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Social Network Models in Veterinary Epidemiology

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O.I.E. modelling workshop, Fort Collins

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Themes

- improve our understanding of the role of population contact structure.
  - Scale-free and small-world networks
- Working with well-understood population structures
  - Livestock movements in GB
- Identify <u>principles</u> that can be applied generically to improve disease control policies
  - The role of “dealers”

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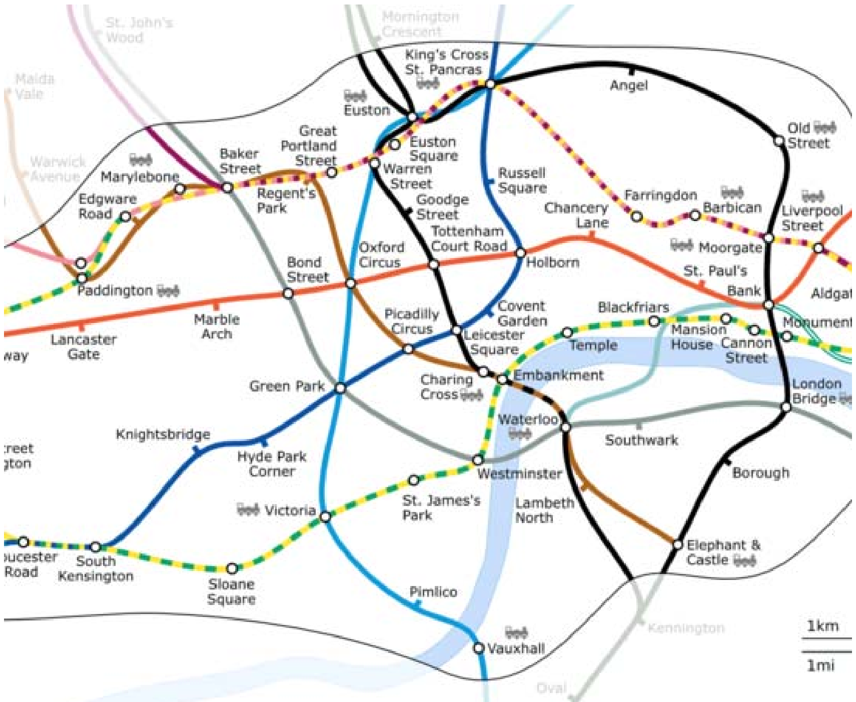
How do network models differ from spatial models?



Harry Beck - 1933

Spatial models – what is the physical distance?

Data required is usually more robust

Often but not always closely related

Network models – what is the epidemiological distance?

Data required is usually more appropriate

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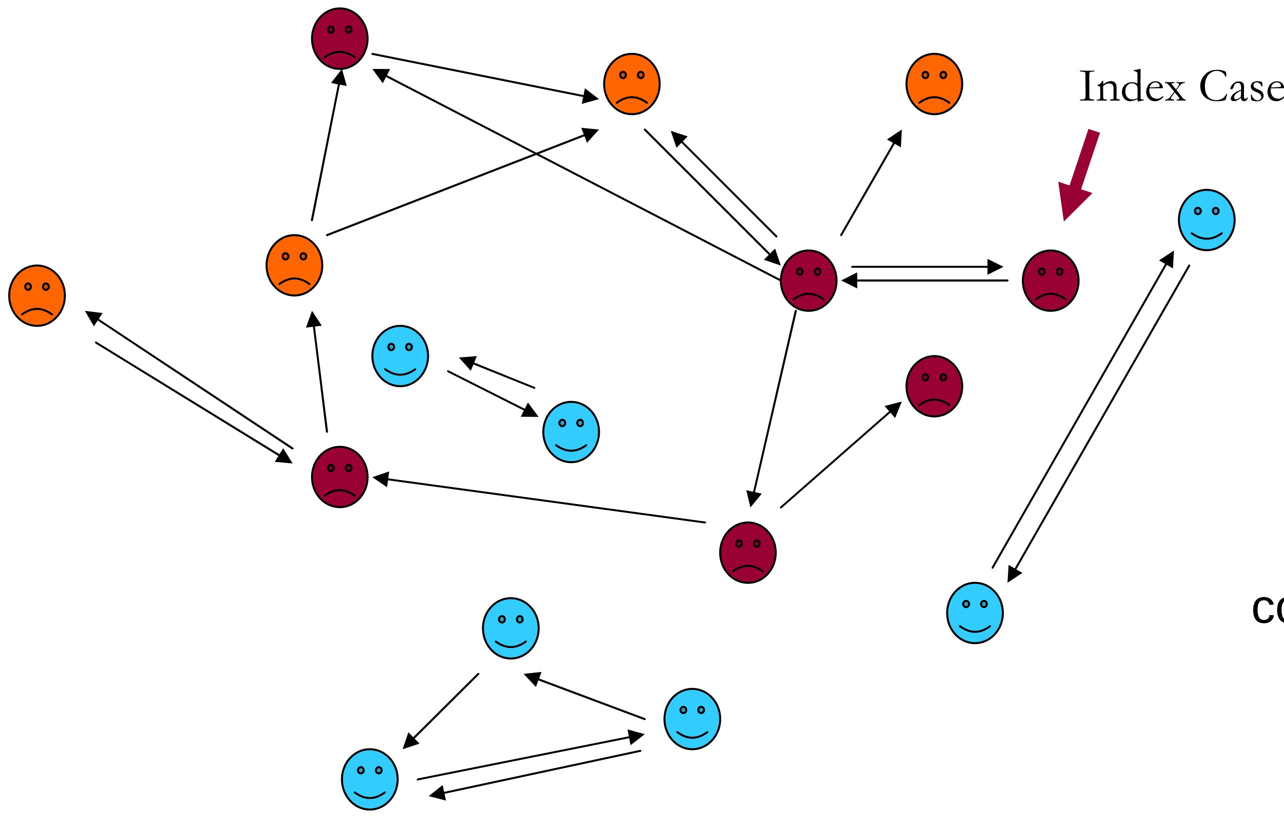
(Static) Network Interpretation of Disease Transmission



Important for contact tracing

Social Network of "Potentially Infected" Nodes/Individuals

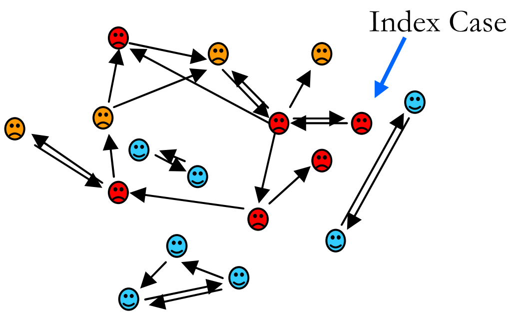
Infected At Risk but not infected Not at risk

The network-based perspective

Parsimonious (ODE) Models   Networks   Micro-simulation

Increasing complexity

$$\frac{dS}{dt} = -\beta IS$$
$$\frac{dI}{dt} = \beta IS - \gamma R$$
$$\frac{dR}{dt} = \gamma R$$



Micro-simulation ← different paradigms → ODEs (dynamics)

→ Networks (population structure)

What do we mean by a large epidemic?

- Percolation: formation of large scale structures from small elements

- Networks are about transmission of "information"
  - Gossip
  - the Internet
  - biomass
  - Epidemics

Basic Reproduction Number/Rate/Ratio (R_0):

- In a **homogeneous, well-mixed system**,

R_0 =<infectious contacts>

caused by introduction of a single infected individual in a wholly susceptible equilibrium population

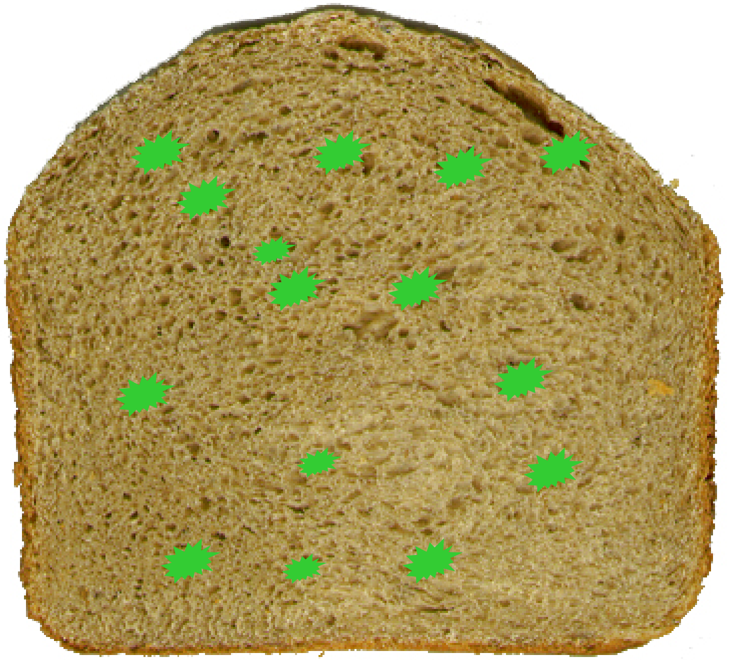
- $R_0 < 1$ implies an epidemic cannot occur
- $R_0 > 1$ implies a pathogen may be successful

Rigorous mathematical defns. exist (Diekmann et al. 1990, Van den Driessche & Watmough, 2002) BUT

Intuitive definition is not well-suited to highly heterogeneous, well-characterised population structures

Percolation

Day 1



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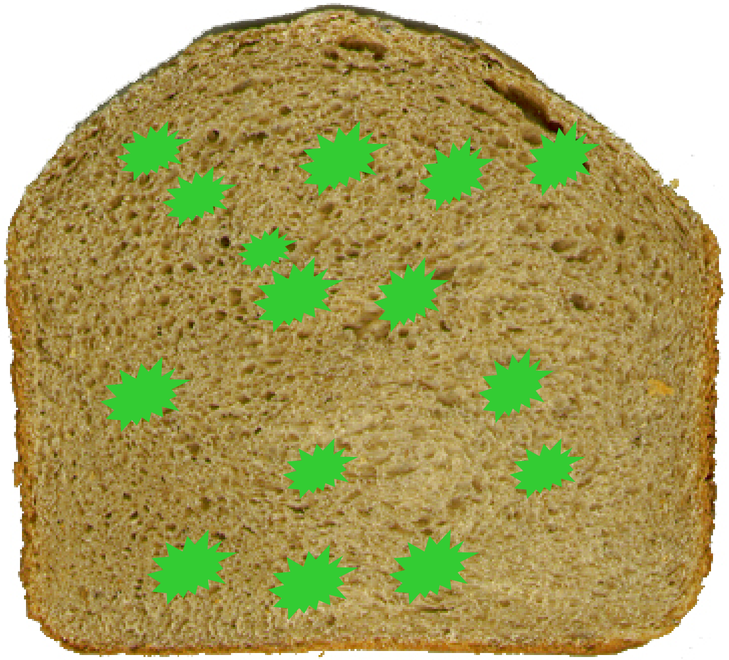
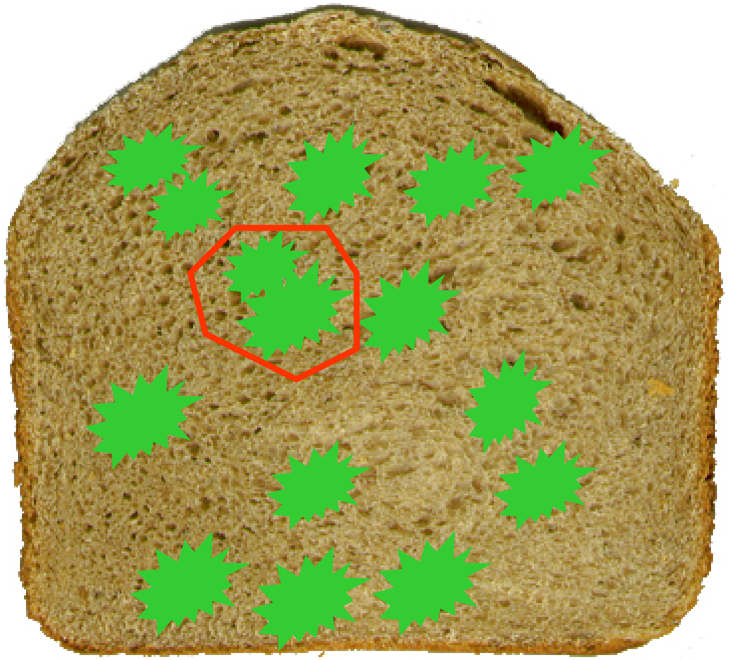
Percolation

