

# Biological Contagion

## Principles of Complex Systems

### Course CSYS/MATH 300, Fall, 2009

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## 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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## Contagion

### 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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# Social contagion

## Optimism according to Ambrose Bierce: (田)

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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# Social contagion

## Eric Hoffer, 1902–1983

There is a grandeur in the uniformity of the mass. **When a fashion, a dance, a song, a slogan or a joke sweeps like wildfire** from one end of the continent to the other, and **a hundred million people roar with laughter**, sway their bodies in unison, **hum one song or break forth in anger and denunciation**, there is the overpowering feeling that in this country we have come nearer the brotherhood of man than ever before.

▶ Hoffer (田) was an interesting fellow...

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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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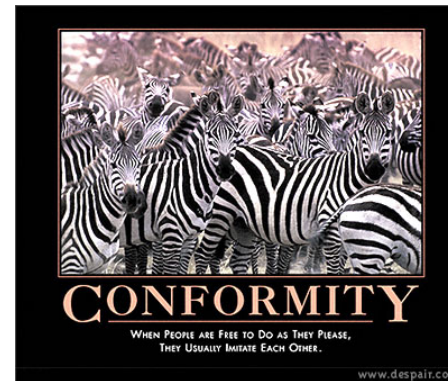
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# Imitation



despair.com

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

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

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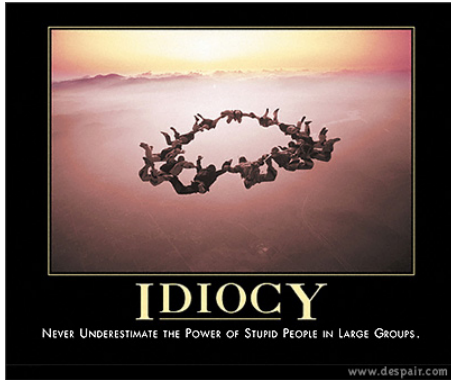
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## The collective...



despair.com

“Never Underestimate the Power of Stupid People in Large Groups.”

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## 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...
- ▶ Just **Spreading** might be a more neutral word
- ▶ But contagion is kind of exciting...

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## Examples of non-disease spreading:

### Interesting infections:

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

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## Contagions

### Two main classes of contagion

1. **Infectious diseases:** tuberculosis, HIV, ebola, SARS, influenza, ...
2. **Social contagion:** fashion, word usage, rumors, riots, religion, ...

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# Mathematical Epidemiology

## The standard SIR model<sup>[5]</sup>

- ▶ = 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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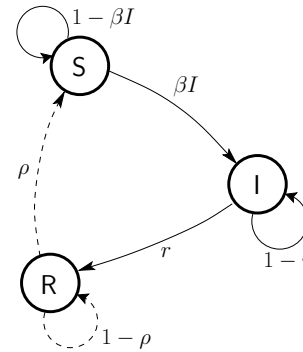
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# Mathematical Epidemiology

## Discrete time automata example:



Transition Probabilities:

- $\beta$  for being infected given contact with infected
- $r$  for recovery
- $\rho$  for loss of immunity

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# Mathematical Epidemiology

## Original models attributed to

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

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# Independent Interaction models

## Differential equations for continuous model

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

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

$$\frac{d}{dt}R = rI - \rho R$$

$\beta$ ,  $r$ , and  $\rho$  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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# Reproduction Number $R_0$

## 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 =  $\beta$
- ▶ At time  $t = 1$ , single Infective remains infected with probability  $1 - r$
- ▶ At time  $t = k$ , single Infective remains infected with probability  $(1 - r)^k$

# Reproduction Number $R_0$

## Discrete version:

- ▶ Expected number infected by original Infective:

$$\begin{aligned} R_0 &= \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots \\ &= \beta \left( 1 + (1 - r) + (1 - r)^2 + (1 - r)^3 + \dots \right) \\ &= \beta \frac{1}{1 - (1 - r)} = \beta/r \end{aligned}$$

