Biological Contagion

Principles of Complex Systems
Course CSYS/MATH 300, Fall, 2009

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Outline

Contagion

A confusion of contagions:

- Is Harry Potter some kind of virus?
- What about the Da Vinci Code?
- Does Sudoku spread like a disease?
- Religion?
- Democracy...?

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Naturomorphisms

- "The feeling was contagious."
- "The news spread like wildfire."
- "Freedom is the most contagious virus known to man."
  —Hubert H. Humphrey, Johnson's vice president
- "Nothing is so contagious as enthusiasm."
  —Samuel Taylor Coleridge

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The doctrine that everything is beautiful, including what is ugly, everything good, especially the bad, and everything right that is wrong. ...

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The doctrine that everything is beautiful, including what is ugly, everything good, especially the bad, and everything right that is wrong. ... It is hereditary, but fortunately not contagious.

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Eric Hoffer, 1902–1983

There is a grandeur in the uniformity of the mass.

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The spread of fanaticism

Hoffer's acclaimed work: "The True Believer: Thoughts On The Nature Of Mass Movements" (1951) [3]

Quotes-aplenty:

- "We can be absolutely certain only about things we do not understand."
- "Mass movements can rise and spread without belief in a God, but never without belief in a devil."
- "Where freedom is real, equality is the passion of the masses. Where equality is real, freedom is the passion of a small minority."

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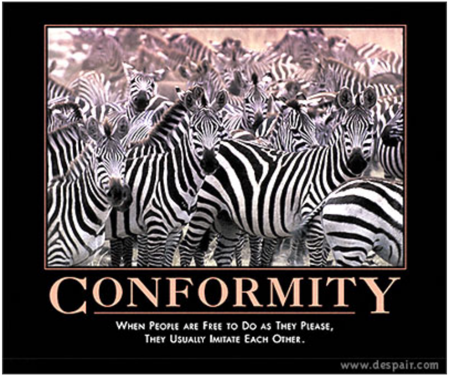
Imitation

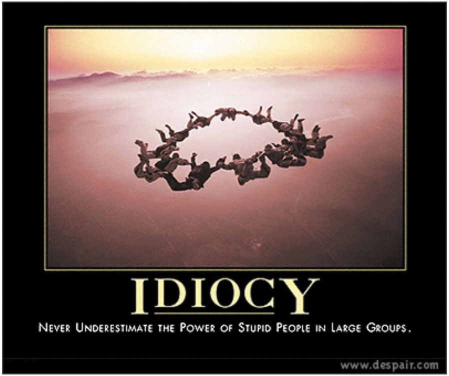


despair.com

"When people are free to do as they please, they usually imitate each other."

—Eric Hoffer
"The Passionate State of Mind" [4]

The collective...



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"Never Underestimate the Power of Stupid People in Large Groups."

Contagion

Definitions

- (1) The spreading of a quality or quantity between individuals in a population.
- (2) A disease itself:
  the plague, a blight, the dreaded lurgi, ...
- from Latin: *con* = 'together with' + *tangere* 'to touch.'
- Contagion has unpleasant overtones...
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Examples of non-disease spreading:

Interesting infections:

- Spreading of buildings in the US. (⊞)
- Viral get-out-the-vote video. (⊞)

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Contagions

Two main classes of contagion

1. Infectious diseases

2. Social contagion

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   tuberculosis, HIV, ebola, SARS, influenza, ...
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Two main classes of contagion

1. Infectious diseases:
   tuberculosis, HIV, ebola, SARS, influenza, ...

2. Social contagion:
   fashion, word usage, rumors, riots, religion, ...

Outline

The standard SIR model [5]

- = basic model of disease contagion
- Three states:
    1. S = Susceptible
    2. I = Infective/Infectious
    3. R = Recovered or Removed or Refractory
- $S(t) + I(t) + R(t) = 1$
- Presumes random interactions (mass-action principle)
- Interactions are independent (no memory)
- Discrete and continuous time versions

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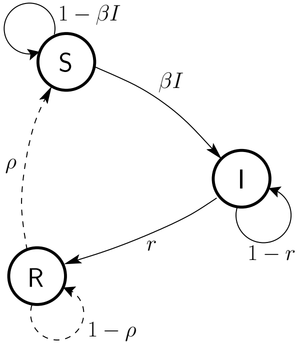
Discrete time automata example:



