Epidemics in Networks
Introduction

Joel C. Miller & Tom Hladish

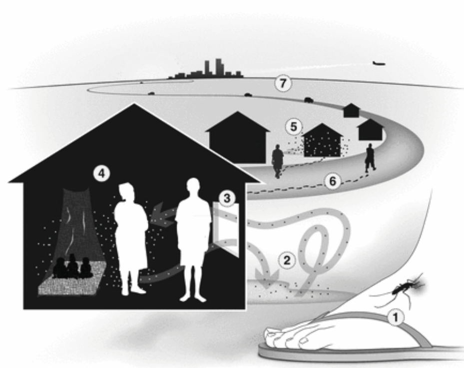
13–15 July 2015

Infectious Diseases

Common thread:
enter a host → multiply in host → spread to another host

→

←



Recently eliminated diseases

- Smallpox
  Eliminated by vaccination
- Rinderpest (livestock)
  Eliminated by vaccination
- SARS
  Eliminated by contact reduction
- Influenza A H1N1, pre-swine flu version
  Outcompeted by new strain

Nearly eliminated diseases

- Polio
- Guinea Worm

Recent emerging diseases

- HIV
- SARS
- 2009 Influenza A H1N1
- Ebola
- MERS

Introduction

Why model disease spread?

Disease spread

Networks

References

Why model disease spread?

We want to build mathematical models for infectious disease spread that:

- Predict future disease dynamics so that policy makers can prepare resources.
- Identify critical/efficient targets for intervention.
- Identify gaps in our knowledge.

Art is a lie that makes us realize truth
Pablo Picasso

Everything should be made as simple as possible, but not simpler.
"A. Einstein"

How complex should a model be?

Modeling $\not\equiv$ mountain climbing

$$\boxed{\begin{aligned}\dot{S} &= -\beta k I S \\ \dot{I} &= \beta k I S - \gamma I \\ \dot{R} &= \gamma I\end{aligned}} \not\equiv$$

- "Because it's there" isn't a good reason to include something in a model.
- Only include things that could affect decisions/improve policy.
- Sometimes intuition is good enough — it's usually a simple mathematical model.
- But when there are feedbacks or opposing effects, I don't trust mine.

Disease spread

There are two major features that affect population-scale disease spread:

- Relation between mode of transmission and population structure.
- How the immune system responds to exposure.

Mode of transmission

Potential spread mechanisms:

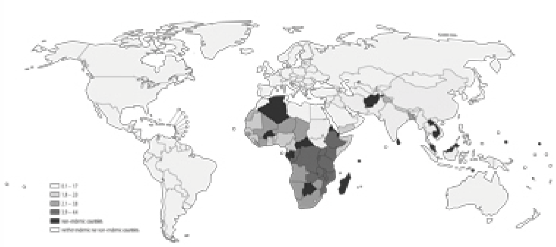
- Environmental & food contamination
- Blood-feeding arthropods
- Direct contact

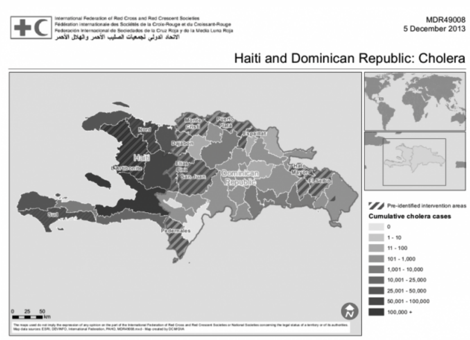
Environmental contamination

Cholera

Environmental contamination

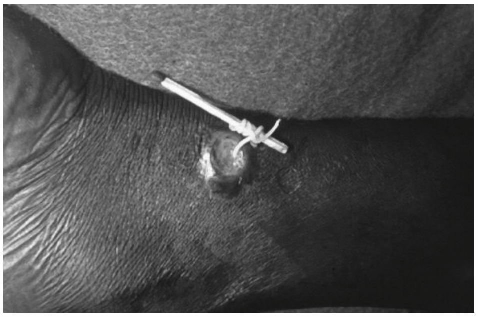
Cholera





Environmental contamination

Guinea Worm



Vectors

Malaria, Chikungunya, Dengue, West Nile

Vectors
Chagas

Vectors
Lyme

Vectors

also Anaplasmosis, Babesiosis, Borrelia, Rocky Mountain Spotted Fever, Crimean-Congo Hemorrhagic Fever, . . .