Day 2



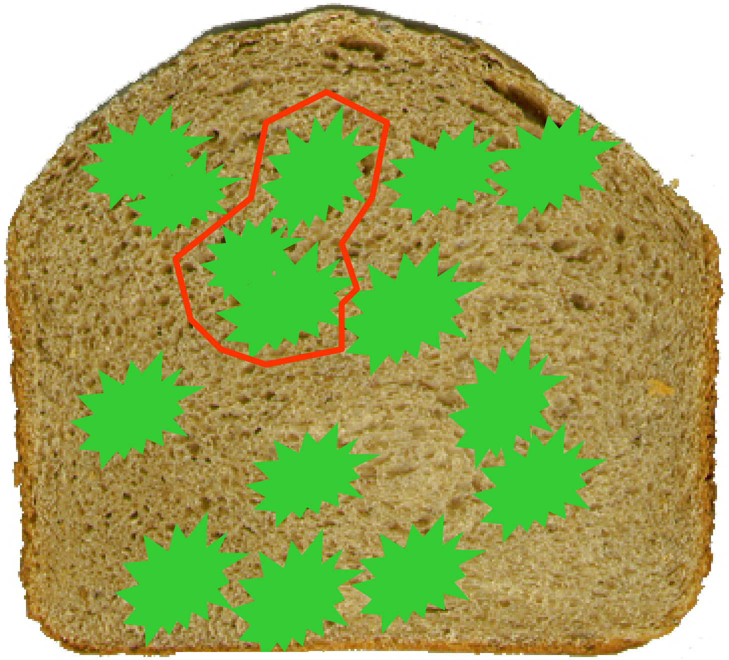
Percolation

Day 3



Percolation

Day 4



Percolation

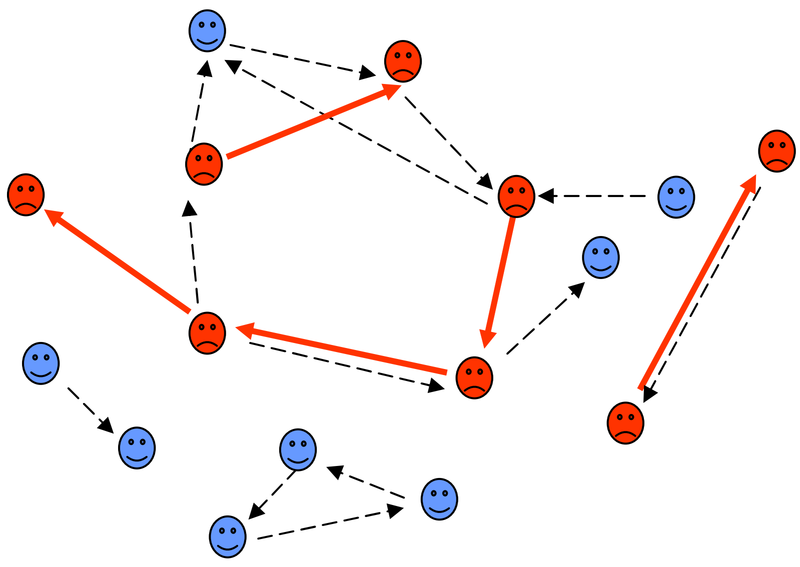
Day 5

The Largest Component (Patch of Mould) Spans the Popn.

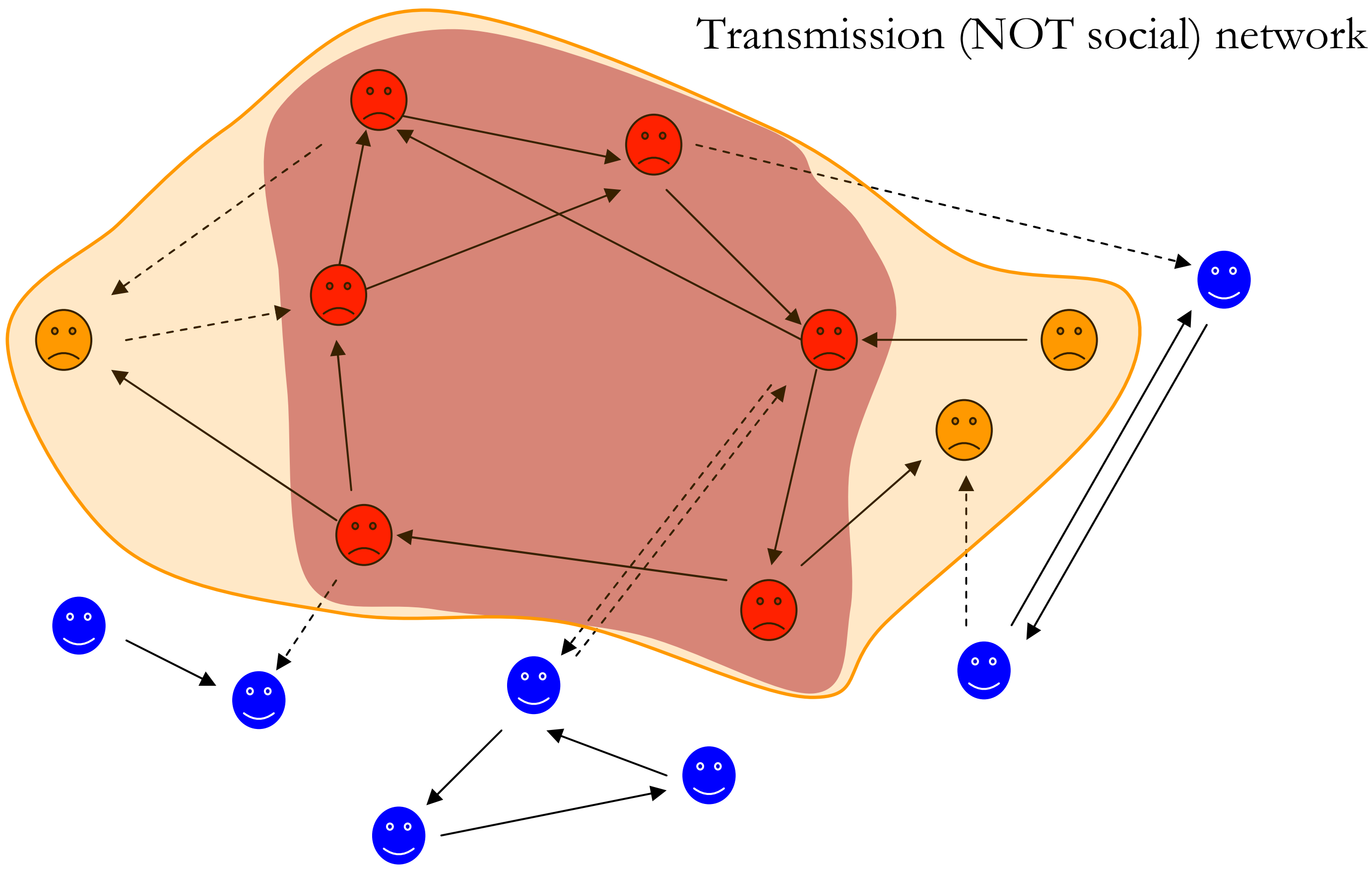
Percolation and transmission network interpretation

- Identify weighted probability of transmission between premises and "thin" network
  - Strength of link (e.g. number of livestock moved)
  - Vulnerability to and potential for transmission (e.g. size of farm, species mix)
- Reduces complicated systems to a simple analytically tractable unweighted, directed network
- Stochastically generated (requires multiple realisations)

- BUT hides transmission dynamics



Giant Connected Components



Upper/lower estimates of final epidemic size (if disease enters the GSSC)

Giant Strongly Connected Component

Giant Weakly Connected Component

Other

Percolation Interpretation of R_0

- Below percolation threshold, GSCC size (N_{GSCC}) fixed w.r.t. total population size (N_{pop}), i.e.

$$\lim_{N_{pop}\to\infty}\left(\frac{N_{GSCC}}{N_{pop}}\right)=0$$

- Above percolation threshold

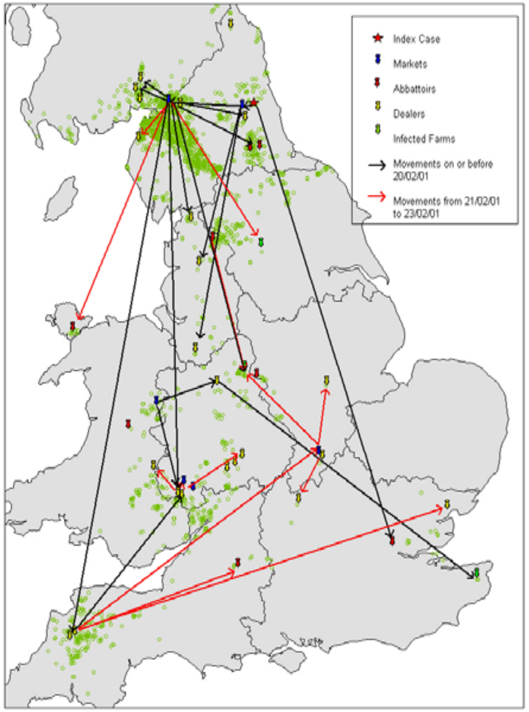
$$\lim_{N_{pop}\to\infty}\left(\frac{N_{GSCC}}{N_{pop}}\right)=f>0$$

Large Epidemic ⟷ Percolation Threshold ⟷ $R_0 = 1$

Sometimes!

Role of Livestock Movements, FMD in Great Britain

- 2001 Epidemic
  - Over £5 billion to control
  - 8 million livestock culled
- National dissemination of disease driven by movements
- Largely due to markets and "dealers"
- 6 day movement standstill – what would happen now?



Kao, 2002 adapted from Gibbens et al., 2001

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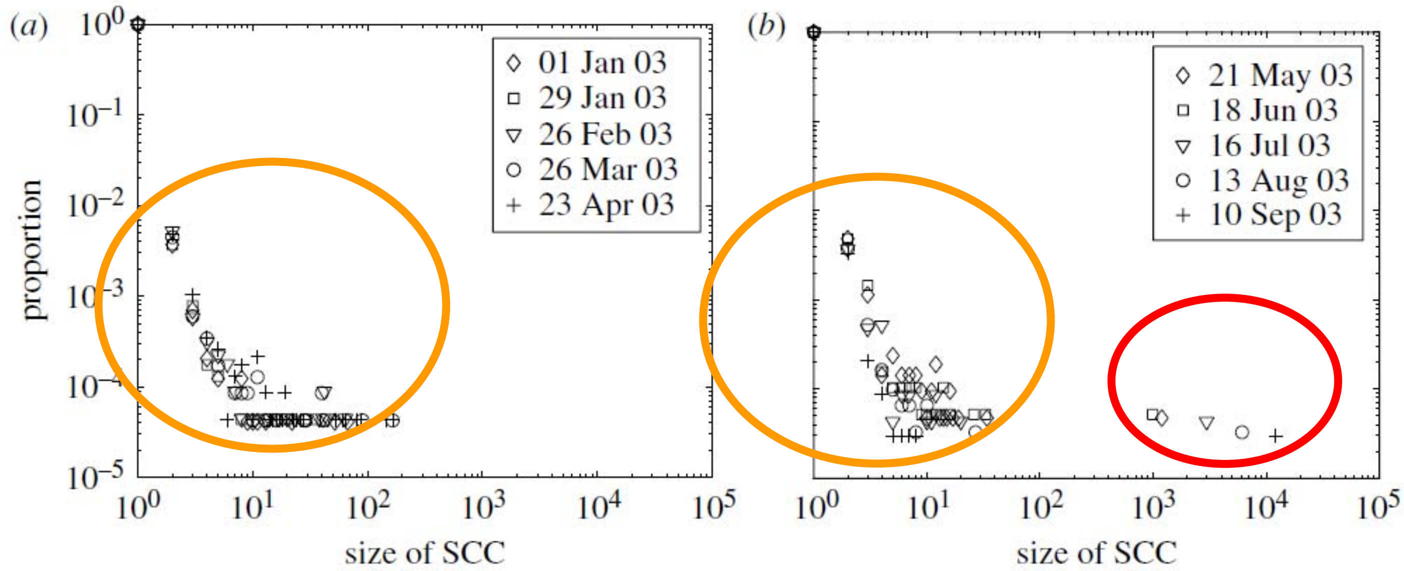
Livestock Databases

- Cattle Tracing System (1998) records all individual cattle movements
- Animal Movements Licensing System (2002) and Scottish Animal Movements System record all batch sheep, pig, goat, deer movements
- Agricultural Census – annual snapshot of location, type and composition of all agricultural premises

The percolation threshold in sheep movements



For a fixed probability of transmission per infected sheep, a single large cluster of connected premises (indicative the risk of a large epidemic) appears for some months, but not others.

