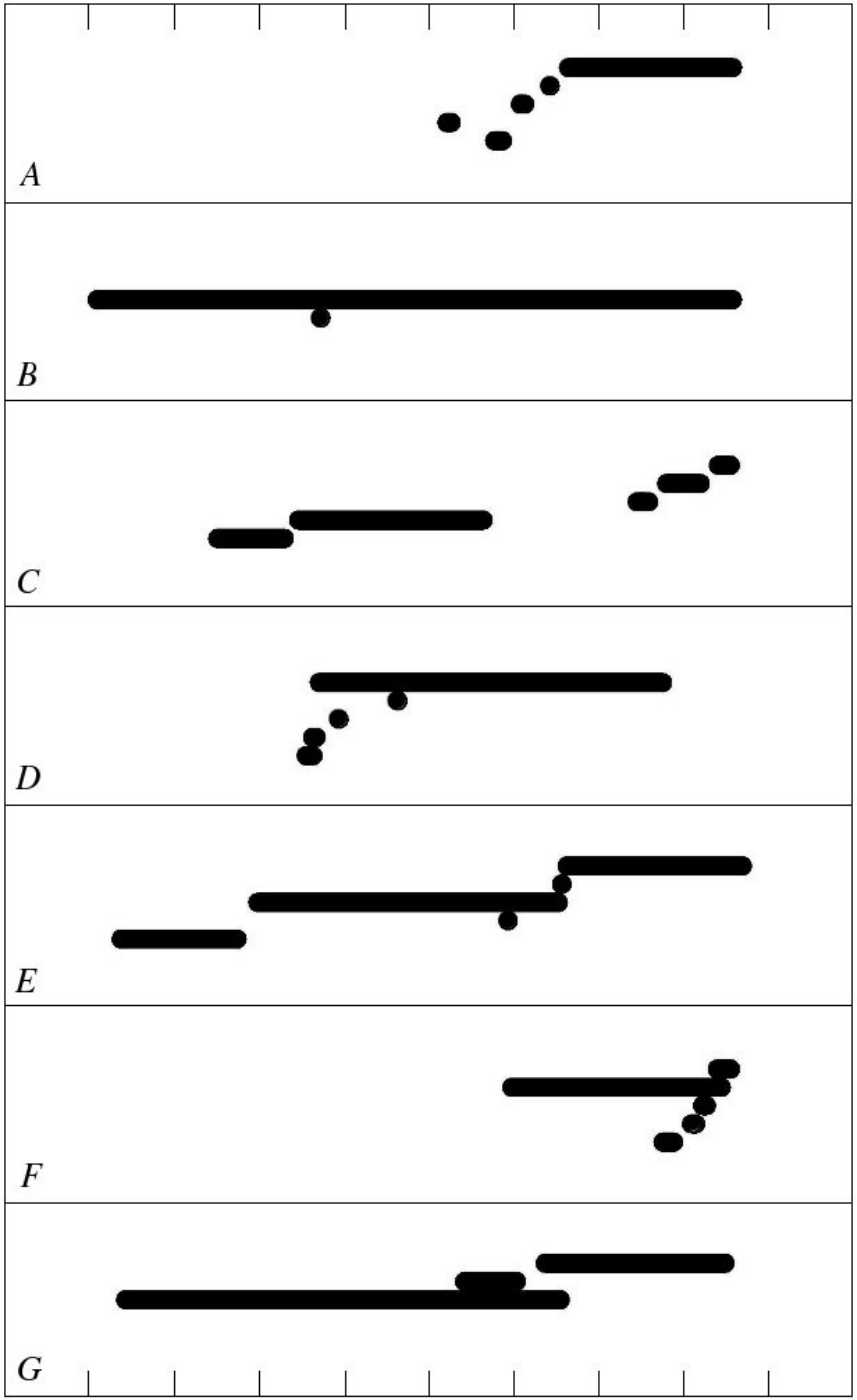


Karrer and Newman *PRE* 2011

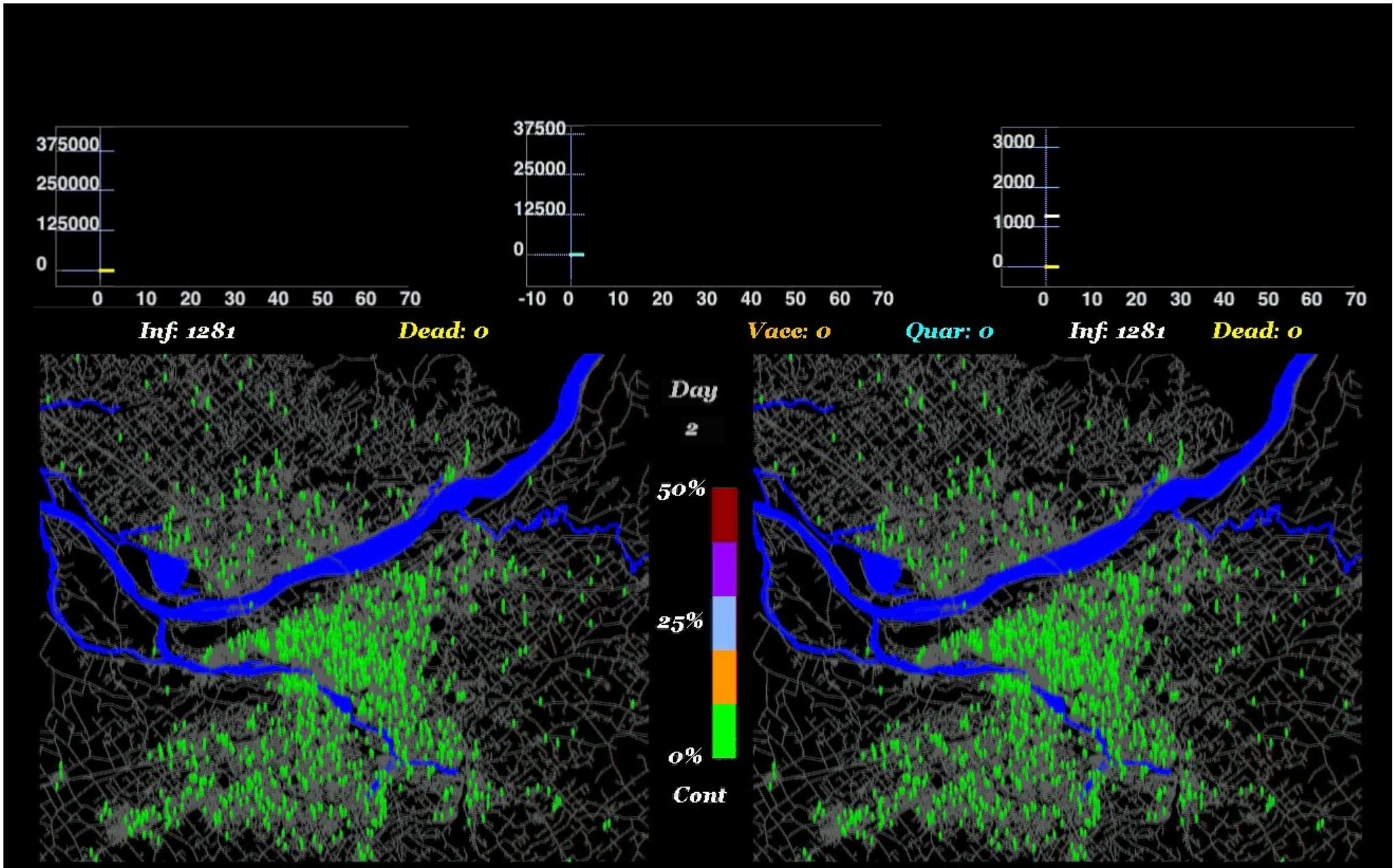
Simulated contact network



Meyers, Pourbohloul, Newman, Skowronski, Brunham, *J. Theor. Biol.*, **232**, 71-81 (2004)