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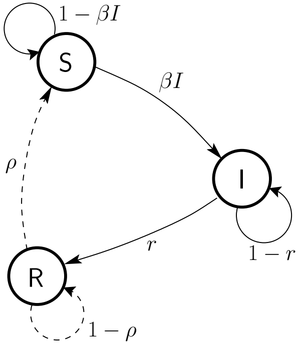

Transition Probabilities:

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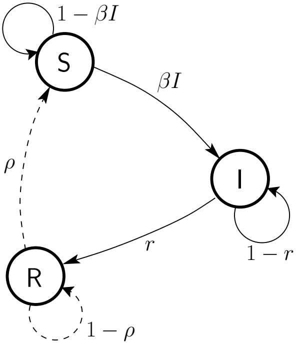

Transition Probabilities:

β for being infected given contact with infected

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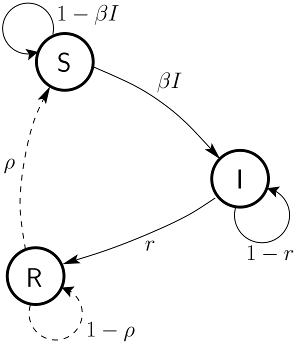

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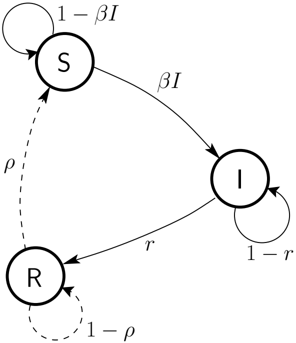

Transition Probabilities:

β for being infected given contact with infected
r for recovery
ρ for loss of immunity

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Original models attributed to

- 1920's: Reed and Frost
- 1920's/1930's: Kermack and McKendrick [?, ?, ?]
- Coupled differential equations with a mass-action principle

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Independent Interaction models

Differential equations for continuous model

$$\frac{\mathrm{d}}{\mathrm{d}t}S = -\beta IS + \rho R$$

$$\frac{\mathrm{d}}{\mathrm{d}t}I = \beta IS - rI$$

$$\frac{\mathrm{d}}{\mathrm{d}t}R = rI - \rho R$$

β, r, and ρ are now rates.

Reproduction Number R_0:

- R_0 = expected number of infected individuals resulting from a single initial infective
- Epidemic threshold: If $R_0 > 1$, 'epidemic' occurs.

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Discrete version:

- Set up: One Infective in a randomly mixing population of Susceptibles
- At time $t = 0$, single infective random bumps into a Susceptible
- Probability of transmission = β
- At time $t = 1$, single Infective remains infected with probability $1 - r$
- At time $t = k$, single Infective remains infected with probability $(1 - r)^k$

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- Expected number infected by original Infective:

$$R_0 = \beta + (1-r)\beta + (1-r)^2\beta + (1-r)^3\beta + \dots$$

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For S_0 initial infectives ($1 - S_0 = R_0$ immune):

$$R_0 = S_0\beta/r$$

Independent Interaction models

For the continuous version

- Second equation:

$$\frac{\mathrm{d}}{\mathrm{d}t} I = \beta S I - r I$$

- Number of infectives grows initially if

$$\beta S(0) - r > 0$$

- Same story as for discrete model.

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$$\beta S(0) - r > 0 \Rightarrow \beta S(0) > r$$

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- Number of infectives grows initially if

$$\beta S(0) - r > 0 \Rightarrow \beta S(0) > r \Rightarrow \beta S(0)/r > 1$$

- Same story as for discrete model.

Independent Interaction models

For the continuous version

- Second equation:

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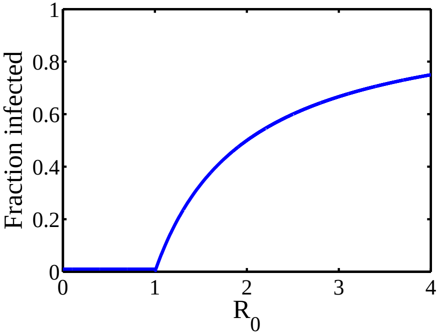

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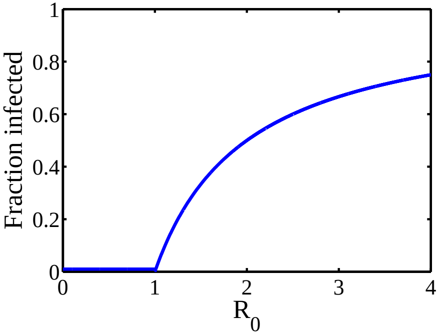

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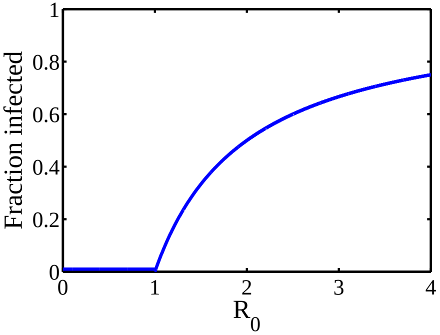

- Continuous phase transition.
- Fine idea from a simple model.