Movements of sheep in 2005

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Things to Note

- Natural candidate for network models
- There is significant spatial and temporal heterogeneity in the pattern of movements
  - Can simple models tell us anything?
  - Network models handle spatial heterogeneity very well, but what about the temporal ones?
- Most movements are short range (geographically)
- Most premises are the source of relatively few movements

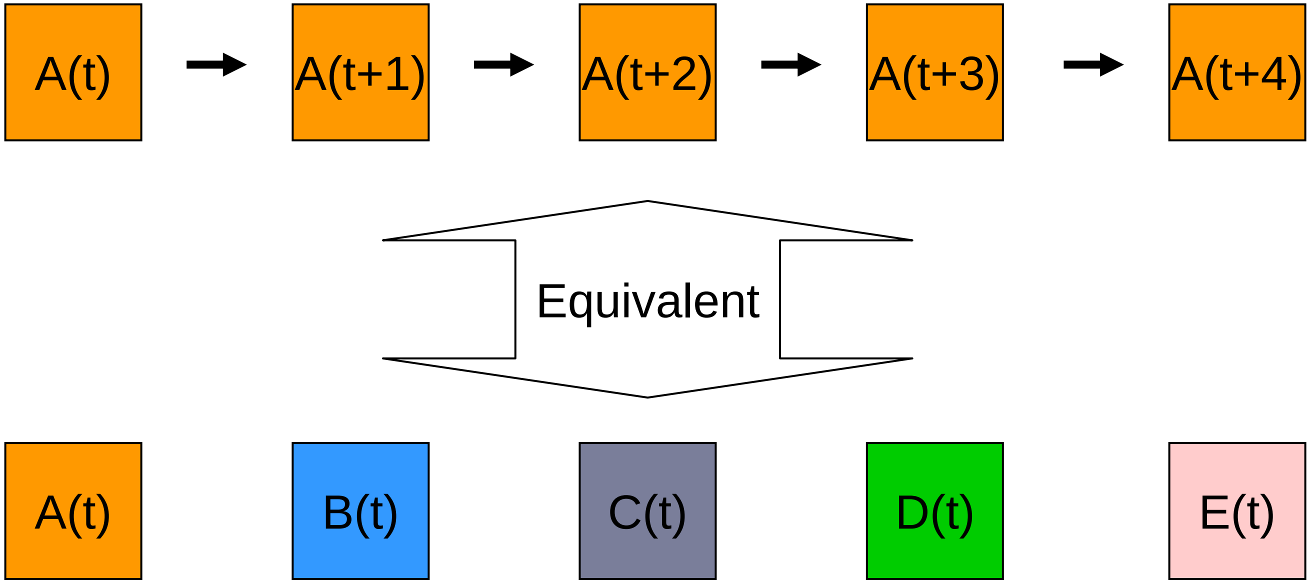
BUT

1. Some premises are very active
2. Some movements are very long range

I. How do we deal with network dynamics?

What do you do when connections appear and disappear over time?

The Ergodic Hypothesis

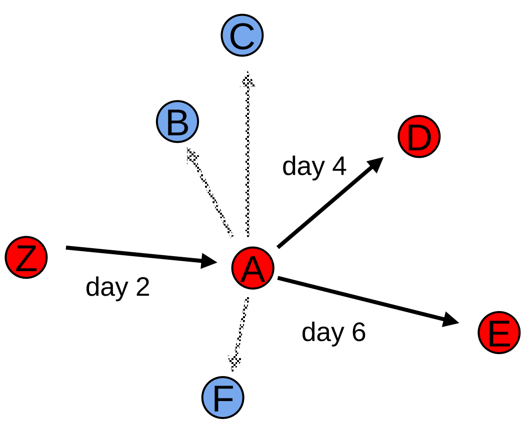


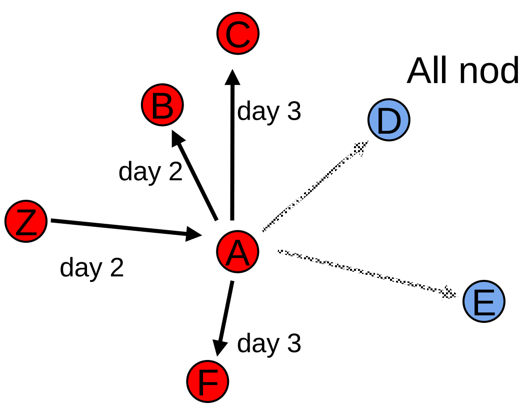
- Under ergodic conditions, one system followed through time is equivalent to a single snapshot of multiple systems

What is an "Equivalent" Static Representation?

	Dynamic Simulation			Static Network			
Day	From	To		Day	From	To	
2	**Z**	**A**	Infection event	**2**	**Z**	**A**	Infection event
			4 Day infectious period				
1	A	B	No infection	**1**	**A**	**B**	Infection event
1	A	F	No infection	**1**	**A**	**F**	Infection event
2	A	C	No infection	**2**	**A**	**C**	No infection
4	**A**	**D**	Infection event	4	A	D	No infection
6	**A**	**E**	Infection event	6	A	E	No infection

Dynamic simulation
"A" infectious
days 3 to 6



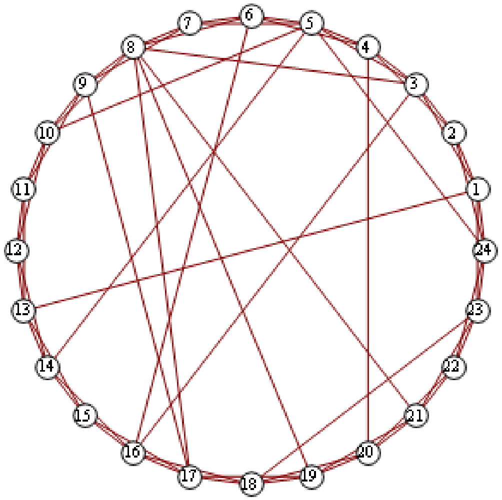


Static transmission network
All nodes infectious
days 0 to 3

Create a static (directed) transmission network by constructing links starting from day zero for all nodes for the length of the infectious period (accounting for latency)

Dynamic Small World Network

- Relatively few “long distance” connections connecting otherwise locally connected individuals
- Local connections fixed
- Allow long distance connections to switch at a rate σ

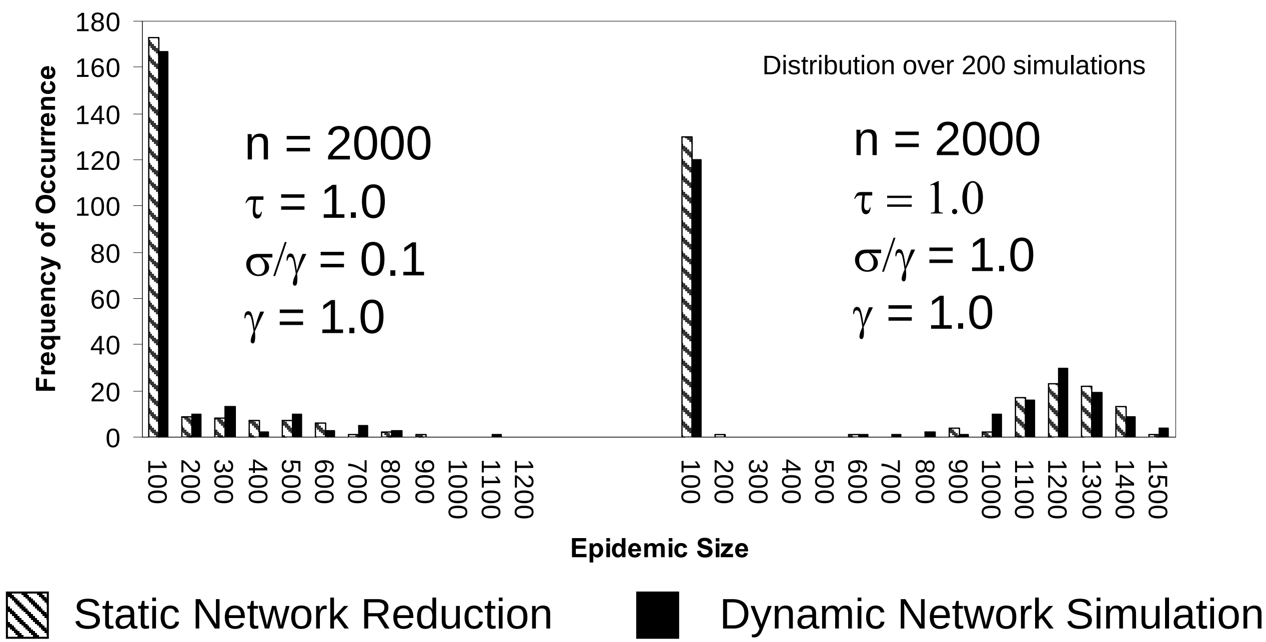


Watts & Strogatz, 1998

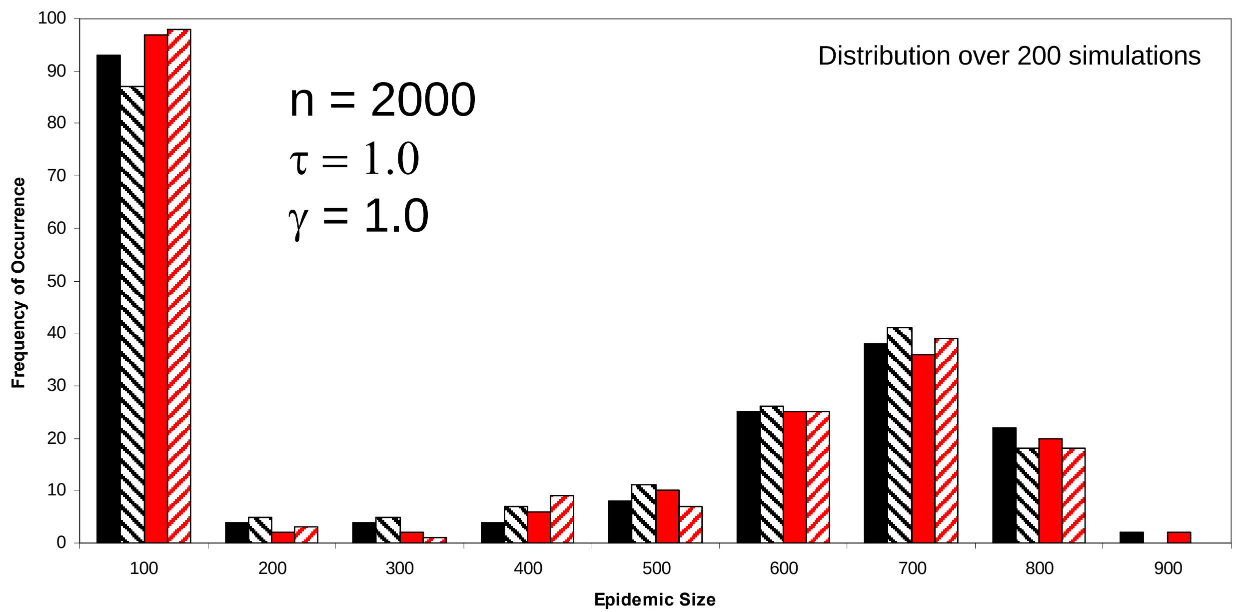
Effect of Link Switching on Small world networks