Direct contact

Influenza, SARS, MERS, Ebola, . . .

Sexual contact

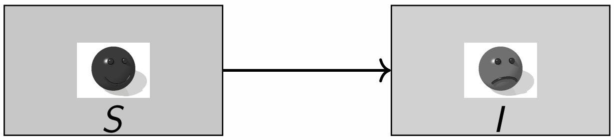
An important special case of direct contacts is sexual contacts: HIV, Gonorrhea, Chlamydia, . . .

Immune response

The response of the immune system determines what effect an exposure has on an individual and whether that individual will trasnmit to others.
Some possible outcomes of infection:

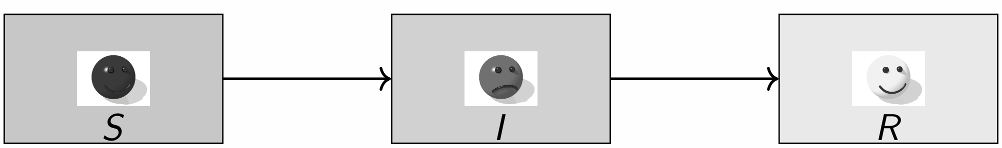
- Remains infected forever: SI
- Gains permanent immunity: SIR
- Recovers but can be reinfected: SIS

SI



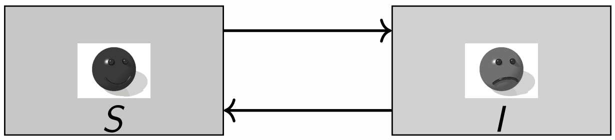
Political belief,

SIR



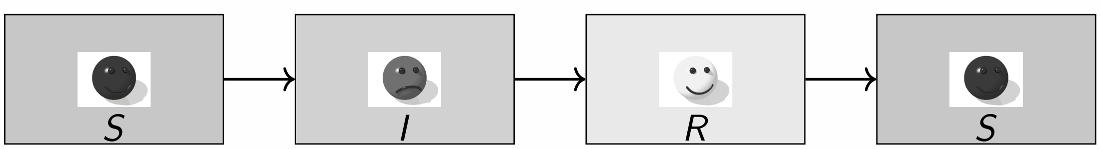
Measles, Mumps, Rubella, Pertussis

SIS



Many parasites (e.g., lice)

SIRS



Dengue (sort of), Pertussis, Influenza,

What is a contact network?

A network is a collection of individuals who are joined together based on interactions that may spread the disease in question. These connections (edges) may be:

- Transient (sex workers or random encounter in crowded market)
- Weighted (sharing an office versus brief daily conversation)
- Clustered (*Cause your friends are my friends and my friends are your friends, the more we get together the happier we'll be*)
- Heterogeneously distributed
- Directed.
- ...

Network definition

- A network is a collection of nodes which are joined into pairs by edges.
- Two nodes that are joined together are called neighbors. The number of neighbors a given node has is its degree, k.
- There is no real difference between the definitions of "network" and "graph".
- I will tend to use the terminology "partner" for neighbor and "partnership" for edge.

Network Properties

There are a number of things we can measure:

- Degree distribution: $P(k)$, the proportion of nodes with degree k.
- Clustering: frequency of short cycles [not common in sexual networks].
- Edge weights: some edges may have higher transmission probabilities than others.
- Dynamic networks: Partnerships may change in time. Individuals may enter/leave the population.
- Assortativity: Individuals may actively select similar partners. In particular, partners with similar degree.