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Many variants of the SIR model:

- SIS: susceptible-infective-susceptible
- SIRS: susceptible-infective-recovered-susceptible
- compartment models (age or gender partitions)
- more categories such as 'exposed' (SEIRS)
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Disease spreading models

For novel diseases:

1. Can we predict the size of an epidemic?
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R_0 and variation in epidemic sizes

R_0 approximately same for all of the following:

- 1918-19 “Spanish Flu” $\sim$ 500,000 deaths in US
- 1957-58 “Asian Flu” $\sim$ 70,000 deaths in US
- 1968-69 “Hong Kong Flu” $\sim$ 34,000 deaths in US
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Size distributions are important elsewhere:

- earthquakes (Gutenberg-Richter law)
- city sizes, forest fires, war fatalities
- wealth distributions
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Power laws distributions are common but not obligatory...

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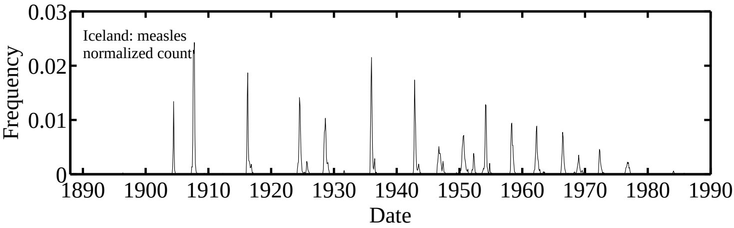
Feeling Ill in Iceland

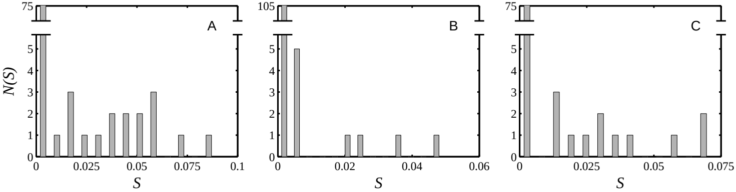
Caseload recorded monthly for range of diseases in Iceland, 1888-1990



- Treat outbreaks separated in time as ‘novel’ diseases.

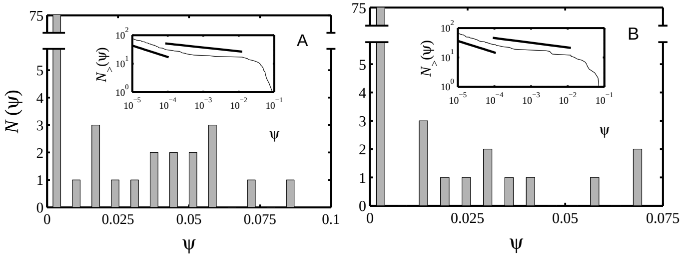
Really not so good at all in Iceland

Epidemic size distributions $N(S)$ for Measles, Rubella, and Whooping Cough.



Spike near $S = 0$, relatively flat otherwise.

Measles & Pertussis



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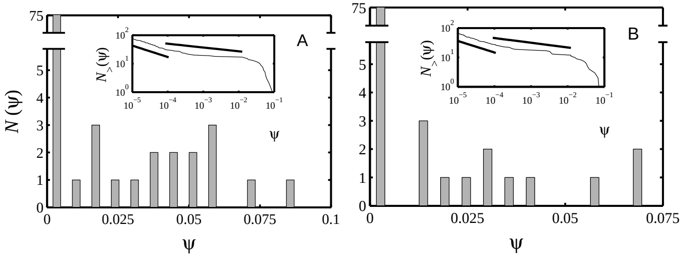

Insert plots:
Complementary cumulative frequency distributions:

$$N(\Psi' > \Psi) \propto \Psi^{-\gamma+1}$$

Limited scaling with a possible break.