- SIR epidemic
- Static network: critical infection rate/link $\tau_{perc} \sim 1.05$

1. Static and dynamic pictures are the same
2. Link switching lowers the percolation threshold

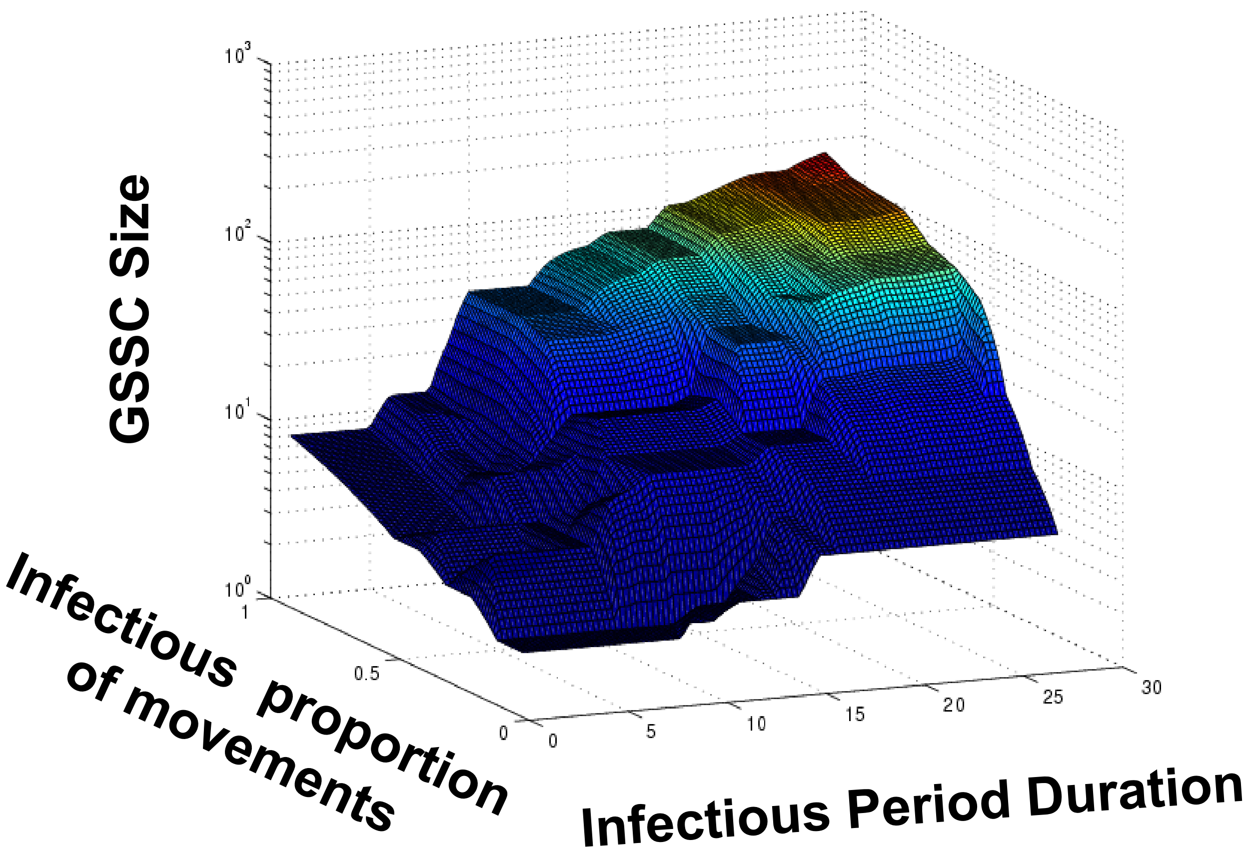


Change is due to saturation effects



Static Network Reduction / Dynamic Network Simulation: $\sigma/\gamma = 10$, $\sigma/\gamma = 0.1$

Growth of the GSCC from 19/05/04



From Kao et al., 2006

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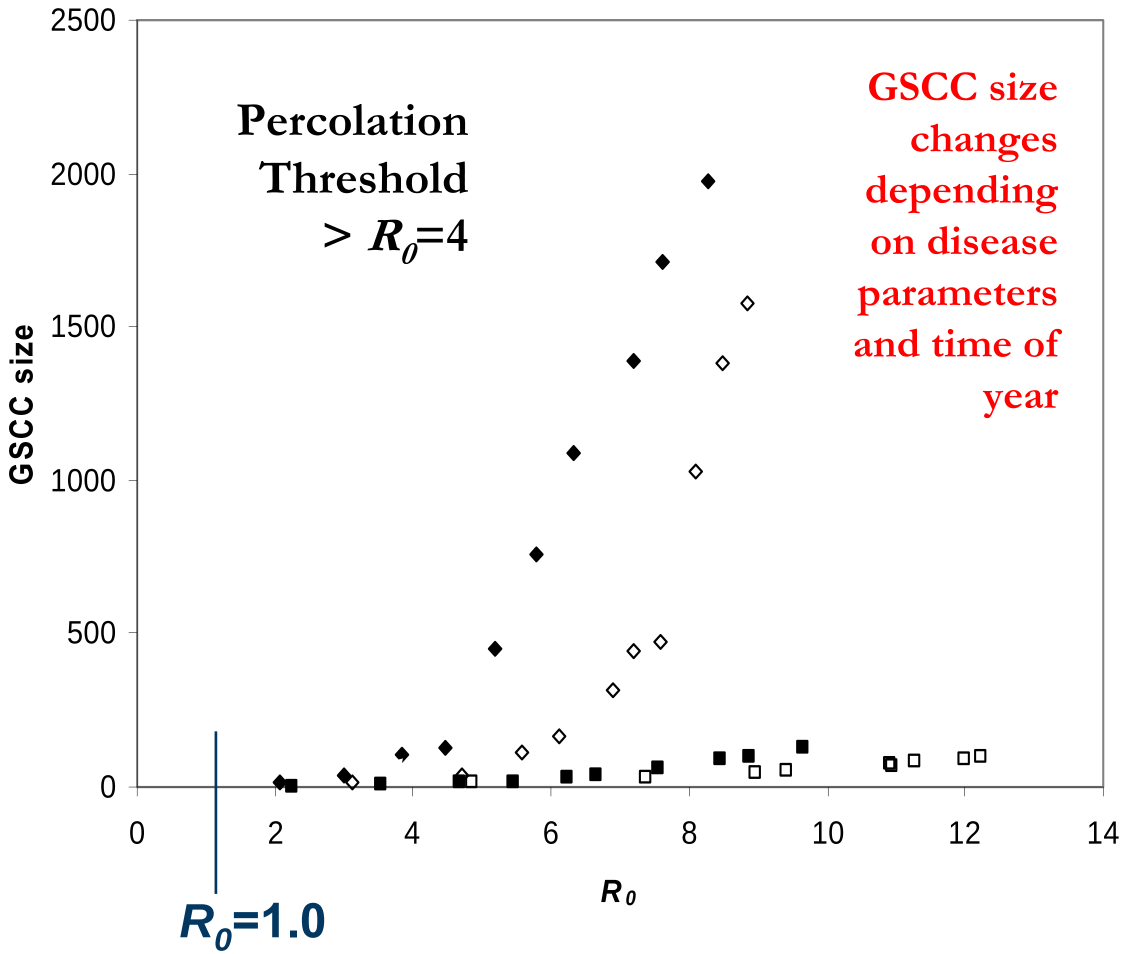
Ergodic Behaviour? Growth of the GSCC vs. R_0



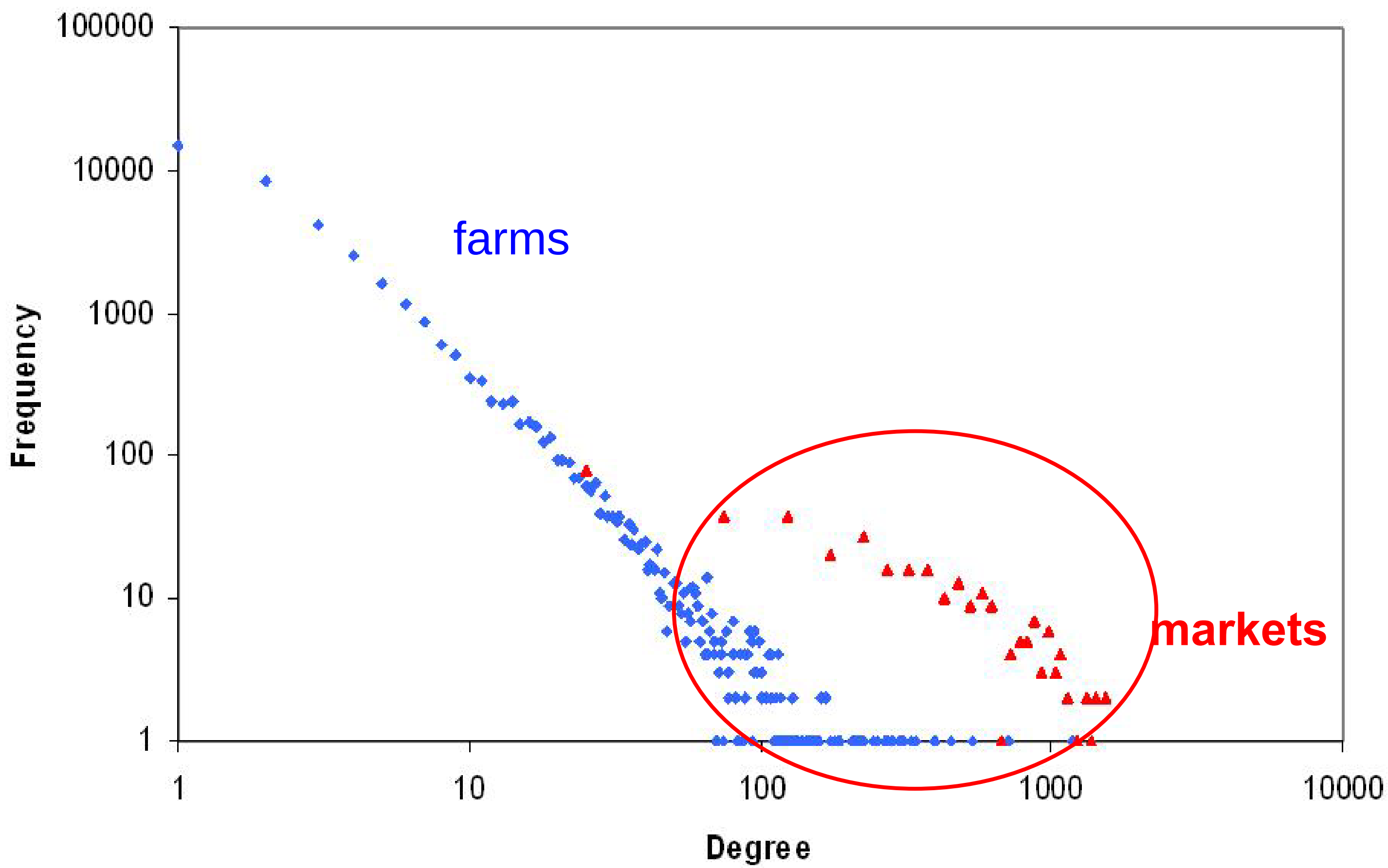
(♦) - 28 days infectious period from 19/05/04
(◊) - 28 days infectious period from 05/11/03
(■) - 7 days infectious period from 19/05/04
(□) - 7 days infectious period from 05/11/03

