Heterogeneity, contact patterns and modeling options

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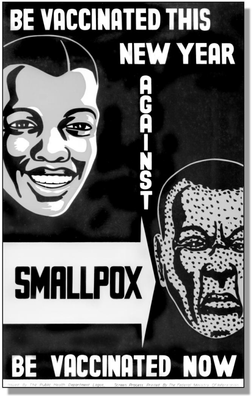
MMED 2017

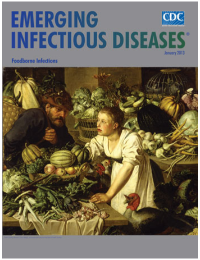
Goals

- Explain the importance of heterogeneity on patterns of disease spread
  - Focus on different types of human heterogeneity
- Discuss ways in which homogeneous models fail to match observed dynamics
- Use simple models to explore qualitative effects of heterogeneity on modeling conclusions
- Briefly introduce some methods that are used to incorporate heterogeneity in models

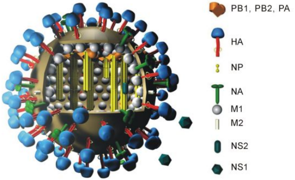
The resilience of infectious disease

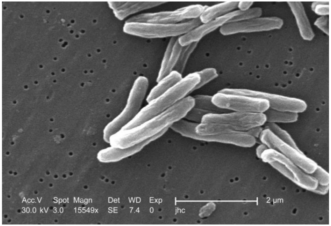
1967: It's time to close the book on infectious diseases





Pathogen evolution





Human heterogeneity

Human heterogeneity

Human heterogeneity

Expanding our models

- **Homogeneous** models assume everyone has the same:
  - disease characteristics (e.g. susceptibility, tendency to transmit)
  - mixing rate
  - probability of mixing with each person
- **Heterogeneous** models allow people to be different

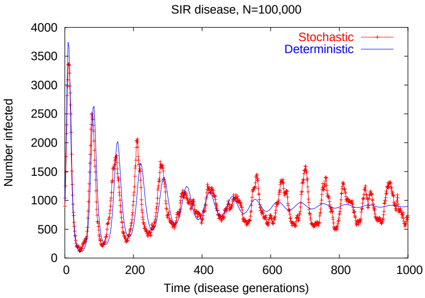
The basic reproductive number

- $\mathcal{R}_0$ is the number of people who would be infected by an infectious individual *in a fully susceptible population.*

- $\mathcal{R}_0 = \beta/\gamma = \beta D = (cp)D$
  - c: Contact Rate
  - p: Probability of transmission (infectivity)
  - D: Average duration of infection

- A disease can invade a population if and only if $\mathcal{R}_0 > 1$.

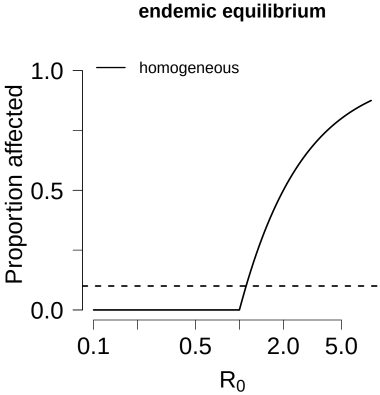
Equilibrium



Equilibrium analysis

- $\mathcal{R}_{\text{eff}}$ is the number of people who would be infected by an infectious individual *in a general population.*
- $\mathcal{R}_{\text{eff}} = \mathcal{R}_0 \dfrac{S}{N} = pcD\dfrac{S}{N}$
- At equilibrium: $\mathcal{R}_{\text{eff}} = \mathcal{R}_0 \dfrac{S}{N} = 1$.
- Thus: $\dfrac{S}{N} = 1/R_0$.
- Proportion 'affected' is $V = 1 - S/N = 1 - 1/R_0$.