Power law distributions

Measured values of γ:

- measles: 1.40 (low Ψ) and 1.13 (high Ψ)
- pertussis: 1.39 (low Ψ) and 1.16 (high Ψ)

- Expect $2 \le \gamma < 3$ (finite mean, infinite variance)
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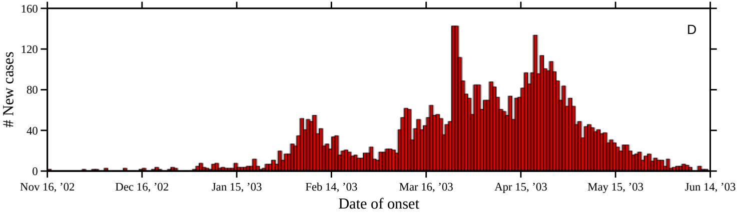

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- Importance of rare, stochastic events.

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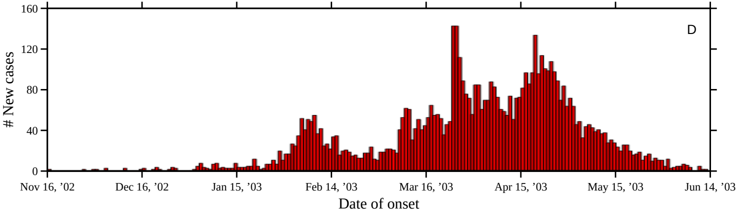

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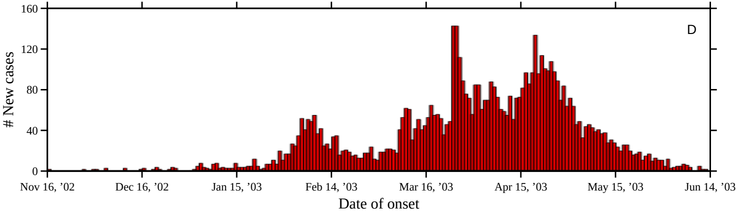

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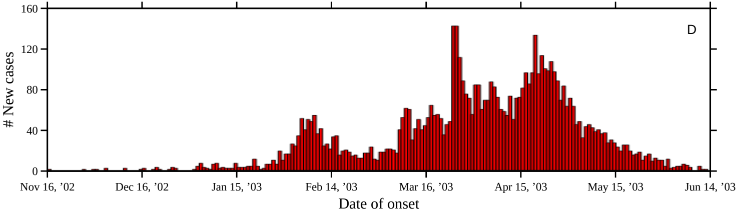

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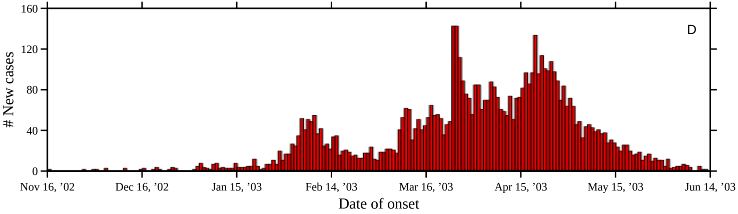

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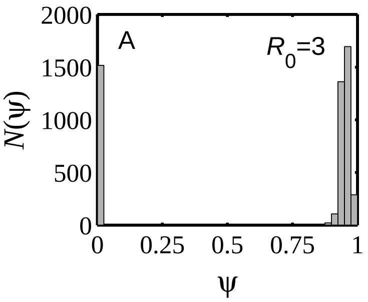
Outline

The challenge

So... can a simple model produce

1. broad epidemic distributions
   and
2. resurgence ?

Size distributions



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  2. Sophisticated metapopulation models

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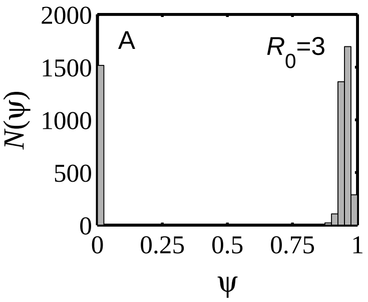

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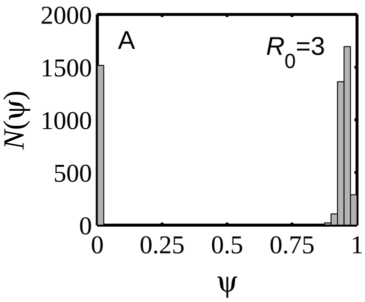

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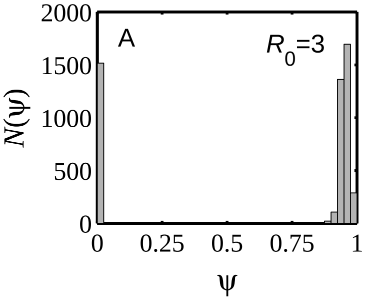

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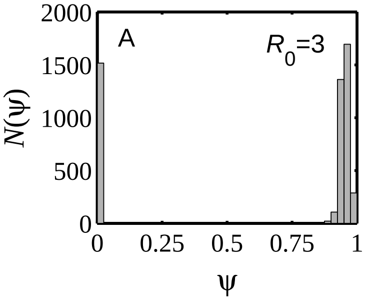

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Burning through the population

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- The physicist's approach:
  "if it works for magnets, it'll work for people..."