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:

$$\frac{d}{dt}I = \beta SI - rI$$

$$\frac{d}{dt}I = (\beta S - r)I$$

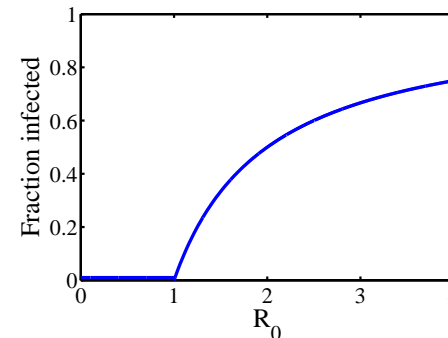
- ▶ Number of infectives grows initially if

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

- ▶ Same story as for discrete model.

# Independent Interaction models

Example of epidemic threshold:



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

# Independent Interaction models

## 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**)
- ▶ recruitment (migration, birth)

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# Disease spreading models

## For novel diseases:

1. Can we predict the size of an epidemic?
2. How important is the reproduction number  $R_0$ ?

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# $R_0$ and variation in epidemic sizes

## $R_0$ approximately same for all of the following:

- ▶ 1918-19 "Spanish Flu" ~ 500,000 deaths in US
- ▶ 1957-58 "Asian Flu" ~ 70,000 deaths in US
- ▶ 1968-69 "Hong Kong Flu" ~ 34,000 deaths in US
- ▶ 2003 "SARS Epidemic" ~ 800 deaths world-wide

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# Size distributions

## Size distributions are important elsewhere:

- ▶ earthquakes (Gutenberg-Richter law)
- ▶ city sizes, forest fires, war fatalities
- ▶ wealth distributions
- ▶ 'popularity' (books, music, websites, ideas)
- ▶ **Epidemics?**

Power laws distributions are common but not obligatory...

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# Size distributions

## Really, what about epidemics?

- ▶ Simply hasn't attracted much attention.
- ▶ Data not as clean as for other phenomena.

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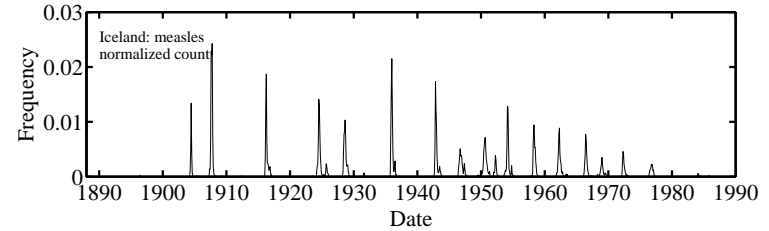
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# Feeling Ill in Iceland

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



- ▶ Treat outbreaks separated in time as 'novel' diseases.

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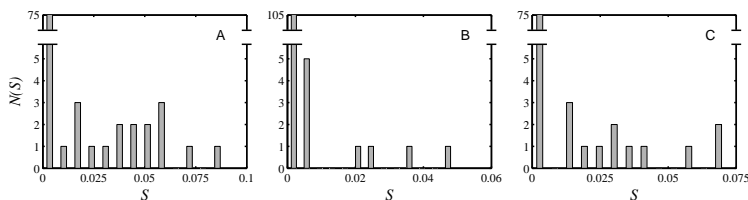
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# Really not so good at all in Iceland

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



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

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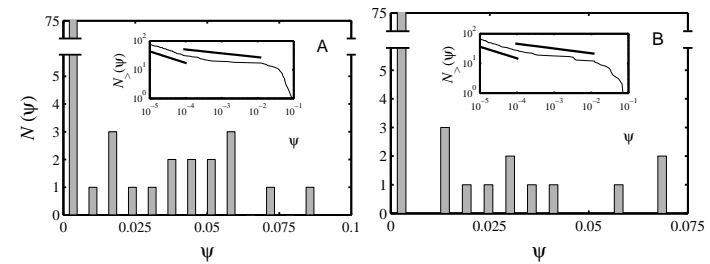
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# Measles & Pertussis



Insert plots:  
Complementary cumulative frequency distributions:

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

Limited scaling with a possible break.