Homogeneous endemic curve

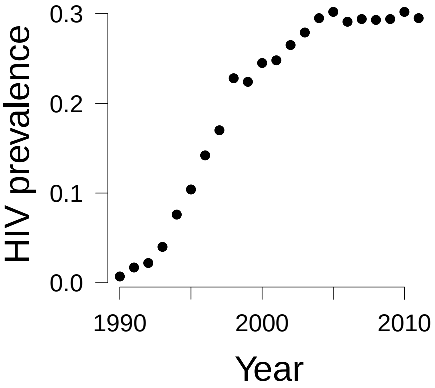


- Threshold value
- Sharp response to changes in factors underlying transmission
- Works – sometimes

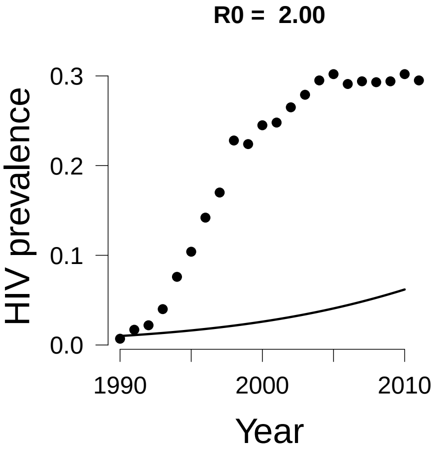
Proportion affected and disease prevalence

- For diseases with no recovery, V is the disease prevalence
- For other diseases, the equilibrium value of $P = I/N$ will be equal to V times the ratio of time spent sick to the time spent immune.
- Example: measles before vaccination
  - $V = 0.95$
  - $\bar{P} = 0.95 \times (2\mathrm{wk}/60\mathrm{yr})$.