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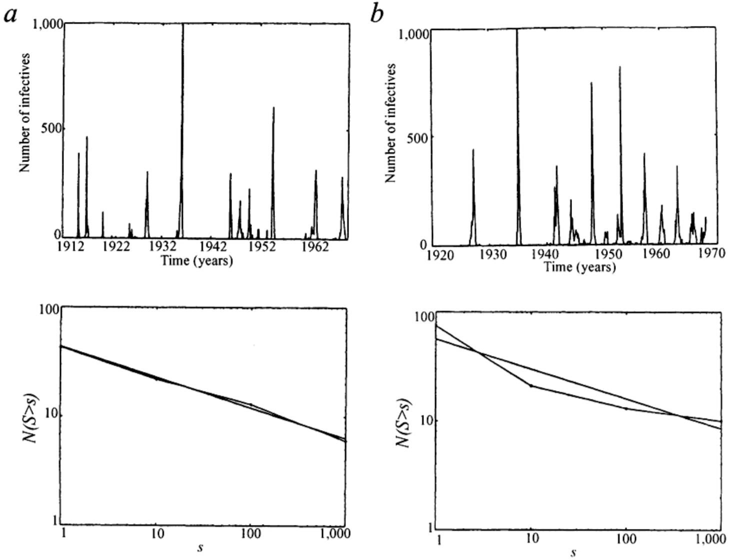

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- Community based mixing: Longini (two scales).
- Eubank et al.'s EpiSims/TRANSIMS—city simulations.
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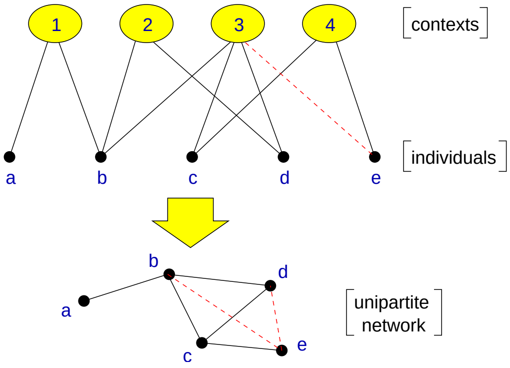

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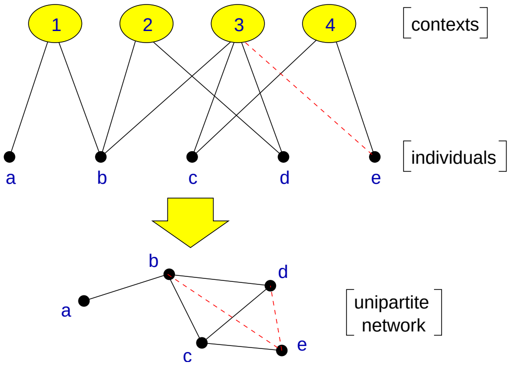

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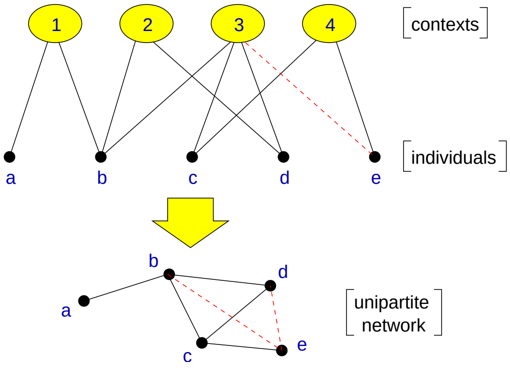

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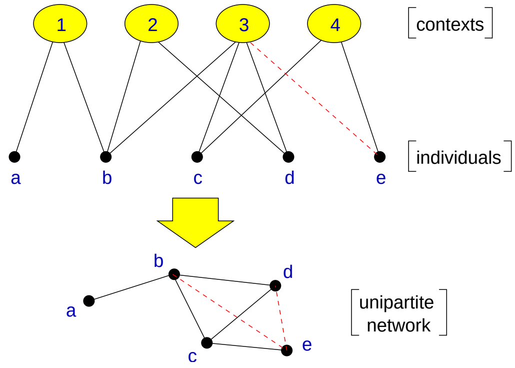

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Idea for social networks: incorporate identity.