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# Power law distributions

## Measured values of $\gamma$ :

- ▶ measles: **1.40** (low  $\Psi$ ) and **1.13** (high  $\Psi$ )
- ▶ pertussis: **1.39** (low  $\Psi$ ) and **1.16** (high  $\Psi$ )
  
- ▶ Expect  $2 \leq \gamma < 3$  (finite mean, infinite variance)
- ▶ When  $\gamma < 1$ , can't normalize
- ▶ Distribution is quite **flat**.

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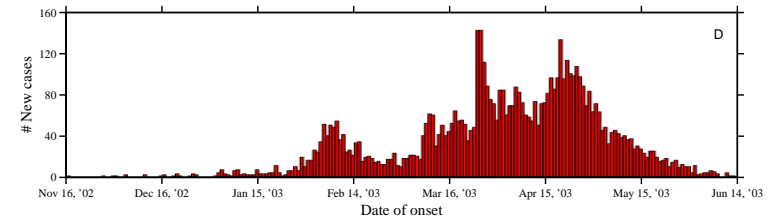
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# Resurgence—example of SARS



- ▶ Epidemic slows... then an infective moves to a new context.
- ▶ Epidemic discovers new 'pools' of susceptibles: **Resurgence**.
- ▶ **Importance of rare, stochastic events.**

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# The challenge

## So... can a simple model produce

1. **broad epidemic distributions** and
2. **resurgence** ?

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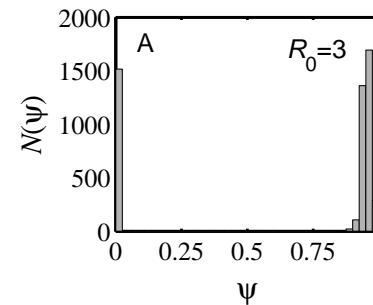
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# Size distributions



Simple models typically produce **bimodal** or **unimodal** size distributions.

- ▶ This **includes** network models: random, small-world, scale-free, ...
- ▶ Exceptions:
  1. Forest fire models
  2. Sophisticated metapopulation models

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## Burning through the population

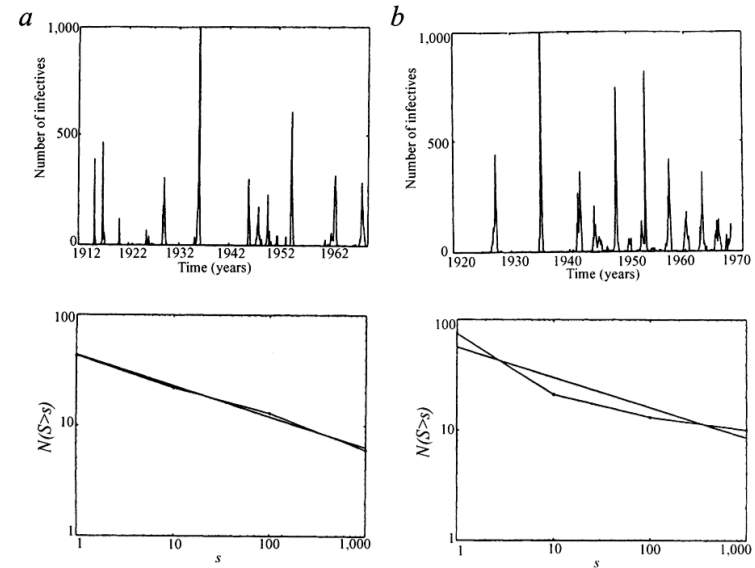
### Forest fire models:<sup>[6]</sup>

- ▶ Rhodes & Anderson, 1996
- ▶ The physicist's approach:  
"if it works for magnets, it'll work for people..."

### A bit of a stretch:

1. Epidemics  $\equiv$  forest fires spreading on 3-d and 5-d lattices.
2. Claim Iceland and Faroe Islands exhibit power law distributions for outbreaks.
3. Original forest fire model not completely understood.