Markets have fixed one day infectious period

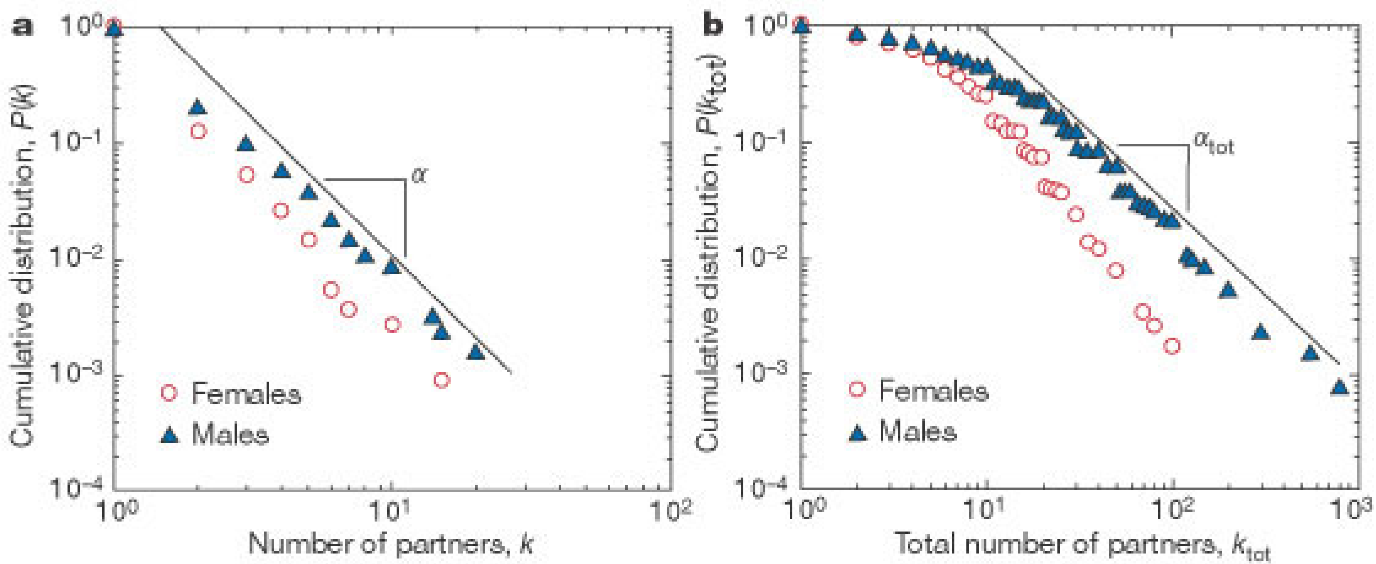
Point II: Some premises are more active than others

The role of heavy-tailed distributions

Out Degree Distn, Sept. 2004



Scale-free Networks



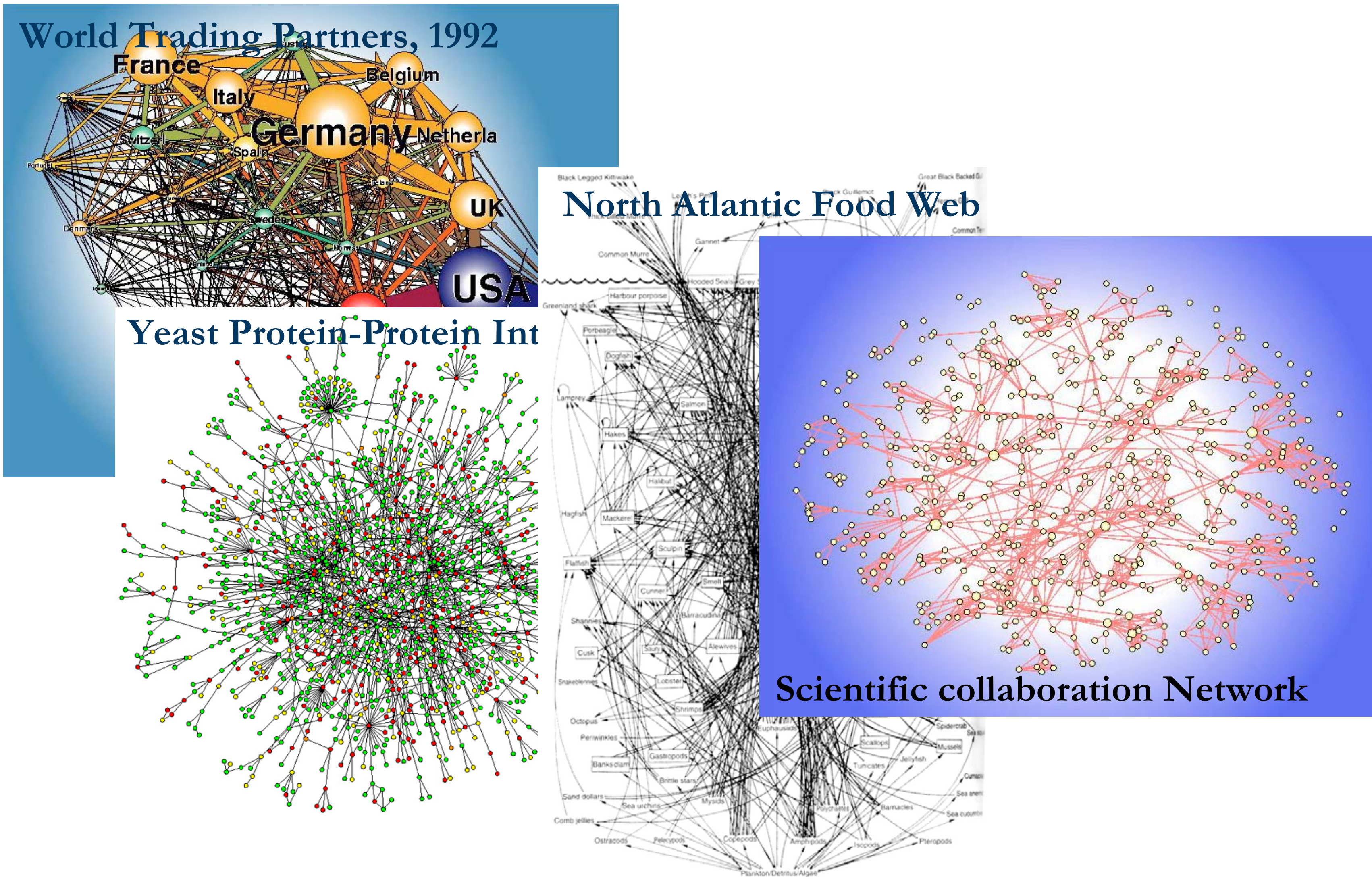
$$P(x) \propto x^{-k}$$

$$2.0 < k < 3.0$$

Variance in an infinite population is infinite!

From Liljeros et al., Nature 2001

Broad applicability of Scale-Free Networks



R_0 in Randomly Mixed Directed Networks

$$R_0 = \frac{\langle k^{in} k^{out} \rangle}{\langle k^{in} \rangle}$$

Covariance between in & out degrees of transmission network

Infectious out links

Infectious in links

$$R_0 = 1$$

percolation threshold in randomly mixed networks

If k^{in} and k^{out} uncorrelated: ➔ $R_0 = \langle k^{in} \rangle = \langle k^{out} \rangle$

$k^{in} = k^{out} = k$ ➔ $R_0 = \langle k^2 \rangle / \langle k \rangle$

See Hethcote and Yorke 1982, Anderson & May 1991, Albert & Barabasi 2000, Schwartz et al. 2002, Kao et al. 2006

Why is network structure important?

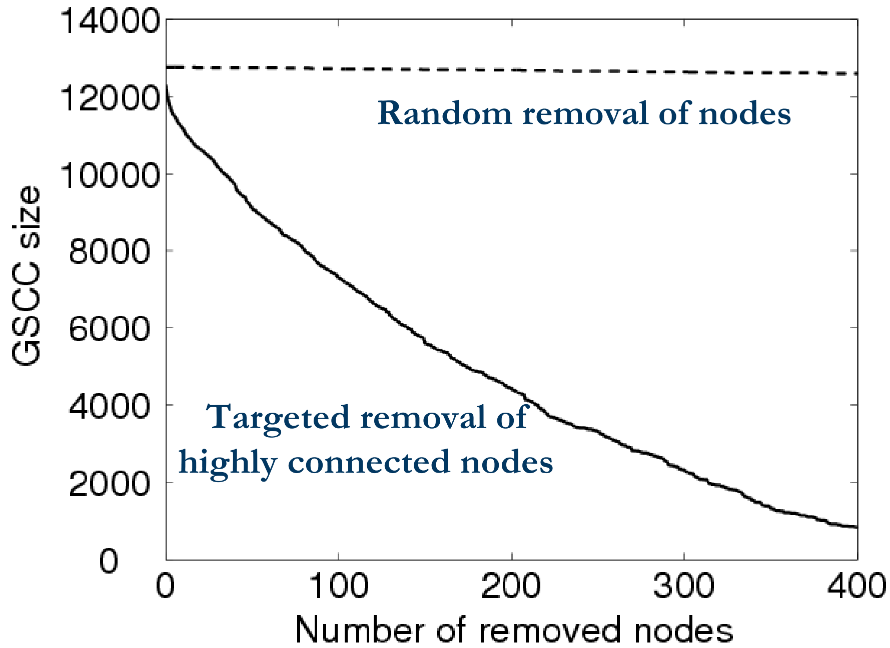
- Many Networks have "Scale-free-like" properties
  - Heavy-tailed distributions
  - Pareto's Law/20-80 Rule
  - The "Matthew Effect"

- 2x as active, 4x as important

$$R_0 = \frac{\langle k^{in} k^{out} \rangle}{\langle k^{in} \rangle}$$

← Reducing covariance rapidly reduces R_0

Can degree distribution be exploited to control epidemics?



Targeted node removal rapidly reduces possible epidemic size

Parameters "inspired by" silent spread period in 2001 FMD epidemic

Point III. Some livestock are sent farther than others

The role of occasional long distance movements

Kevin Bacon Game

Ivan Stalenin

↓ Scandal? (1929)

Julia Eisenstein

↓ Battleship Potemkin (1925)

Andrei Fajt

↓ Silnye dukhom (1967)

Viktoriya Fyodorova

↓ Target (1985)

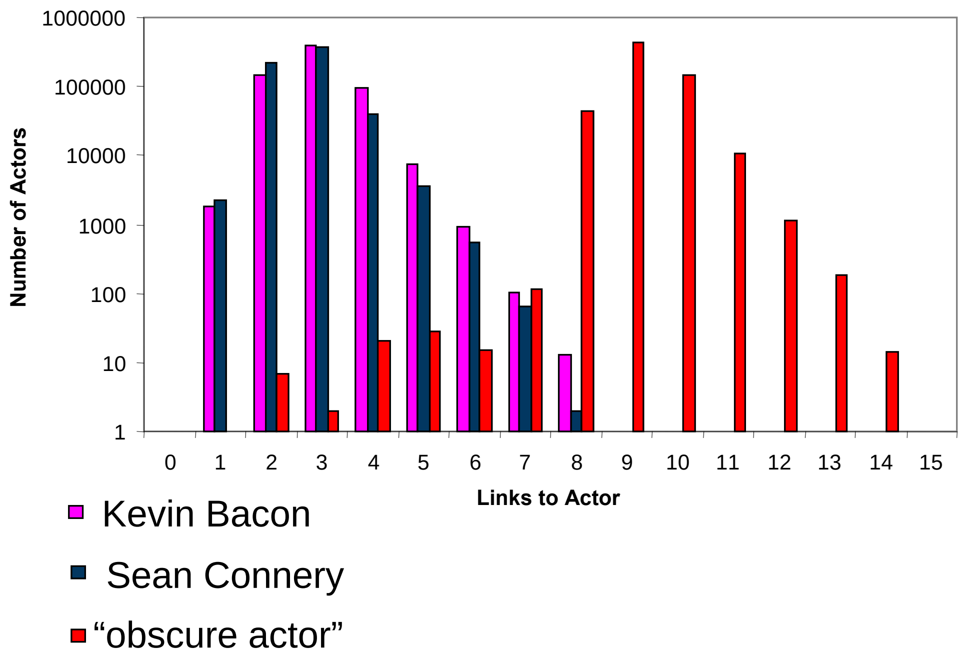
Matt Dillon

↓ Loverboy (2005)