Identity is formed from attributes such as:

- Geographic location
- Type of employment
- Age
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Groups are crucial...

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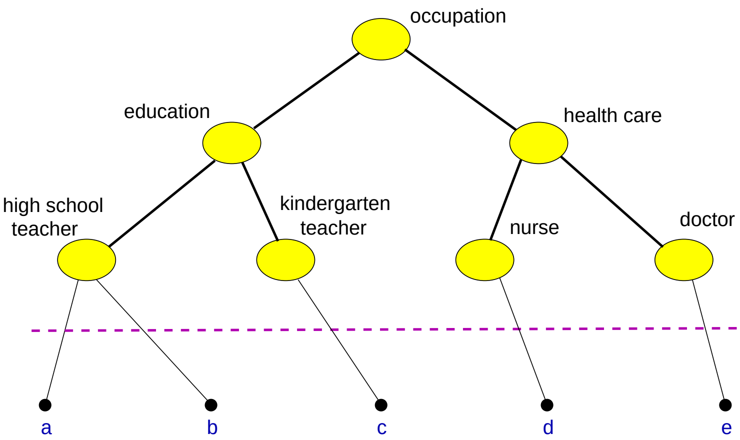
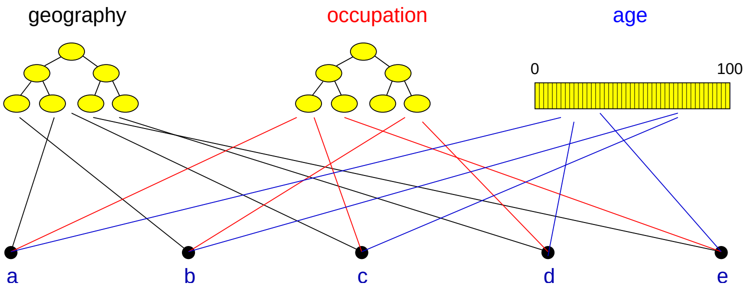
- Attributes $\Leftrightarrow$ Contexts $\Leftrightarrow$ Interactions $\Leftrightarrow$ Networks. [8]

Infer interactions/network from identities



Distance makes sense in identity/context space.

Generalized context space



(Blau & Schwartz [1], Simmel [7], Breiger [2])

A toy agent-based model

Geography—allow people to move between contexts:

- Locally: standard SIR model with random mixing
- discrete time simulation
- β = infection probability
- γ = recovery probability
- P = probability of travel
- Movement distance: $\Pr(d) \propto \exp(-d/\xi)$
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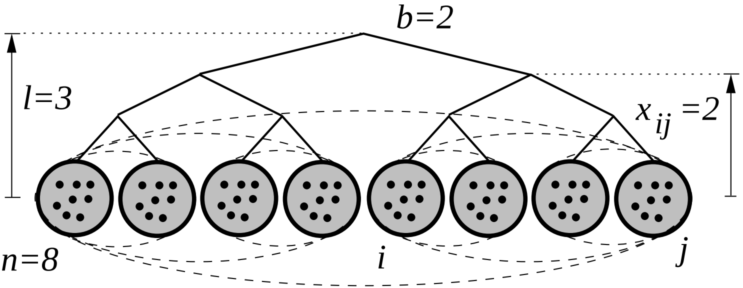
Schematic:



Outline

Model output

- Define P_0 = Expected number of infected individuals leaving initially infected context.
- Need $P_0 > 1$ for disease to spread (independent of R_0).
- Limit epidemic size by restricting frequency of travel and/or range