Social networks

- facebook
- linkedin
- twitter
- ...

These may be more appropriate for spread of ideas or opinions.

Contact networks

- The network of physical interactions.
- Often highly clustered.
- Appropriate for respiratory diseases.
- Often measured by giving people devices that measure physical proximity.

Sexual networks

- Appropriate for sexually transmitted diseases.
- Often low clustering.
- Often highly heterogeneous.
- Transient partnerships may play a large role.

Location–Location networks

- Cities connected by travel of people between them [spread of H1N1].
- Farms connected by movement of animals [foot and mouth].
- Habitats connected by bird migrations [West Nile].

Empirical networks

A number of attempts have been made to measure networks in "the wild". Each case has its own peculiarities.

- Polymod [1]: 7290 participants across 8 European countries recorded information about their contacts during a day.
- Hospital interactions [2]: Employees, patients, and visitors at a pediatric hospital in Rome wore proximity detectors over a week-long period.
- School interactions [3]: Students and employees at a high school wore proximity detectors.
- Tasmanian Devils [4, 5]: Contacts between Tasmanian Devils were measured through collars with proximity detectors.
- Lion interactions [6]: observations of within pride, between pride, and nomadic lion interactions.
- Other wildlife [7].
- Romantic networks [8]

Sample location–location networks

- Livestock movement between farms [9] (and many ongoing studies).
- Patient movement between hospitals: movement of patients in Orange County [10], movement of patients in The Netherlands [11].
- Individual movement between wards within a hospital [12] (and others that I recall seeing, but can't find).
- Travel through airline networks [13] (and many other papers by Colizza and Vespignani).
- Seasonal population movements [14]: study of seasonal population movements for malaria control (phone data, census, satellite imagery).

Agent-based models

A number of groups have done large-scale simulations of populations

- Vancouver [15]: Simulations of individual contacts within the city of Vancouver (N)
- EpiSims [16]: Simulation of all individual movements through Portland, OR (1.6 million people). Later extended to a large number of other cities/regions ($\approx$ 17 million).
- Epicast (based on "Scalable Parallel Short-range Molecular dynamics": SPASM) [17]: Simulation of individual movement throughout the US ($\approx$ 300 million).
- Thailand [18]: Simulated individual interactions in Thailand with the goal of identifying strategy to control pandemic influenza (500000 people).
- South Africa: Simulation by George Seage's group at HSPH for HIV transmission ($\approx$ 6 million?)

References I

[1] Joël Mossong, Niel Hens, Mark Jit, Philippe Beutels, Kari Auranen, Rafael Mikolajczyk, Marco Massari, Stefania Salmaso, Gianpaolo Scalia Tomba, Jacco Wallinga, Janneke Heijne, Malgorzata Sadkowska-Todys, Magdalena Rosinska, and W. John Edmunds.
Social contacts and mixing patterns relevant to the spread of infectious diseases.
PLoS Medicine, 5(3):381–391, 2008.

[2] Anna Machens, Francesco Gesualdo, Caterina Rizzo, Alberto E Tozzi, Alain Barrat, and Ciro Cattuto.
An infectious disease model on empirical networks of human contact: bridging the gap between dynamic network data and contact matrices.
BMC infectious diseases, 13(1):185, 2013.

[3] Marcel Salathé, Maria Kazandjiev, Jung Woo Lee, Philip Levis, Marcus W. Feldman, and James H. Jones.
A high-resolution human contact network for infectious disease transmission.
Proceedings of the National Academy of Sciences, 107(51):22020–22025, 2010.

[4] Rodrigo K Hamede, Jim Bashford, Hamish McCallum, and Menna Jones.
Contact networks in a wild tasmanian devil (sarcophilus harrisii) population: using social network analysis to reveal seasonal variability in social behaviour and its implications for transmission of devil facial tumour disease.
Ecology Letters, 12(11):1147–1157, 2009.