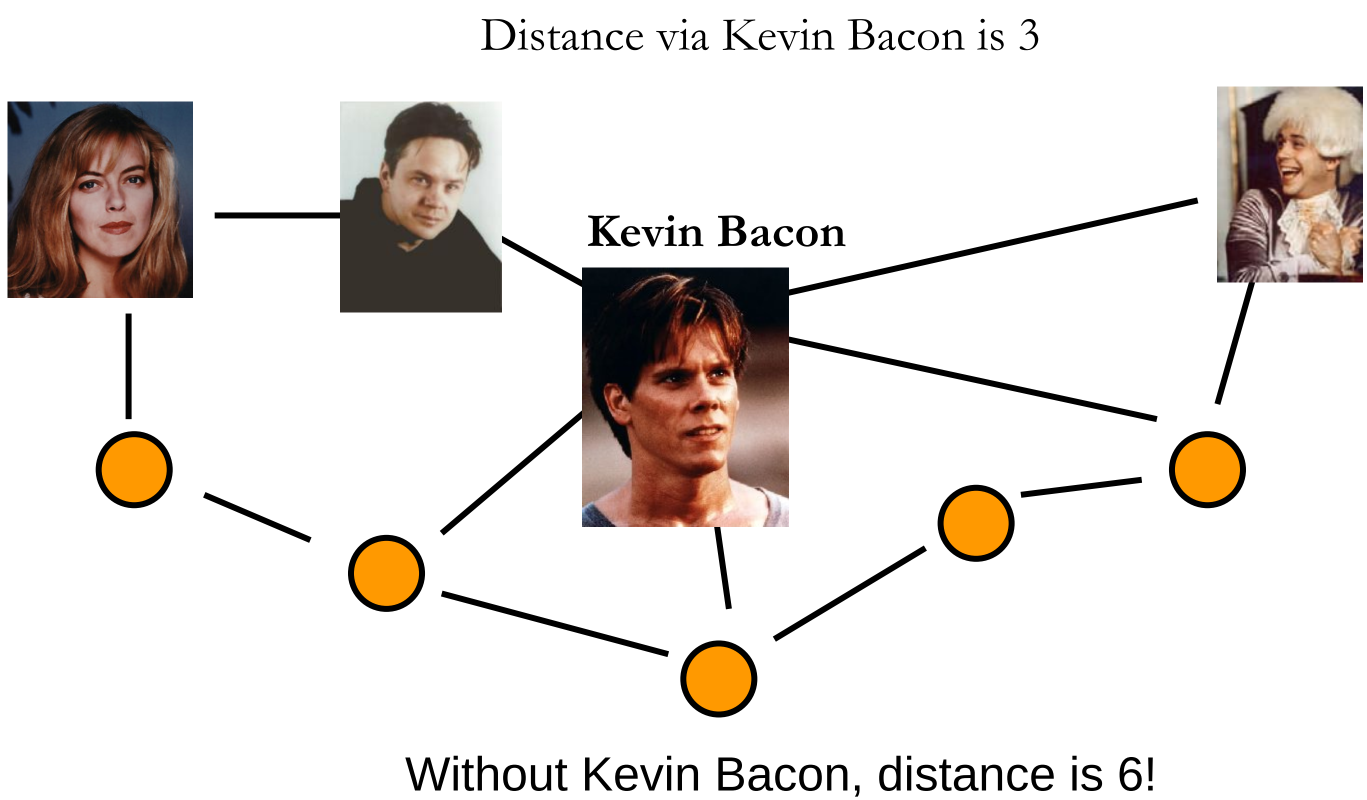
Kevin Bacon

Average link distance: 2.9 824,270 actors

2.3% not linked (IMDB)



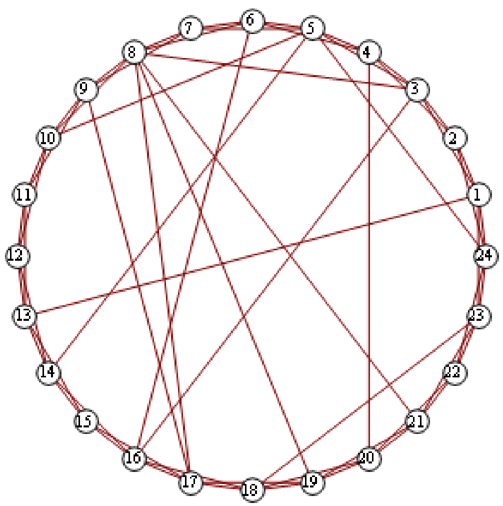
Kevin Bacon Game

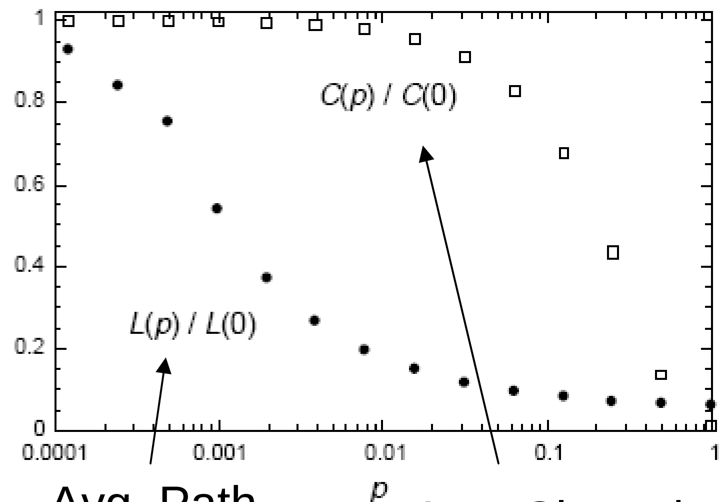


A few actors are at the centre of the Hollywood Universe

Small world Networks

- Relatively few “long distance” connections can connect the world





Avg. Path length

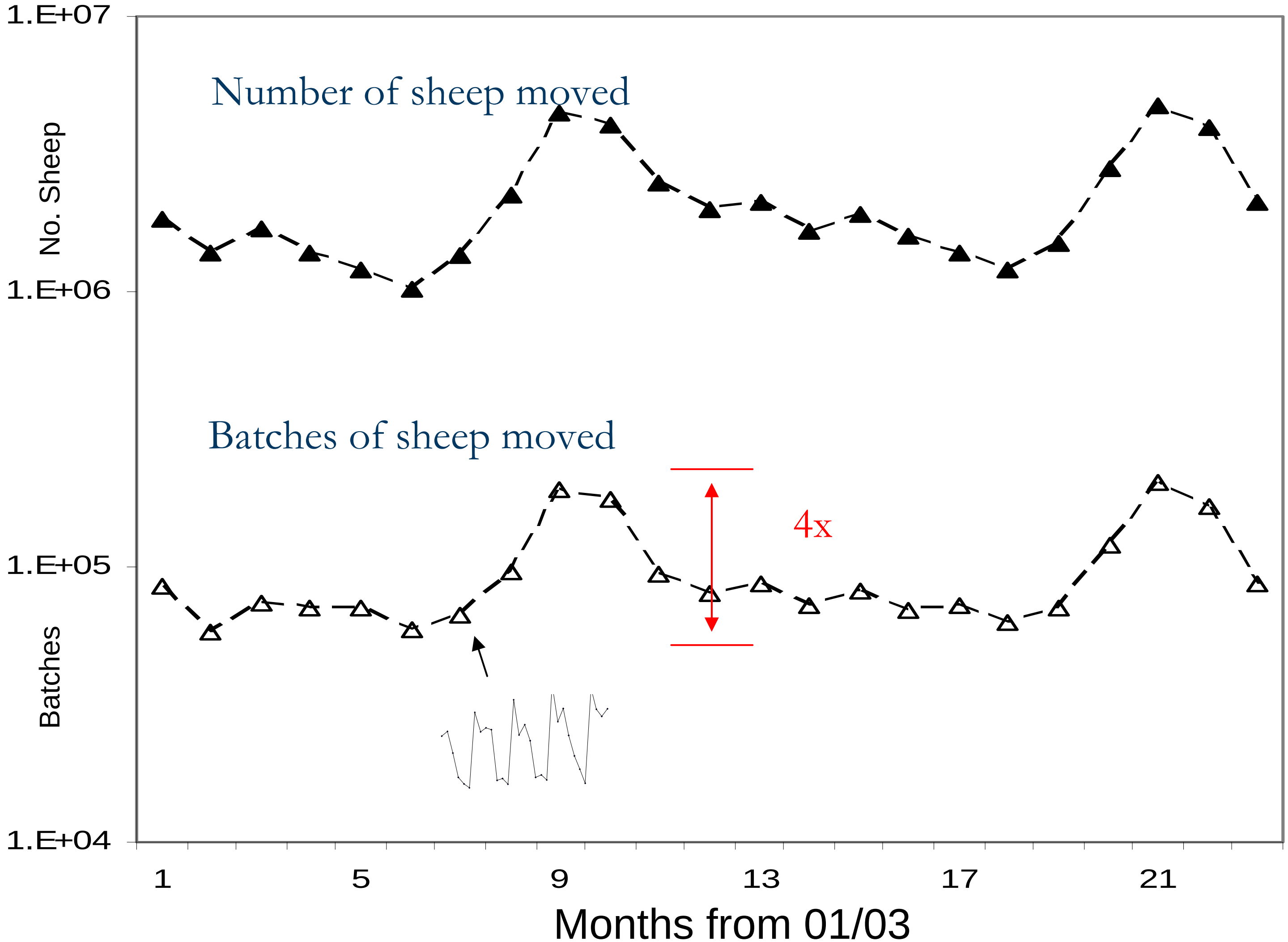
Avg. Clustering coefficient

Epidemics move farther and faster than expected

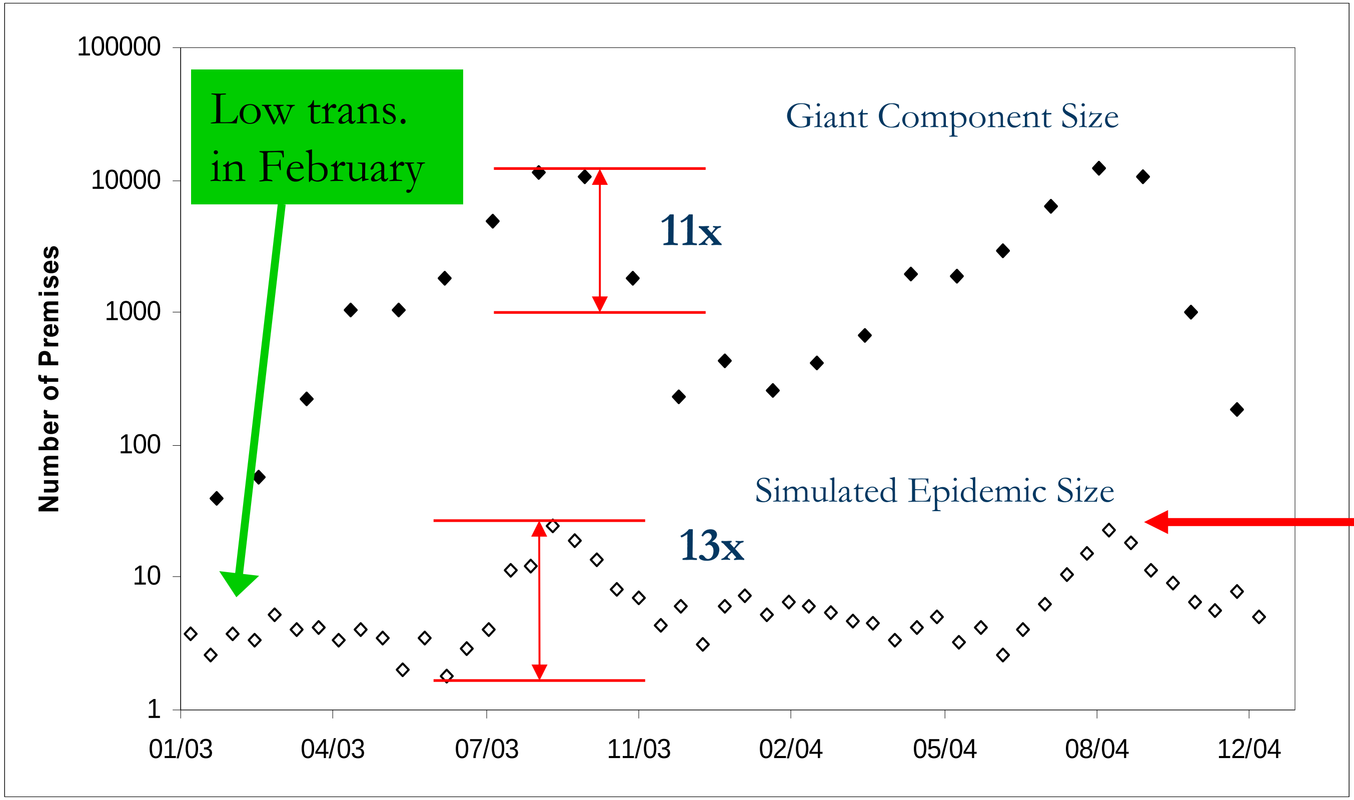
Watts & Strogatz, 1998

Does this principle apply to the GB livestock movement network?