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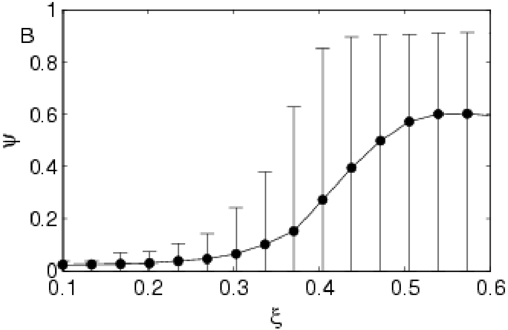
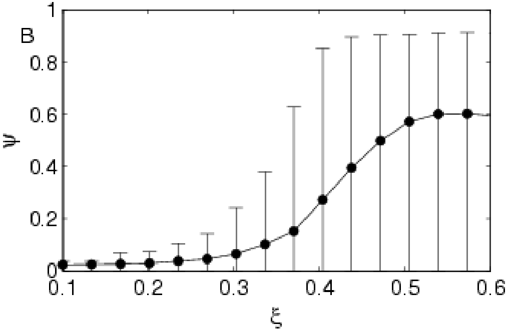
Varying ξ:



- Transition in expected final size based on typical movement distance

Model output

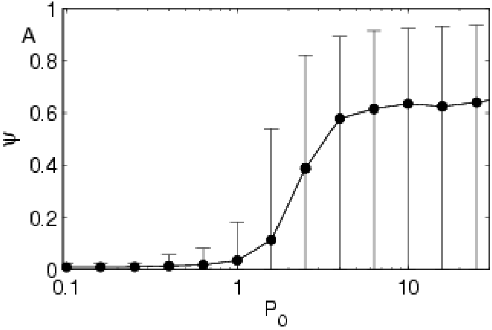
Varying ξ:



- Transition in expected final size based on typical movement distance (sensible)

Model output

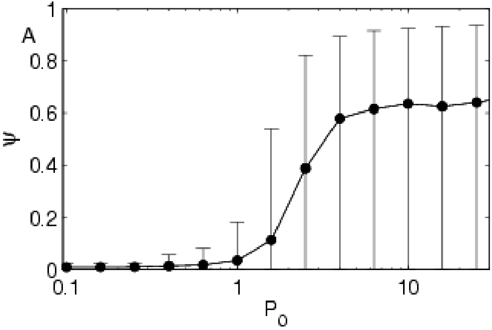
Varying P_0:



- Transition in expected final size based on typical number of infectives leaving first group
- Travel advisories: ξ has larger effect than P_0.

Model output

Varying P_0:



- Transition in expected final size based on typical number of infectives leaving first group (also sensible)
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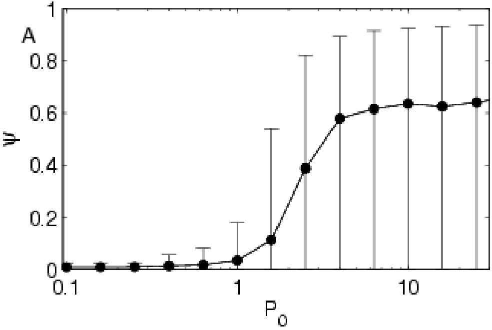
Varying P_0:



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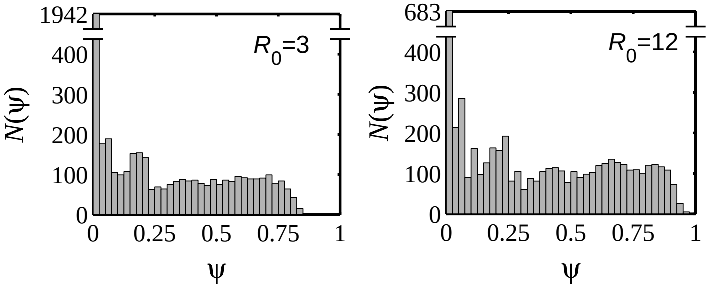
Example model output: size distributions



- Flat distributions are possible for certain ξ and P.
- Different R_0's may produce similar distributions
- Same epidemic sizes may arise from different R_0's

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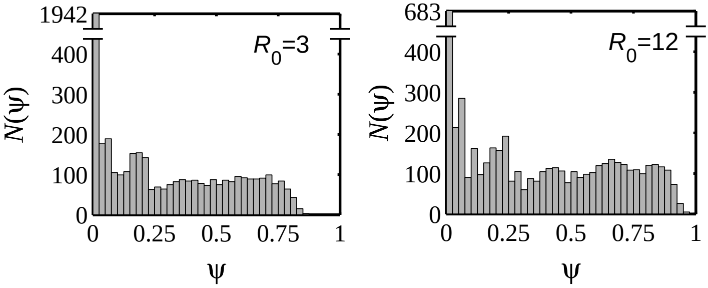