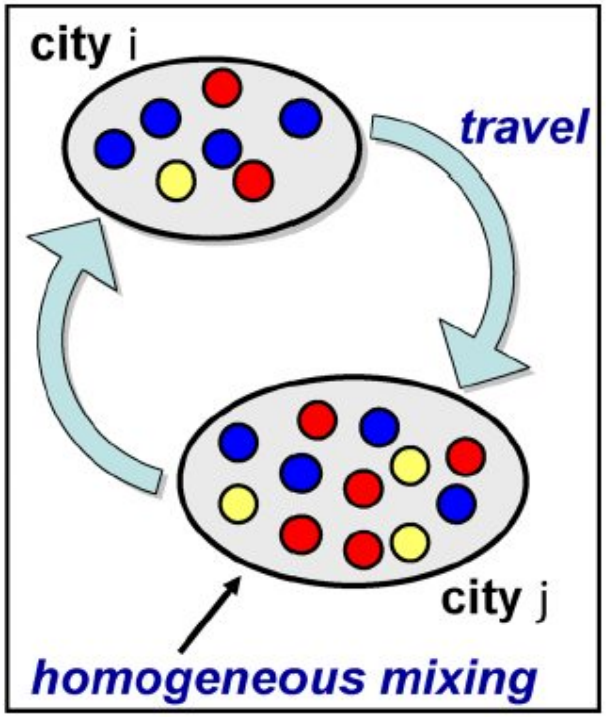


Foxman, Newman, Percha, Holmes, and Aral, *STI* 2006

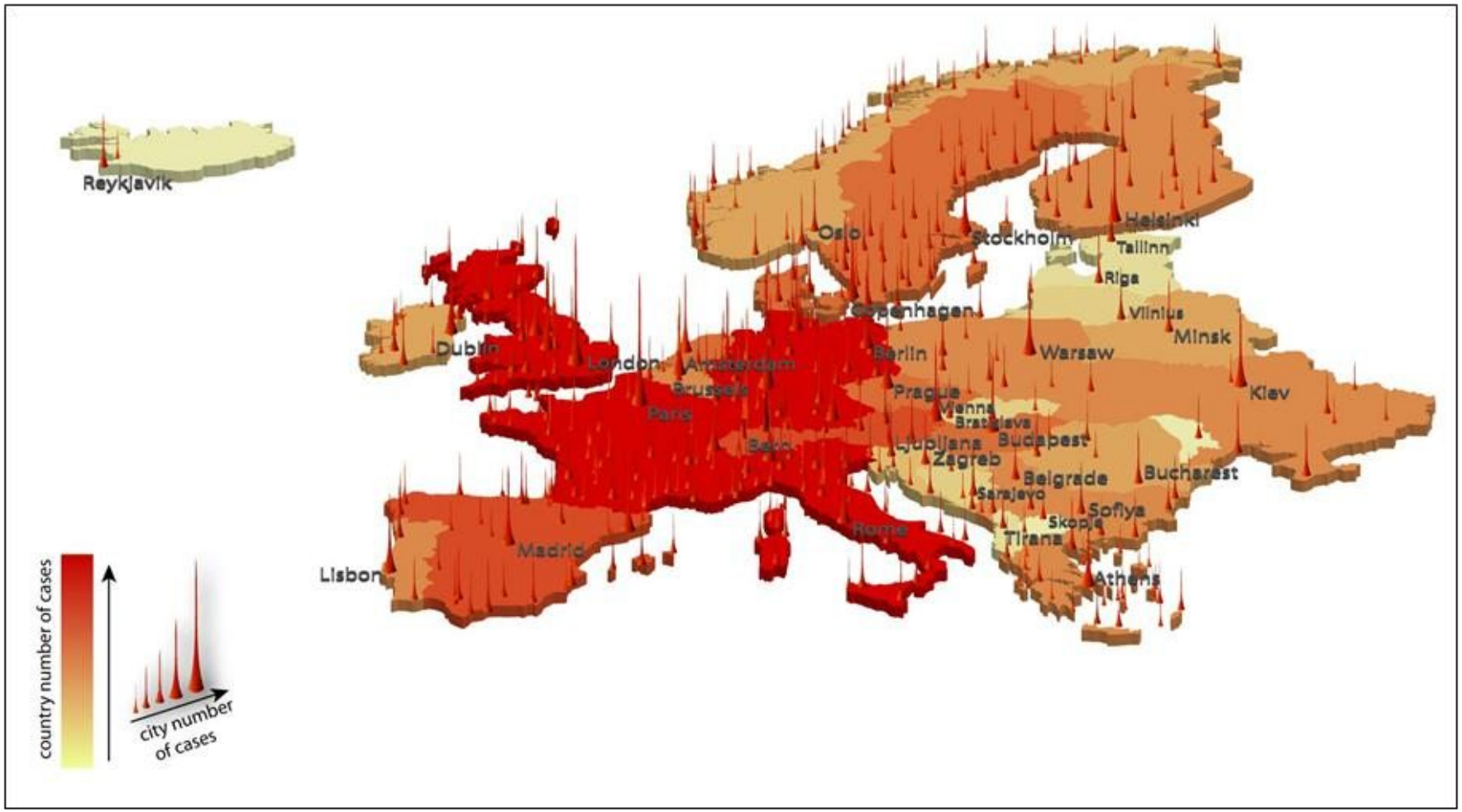


EpiSims (Eubank *et al.*)

Effects of airline travel



Colizza *et al*. 2007



Simulated outbreak of a pandemic influenza in Europe. The epidemic starts in Hanoi, Vietnam, at the beginning of October with R_0=1.9 and no containment interventions are considered. The snapshot refers to the situation in Europe on March 1 of the following year. Countries are shown with a different color corresponding to the average number of cases observed within the country by March 1, from cream (10^3 cases) to red color (10^6 cases). The local situation within each city is represented by peaks whose height scales logarithmically with the number of cases reported in the city, from 10^2 cases to 10^5 cases. Simulations consider 3100 urban areas worldwide (513 in Europe) while for the sake of visualization the map shows only a set of major European cities.

Colizza *et al*. 2007

Acknowledgments

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  - **Austin:** Lauren Meyers
  - **UBC:** Babak Pourbohloul, Danuta Skowronski, Bob Brunham
  - **CDC:** Mike Martin, Stephanie Schrag, Sevgi Aral
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  - McDonnell Foundation