Movements over the Year

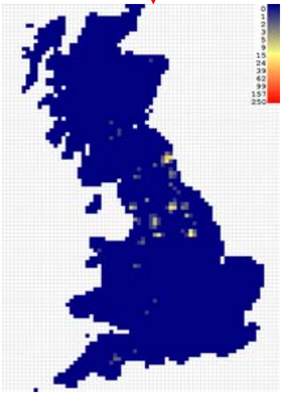


Evidence of Percolation?



Non-parametric simulation (instant replay)

Peak no. IPs ~ 60+ as bad as 2001!



Simulation Parameters for FMD (avg 200 runs)

- **infectious period 3 wks, epidemic for 4 wks (as 2001)**
- **trans. probability = 1/3 for farms, 1/10 for markets**

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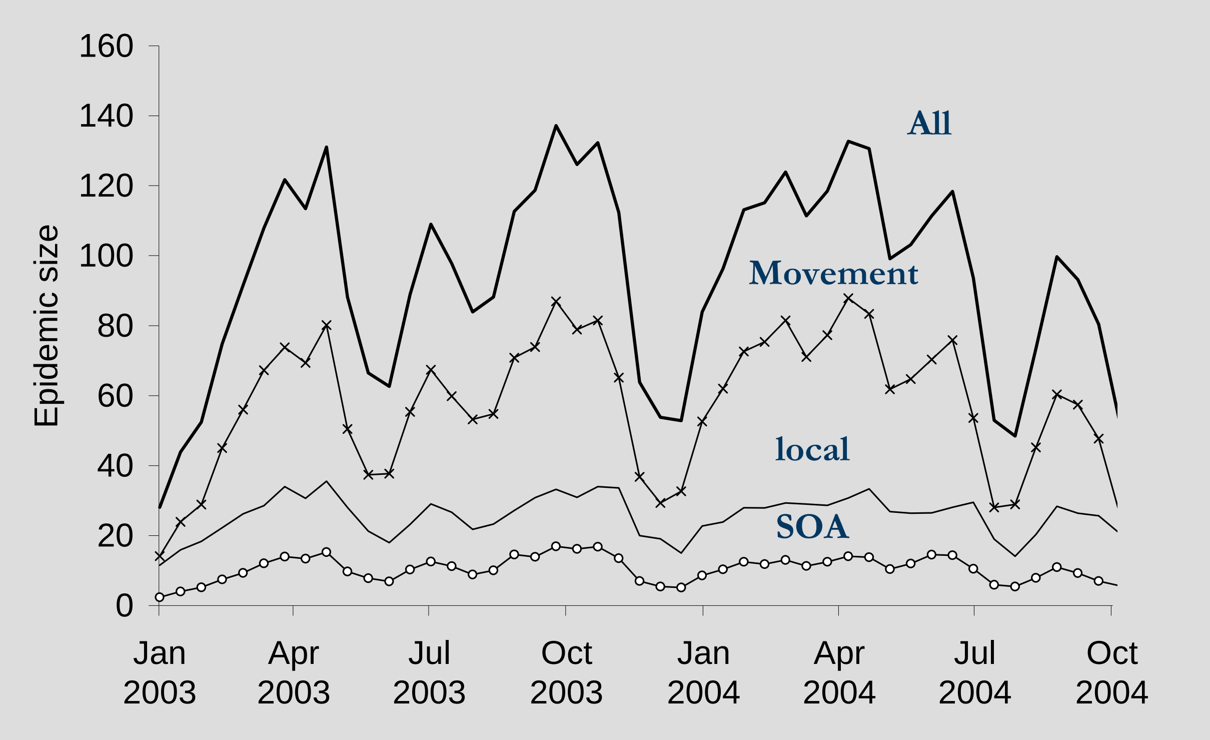
Robustness of the Result



Additional spread due to localised transmission (similar to 2001 FMD levels) & spread between sole occupancy authourities (SOA's)

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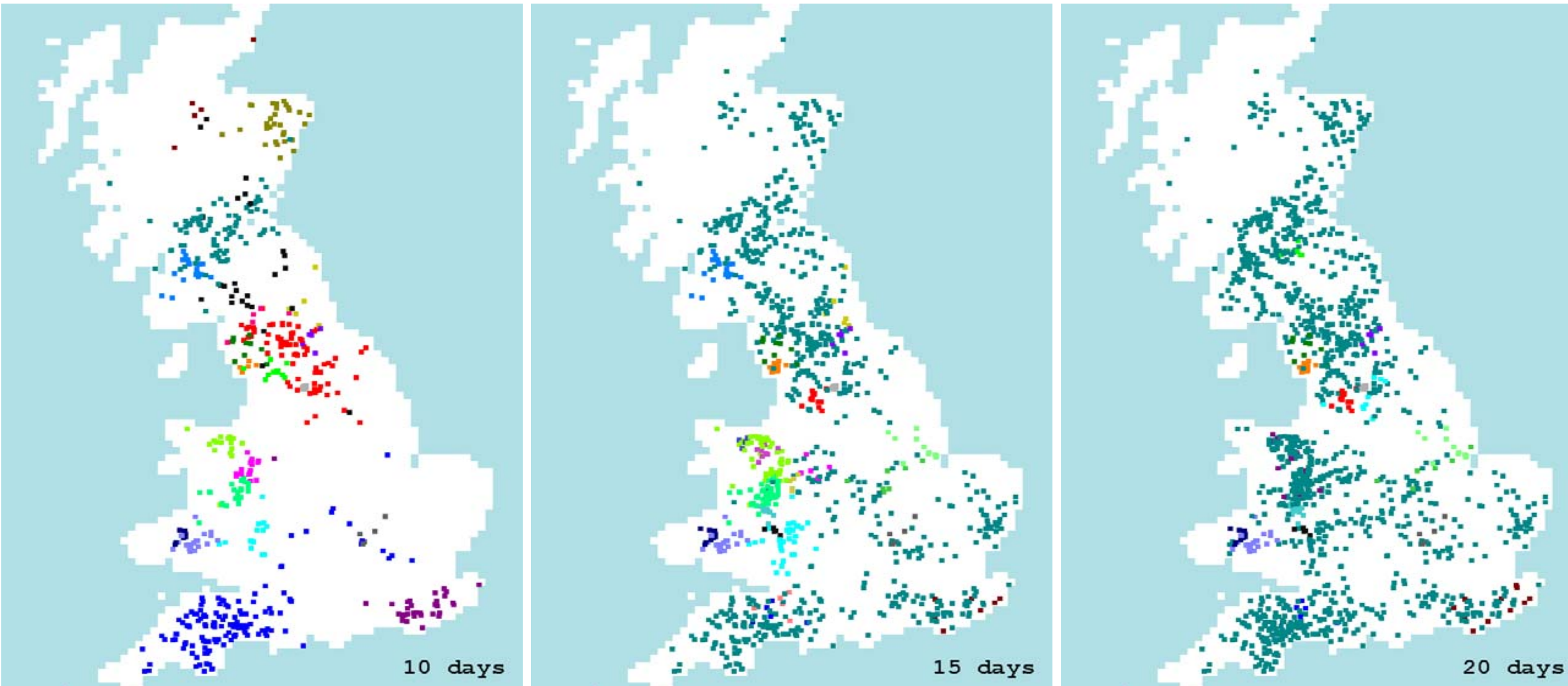
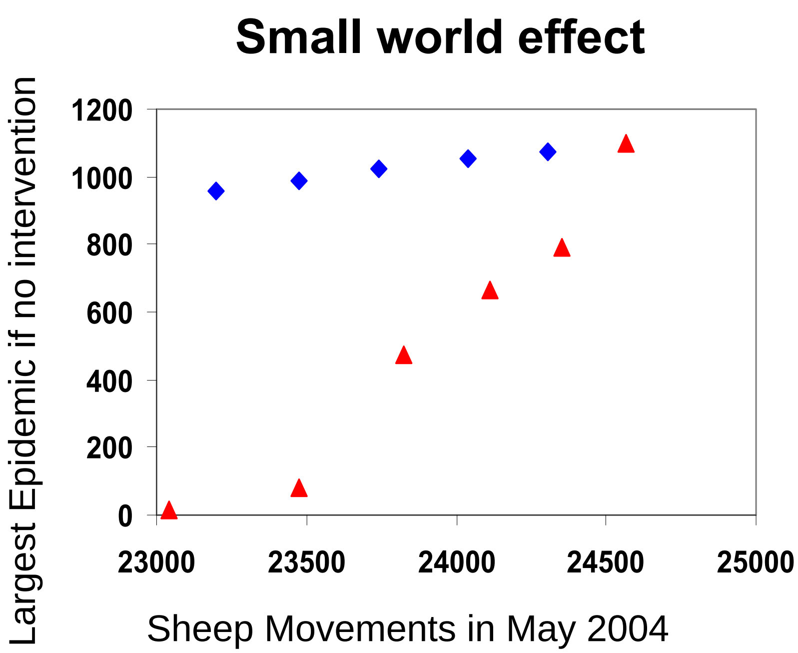
Percolation Threshold (Sheep Network, May 2003)



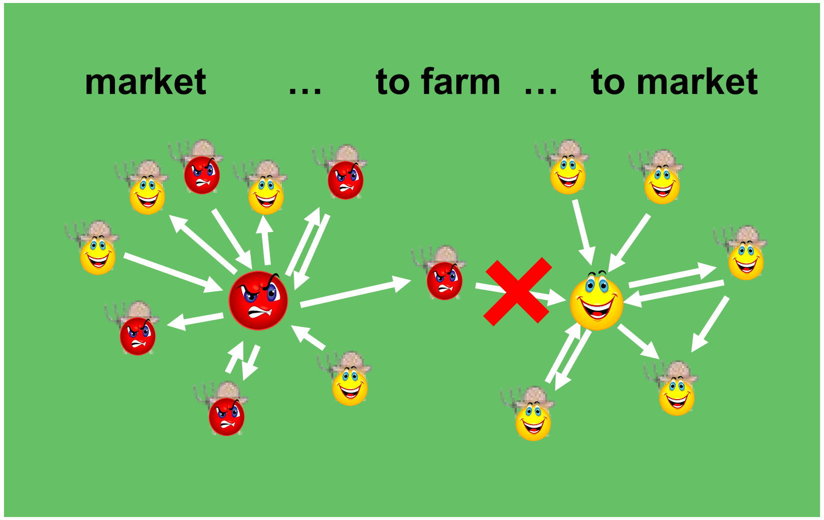
Infectious period

Growth of strongly connected components by increasing infectious period of farms

Can we target biosecurity/surveillance/awareness?



Random removal of movements only slowly reduces epidemic size.
Targeted removal of "linkage movements" does so quickly.