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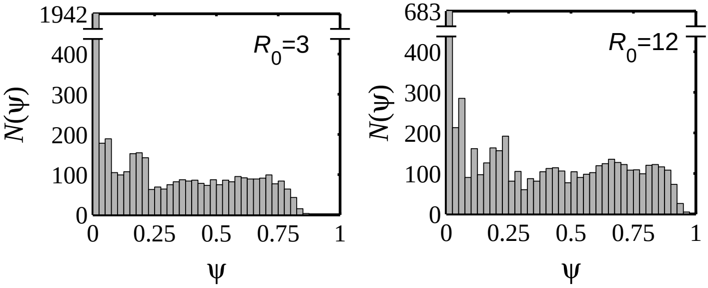

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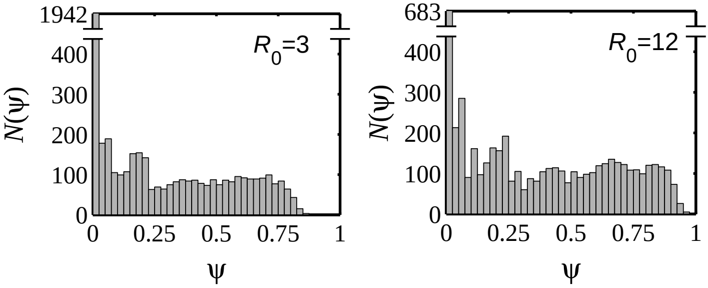

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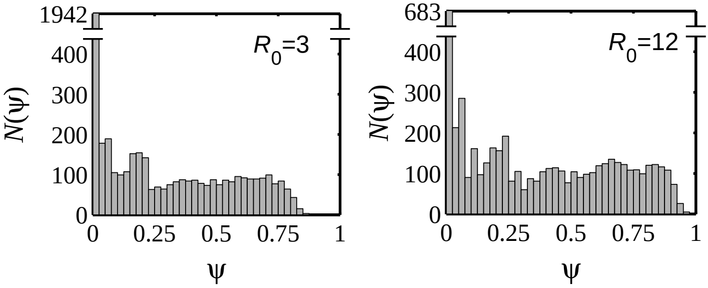

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Model output—resurgence

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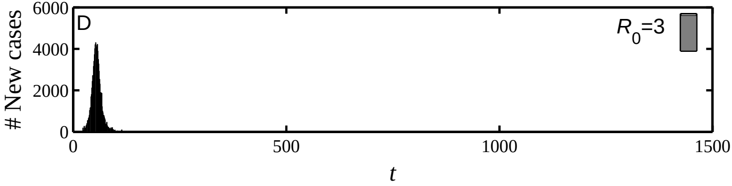
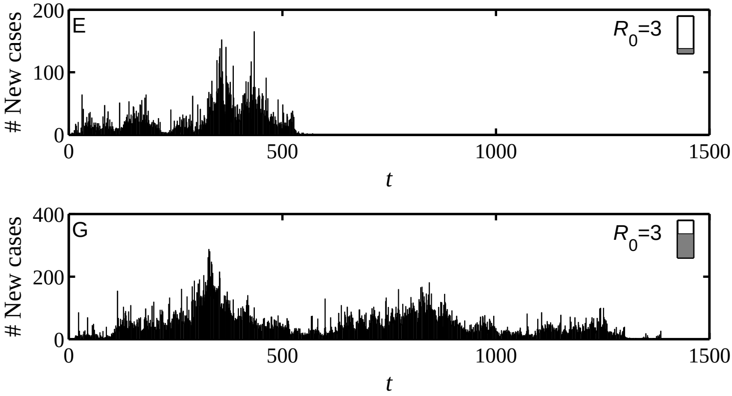


Model output—resurgence

Standard model with transport:



The upshot

Simple multiscale population structure

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+

stochasticity

The upshot

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leads to

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Outline

Conclusions

- For this model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is terribly useful.
- R_0, however measured, is not informative about
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More wondering:

- Exactly how important are rare events in disease spreading?
- Again, what is N?

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Jon Stewart:

"You just bummed the @*!# out of me."

wildbluffmedia.com

- From the Daily Show (⊞) (September 18, 2007)
- The full inteview is here (⊞).

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James K. Galbraith:

NYT But there are at least 15,000 professional economists in this country, and you're saying only two or three of them foresaw the mortgage crisis? [JKG] Ten or 12 would be closer than two or three.

NYT What does that say about the field of economics, which claims to be a science? [JKG] It's an enormous blot on the reputation of the profession. There are thousands of economists. Most of them teach. And most of them teach a theoretical framework that has been shown to be fundamentally useless.

From the New York Times, 11/02/2008 (⊞)

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