## Size distributions



From Rhodes and Anderson, 1996.

## Sophisticated metapopulation models

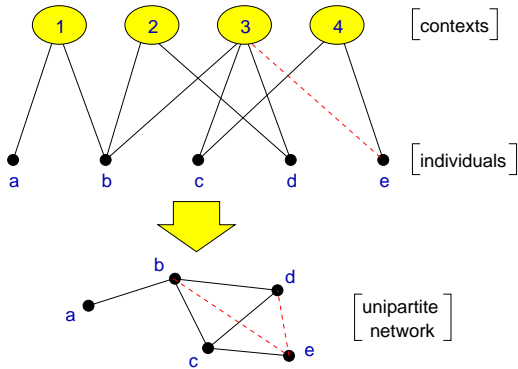
- ▶ Community based mixing: Longini (two scales).
- ▶ Eubank et al.'s EpiSims/TRANSIMS—city simulations.
- ▶ Spreading through countries—Airlines: Germann et al., Corlizza et al.
- ▶ Vital work but perhaps hard to generalize from...
- ▶  $\Rightarrow$  Create a simple model involving multiscale travel
- ▶ Multiscale models suggested by others but not formalized (Bailey, Cliff and Haggett, Ferguson et al.)

## Size distributions

- ▶ Very big question: **What is  $N$ ?**
- ▶ Should we model SARS in Hong Kong as spreading in a neighborhood, in Hong Kong, Asia, or the world?
- ▶ For simple models, we need to know the final size beforehand...

# Improving simple models

## Contexts and Identities—Bipartite networks



- ▶ boards of directors
- ▶ movies
- ▶ transportation modes (subway)

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# Improving simple models

Idea for social networks: incorporate identity.

Identity is formed from attributes such as:

- ▶ Geographic location
- ▶ Type of employment
- ▶ Age
- ▶ Recreational activities

Groups are crucial...

- ▶ formed by people with at least one similar attribute
- ▶ Attributes ⇔ Contexts ⇔ Interactions ⇔ Networks. [8]

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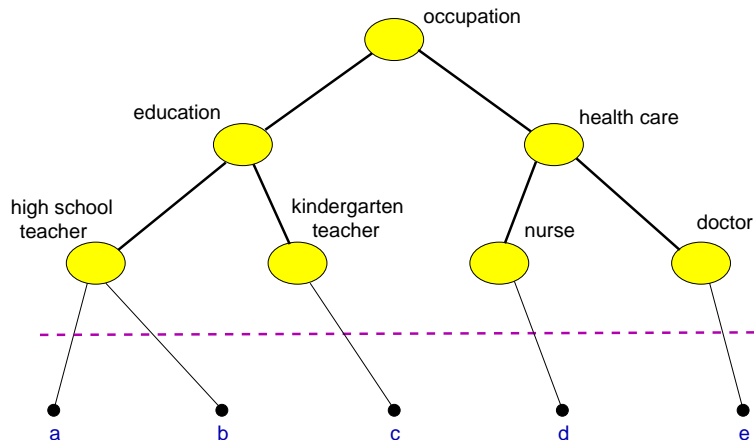
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# Infer interactions/network from identities



Distance makes sense in identity/context space.

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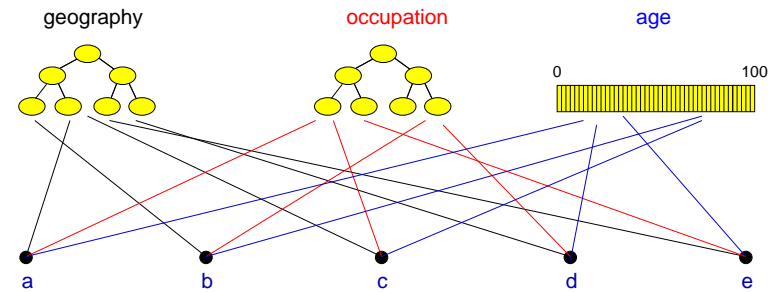
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# Generalized context space



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

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# A toy agent-based model

Geography—allow people to move between contexts:

- ▶ Locally: standard SIR model with random mixing
- ▶ discrete time simulation
- ▶  $\beta$  = infection probability
- ▶  $\gamma$  = recovery probability
- ▶  $P$  = probability of travel
- ▶ **Movement distance:**  $\Pr(d) \propto \exp(-d/\xi)$
- ▶  $\xi$  = typical travel distance

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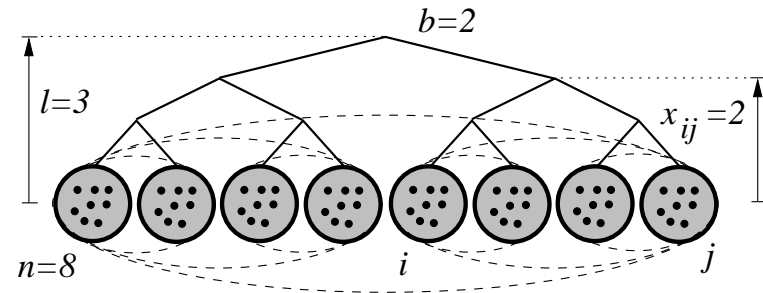
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# A toy agent-based model

Schematic:



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# 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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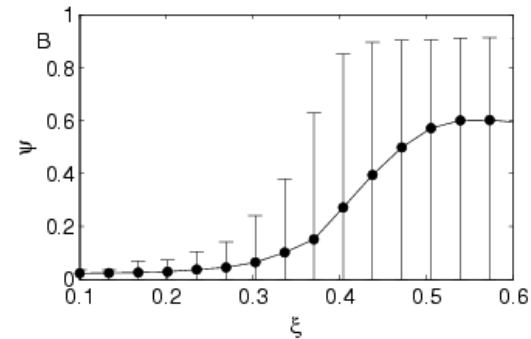
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# Model output

Varying  $\xi$ :



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

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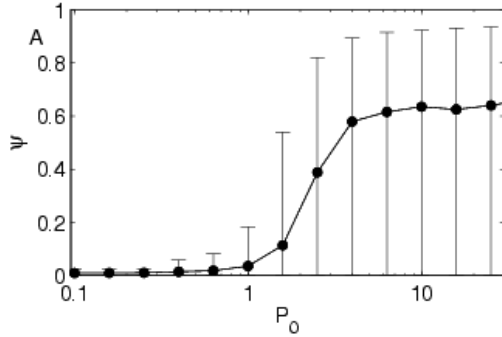
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# Model output

Varying  $P_0$ :



- ▶ Transition in expected final size based on typical number of infectives leaving first group (also sensible)
- ▶ Travel advisories:  $\xi$  has larger effect than  $P_0$ .

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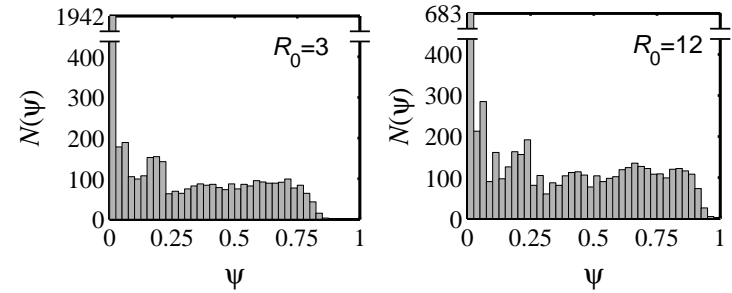
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# Example model output: size distributions



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

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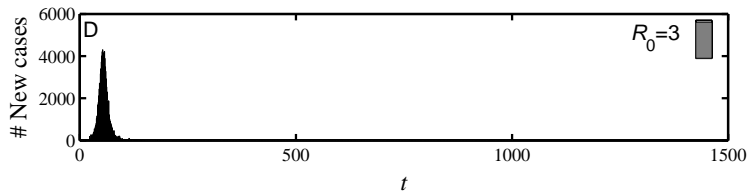
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# Model output—resurgence