Non-parametric simulations starting in 09/06, removal of 2.6% of all movements would have reduced probability of a large epidemic (60+ premises) by 25%

Conclusions

- Studying simple network structures (scale-free networks, small world networks) gives insight into universal properties
- Well-described networks (GB livestock movements) identifies questions and shows us that these principles can apply

AND

- Identify good questions to ask where our knowledge is less extensive
- Target data collection in other situations
- RAPID identification of when vulnerability of the population increases

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Acknowledgements

- I.Z. Kiss (Oxford/Sussex)
  - Network analysis
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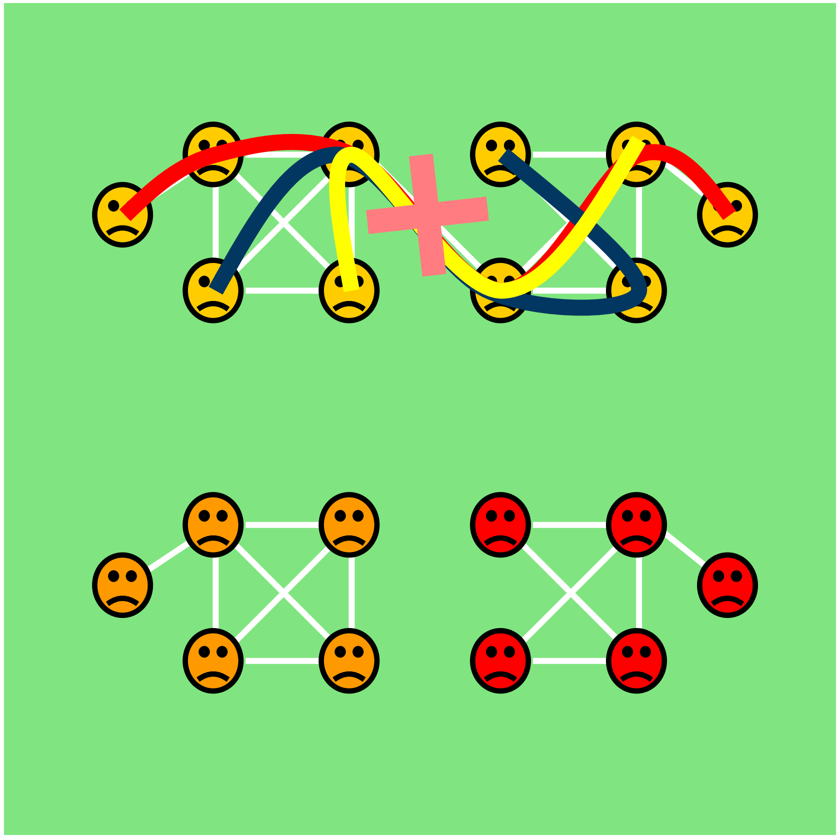
  - Community Structure
- Matt Denwood (Glasgow)
  - Movements movie
- Alun Lloyd (NCSU)
  - Small world networks model
- J. Wilesmith (Defra)
  - Field epidemiology
- RADAR
- Victor del rio Vilas, Colin Birch (VLA)
  - Scrapie data and field work

wellcome trust

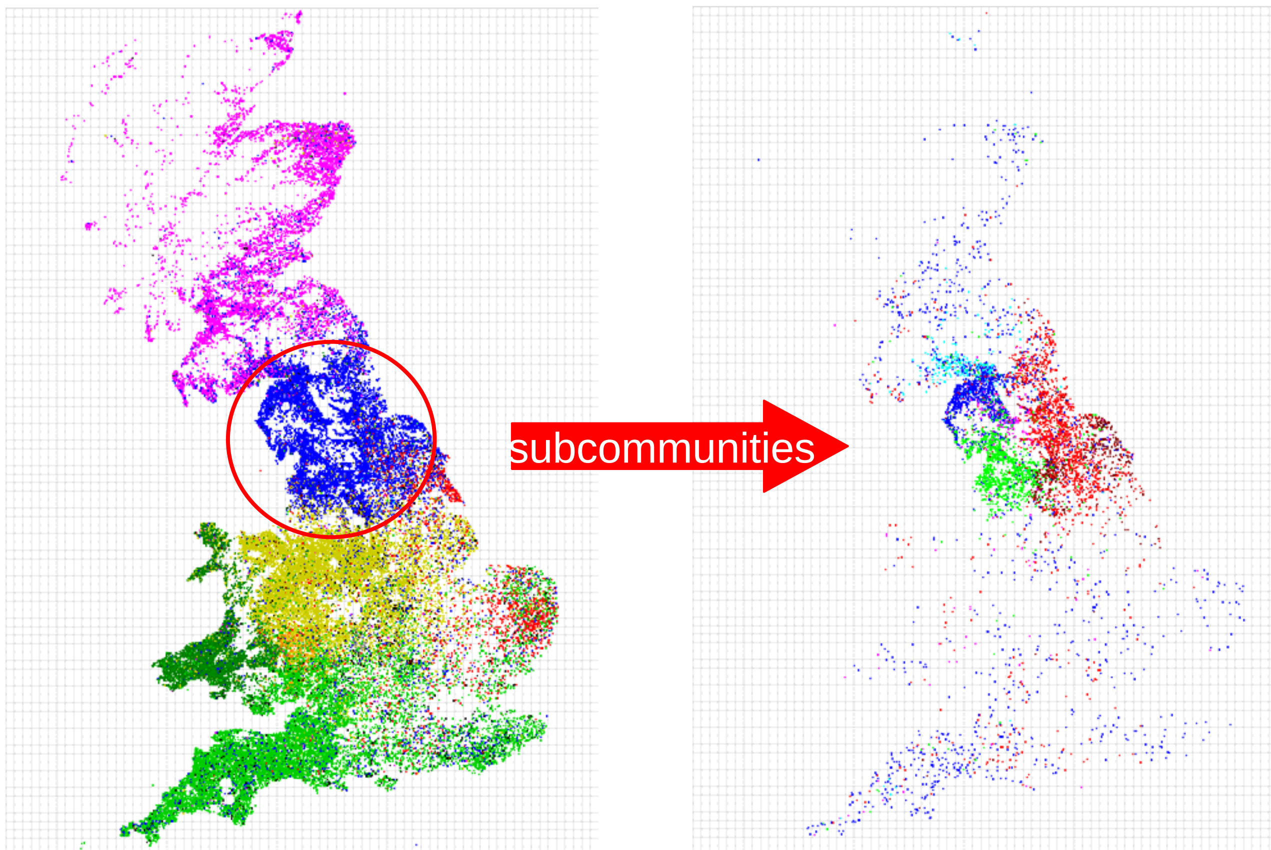
defra
Department for Environment Food and Rural Affairs

Network statistics for the sheep movement network (3)

- “Communities” are groups of premises more closely linked by interactions (sheep movements)
- “Betweenness algorithm”
  - Importance of a link for shortest paths.
  - Sequentially remove these important links, and the network breaks apart into chunks.

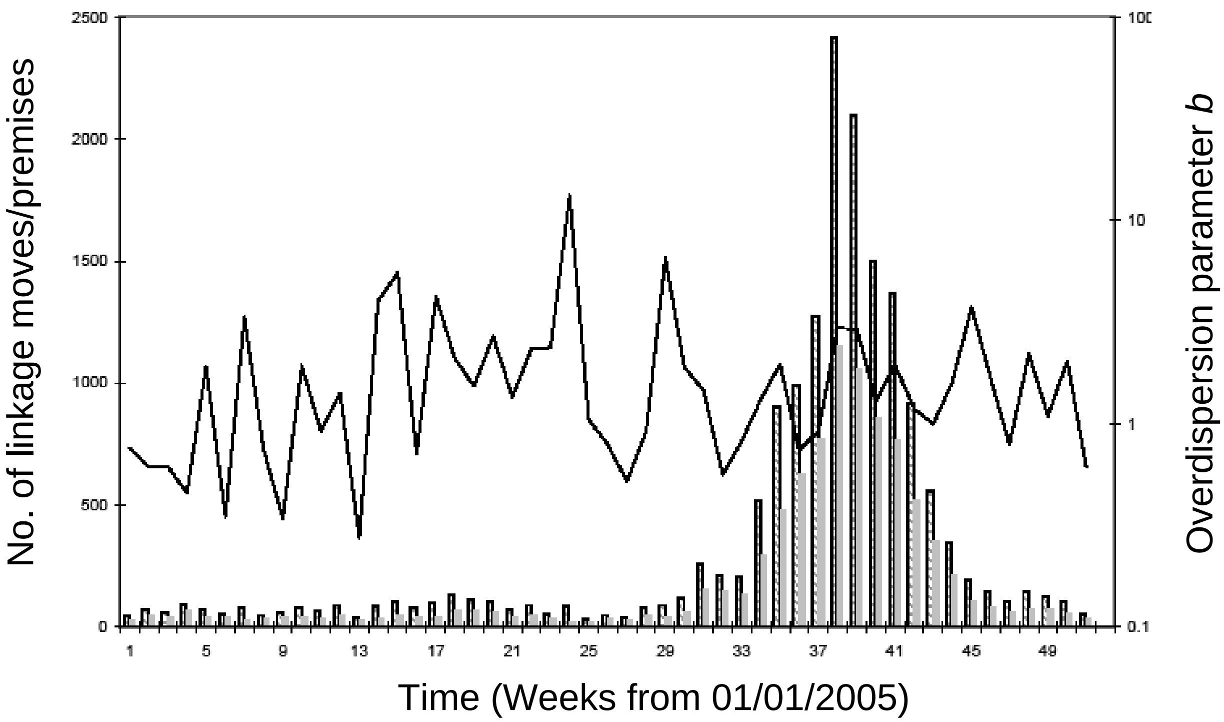


Community Structure



Communities centred on markets

What drives network vulnerability?

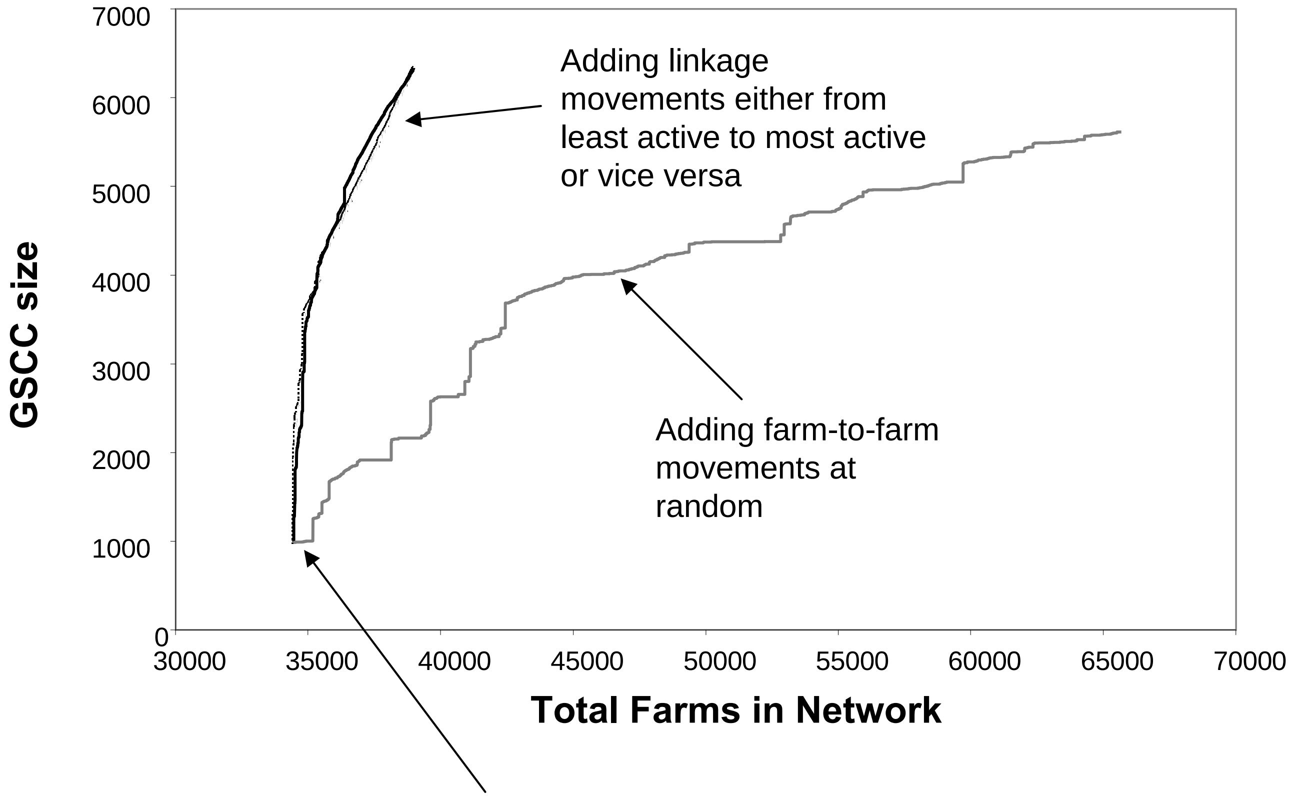


No. of linkage movements/wk

No. of premises active in linkage movements/wk

b where (1+*b*) is the variance-to-mean ratio in premises activity

Who contributes most to network structure?



Estimate of maximum epidemic size of only "local" farm-market interactions are allowed (four week period from 01/09/05)