[5] Rodrigo Hamede, Jim Bashford, Menna Jones, and Hamish McCallum.
Simulating devil facial tumour disease outbreaks across empirically derived contact networks.
Journal of Applied Ecology, 49(2):447–456, 2012.

[6] Meggan E Craft, Erik Volz, Craig Packer, and Lauren Ancel Meyers.
Disease transmission in territorial populations: the small-world network of serengeti lions.
Journal of the Royal Society Interface, 8(59):776–786, 2011.

[7] Meggan E Craft and Damien Caillaud.
Network models: an underutilized tool in wildlife epidemiology?
Interdisciplinary perspectives on infectious diseases, 2011, 2011.

References II

[8] Peter S. Bearman, James Moody, and Katherine Stovel.
Chains of affection: The structure of adolescent romantic and sexual networks.
The American Journal of Sociology, 110(1):44–91, 2004.

[9] I.Z. Kiss, D.M. Green, and R.R. Kao.
The network of sheep movements within great britain: network properties and their implications for infectious disease spread.
Journal of the Royal Society Interface, 3(10):669, 2006.

[10] Susan S Huang, Taliser R Avery, Yeohan Song, Kristen R Elkins, Christopher C Nguyen, Sandra K Nutter, Alaka S Nafday, Curtis J Condon, Michael T Chang, David Chrest, et al.
Quantifying interhospital patient sharing as a mechanism for infectious disease spread.
Infection control and hospital epidemiology: the official journal of the Society of Hospital Epidemiologists of America, 31(11):1160, 2010.

[11] Tjibbe Donker, Jacco Wallinga, and Hajo Grundmann.
Patient referral patterns and the spread of hospital-acquired infections through national health care networks.
PLoS Computational Biology, 6(3):e1000715, 2010.

[12] A Sarah Walker, David W Eyre, David H Wyllie, Kate E Dingle, Rosalind M Harding, Lily O'Connor, David Griffiths, Ali Vaughan, John Finney, Mark H Wilcox, et al.
Characterisation of clostridium difficile hospital ward–based transmission using extensive epidemiological data and molecular typing.
PLoS medicine, 9(2):e1001172, 2012.

[13] Duygu Balcan, Vittoria Colizza, Bruno Gonçalves, Hao Hu, José J Ramasco, and Alessandro Vespignani.
Multiscale mobility networks and the spatial spreading of infectious diseases.
Proceedings of the National Academy of Sciences, 106(51):21484–21489, 2009.

[14] Amy Wesolowski, Nathan Eagle, Andrew J Tatem, David L Smith, Abdisalan M Noor, Robert W Snow, and Caroline O Buckee.
Quantifying the impact of human mobility on malaria.
Science, 338(6104):267–270, 2012.

References III

[15] Lauren Ancel Meyers, Babak Pourbohloul, Mark E. J. Newman, Danuta M. Skowronski, and Robert C. Brunham.
Network theory and SARS: predicting outbreak diversity.
Journal of Theoretical Biology, 232(1):71–81, January 2005.

[16] C. L. Barrett, S. G. Eubank, and J. P. Smith.
If smallpox strikes Portland. . . .
Scientific American, 292(3):42–49, 2005.

[17] Timothy C. Germann, Kai Kadau, Ira M. Longini Jr., and Catherine A. Macken.
Mitigation strategies for pandemic influenza in the United States.
Proceedings of the National Academy of Sciences, 103(15):5935–5940, 2006.

[18] Ira M Longini, Azhar Nizam, Shufu Xu, Kumnuan Ungchusak, Wanna Hanshaoworakul, Derek AT Cummings, and M Elizabeth Halloran.
Containing pandemic influenza at the source.
Science, 309(5737):1083–1087, 2005.