Standard model:



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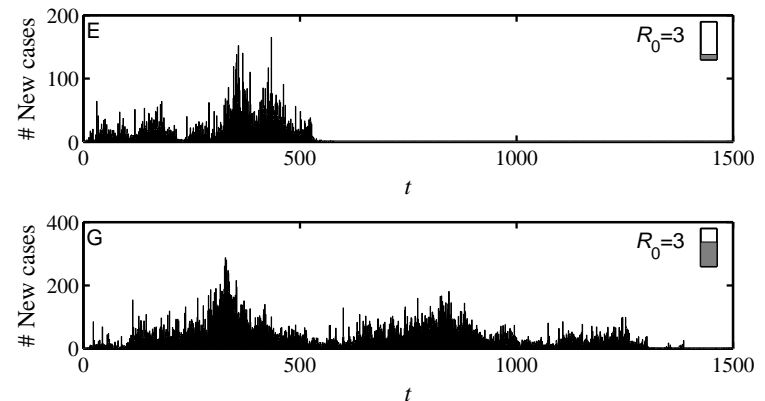
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# Model output—resurgence

Standard model with transport:



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# The upshot

Simple multiscale population structure

+  
stochasticity

leads to

resurgence

+  
broad epidemic size distributions

# 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
  1. how likely the observed epidemic size was,
  2. and how likely future epidemics will be.
- ▶ Problem:  $R_0$  summarises **one** epidemic after the fact and enfold movement, the price of bananas, everything.

# Conclusions

- ▶ Disease spread highly sensitive to population structure
- ▶ Rare events may matter enormously (e.g., an infected individual taking an international flight)
- ▶ More support for controlling population movement (e.g., travel advisories, quarantine)

# Conclusions

## What to do:

- ▶ Need to separate movement from disease
- ▶  $R_0$  needs a friend or two.
- ▶ Need  $R_0 > 1$  and  $P_0 > 1$  and  $\xi$  sufficiently large for disease to have a chance of spreading

## More wondering:

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

# Simple disease spreading models

## Valiant attempts to use SIR and co. elsewhere:

- ▶ Adoption of ideas/beliefs (Goffman & Newell, 1964)
- ▶ Spread of rumors (Daley & Kendall, 1965)
- ▶ Diffusion of innovations (Bass, 1969)
- ▶ Spread of fanatical behavior (Castillo-Chávez & Song, 2003)

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# Predicting social catastrophe isn't easy...

## “Greenspan Concedes Error on Regulation”

- ▶ ... humbled Mr. Greenspan admitted that he had put too much faith in the self-correcting power of free markets ...
- ▶ “Those of us who have looked to the self-interest of lending institutions to protect shareholders’ equity, myself included, are in a state of shocked disbelief”
- ▶ Rep. Henry A. Waxman: “Do you feel that your ideology pushed you to make decisions that you wish you had not made?”
- ▶ Mr. Greenspan conceded: “Yes, I’ve found a flaw. I don’t know how significant or permanent it is. But I’ve been very distressed by that fact.”

New York Times, October 23, 2008 (田)

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# Economics, Schmeconomics

## Alan Greenspan (September 18, 2007):

“I’ve been dealing with these big mathematical models of forecasting the economy ...

If I could figure out a way to determine whether or not people are more fearful or changing to more euphoric,

I don’t need any of this other stuff.

I could forecast the economy better than any way I know.”



<http://wikipedia.org>

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# Economics, Schmeconomics

## Greenspan continues:

“The trouble is that we can’t figure that out. I’ve been in the forecasting business for 50 years. I’m no better than I ever was, and nobody else is. Forecasting 50 years ago was as good or as bad as it is today. And the reason is that human nature hasn’t changed. We can’t improve ourselves.”

## Jon Stewart:

“You just bummed the @\*!# out of me.”



[wildbluffmedia.com](http://wildbluffmedia.com)

- ▶ From the Daily Show (田) (September 18, 2007)
- ▶ The full interview is here (田).

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## Economics, Schmeconomics

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 (田)

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