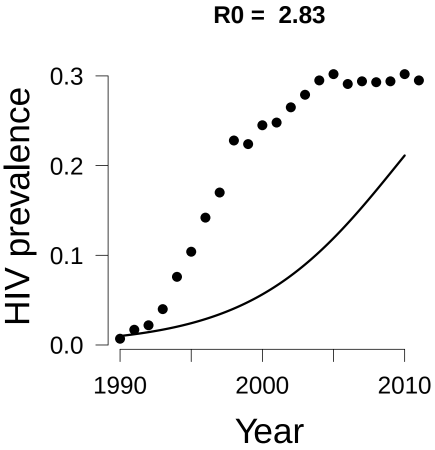
Disease dynamics



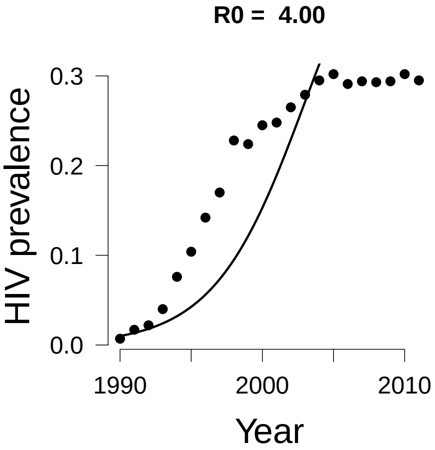
Homogeneous assumptions



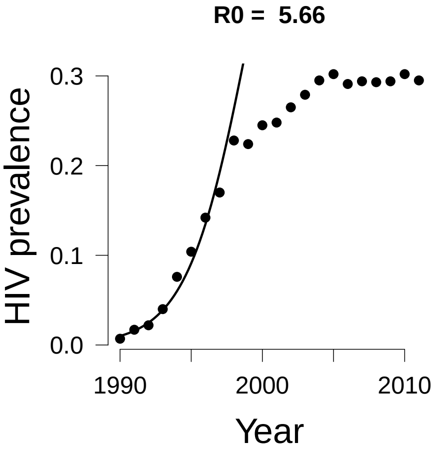
Homogeneous assumptions



Homogeneous assumptions



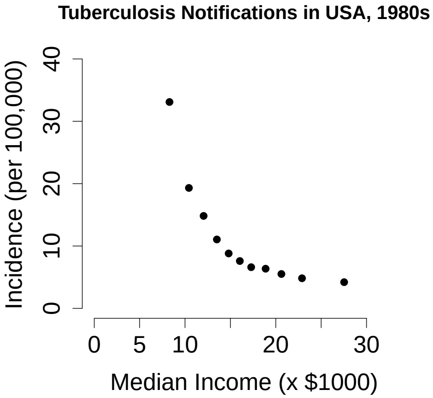
Homogeneous assumptions



Beyond homogeneity

- Flavors of heterogeneity
  - among hosts
  - spatial
  - demographic (discreteness of indviduals)
  - temporal
  - others

Heterogeneity in TB

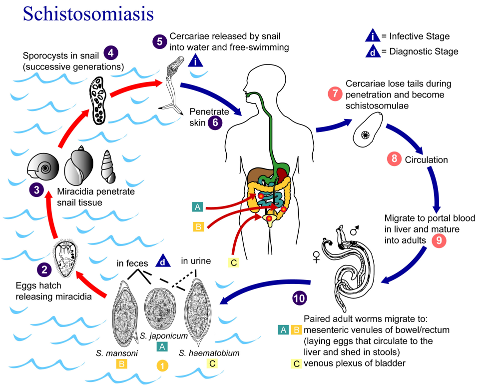


- **Progression**: Nutrition, stress
- **Contact**: Overcrowding, poor ventilation
- **Cure**: Access to medical care

Heterogeneity in other diseases

- **STDs**: Sexual mixing patterns, access to medical care
- **Influenza**: Crowding, nutrition
- **Malaria**: Attractiveness to biting insects, geographical location, immune status
- **Every disease!**

Large-scale heterogeneity



- For schistosomiasis, the worldwide average $\mathcal{R}_0 < 1$
- Disease persists because of specific populations with $\mathcal{R}_0 > 1$.
- This effect operates at many scales.

ICI3D

Equilibrium calculations

- Assume $p = \sigma\tau$ has a susceptibility component and a transmission component:
  - $\mathcal{R}_0 = \sigma\tau cD$
  - $\mathcal{R}_{\text{eff}} = \sigma\tau cDS/N$

Equilibrium calculations with heterogeneity

- τD applies to infectious individuals $\rightarrow \tau_I D_I$
- σ applies to susceptible individuals $\rightarrow \sigma_S$
- c is complicated $\rightarrow c_S c_I / \bar{c}$

Example

- Imagine a disease spread by people who differ only in their effective mixing rates
- If the disease has just started spreading in the population, how do c_S and c_I compare to $\bar{c}$?
  - $c_S \approx \bar{c}$; $c_I > \bar{c}$.
- If the disease is very widespread in the population?
  - $c_S < \bar{c}$; $c_I \to \bar{c}$.

Simpson's paradox

- What happens when a peanut farmer is elected to the US Senate?
- The average IQ goes up in both places!

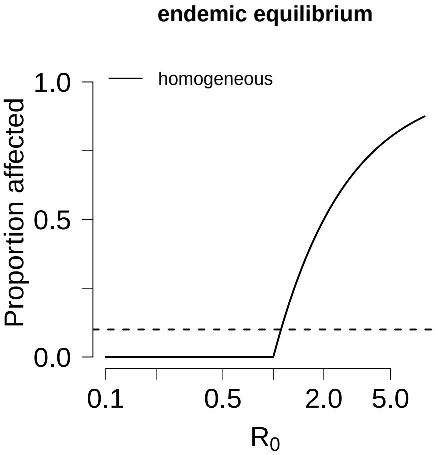
The basic reproductive number

- When the disease invades:
  - The susceptible population $\approx$ the general population
  - The infectious population is likely to have higher values of *c*, *D* and/or τ
- $\mathcal{R}_0$ is typically greater than you would expect from a homogeneous model

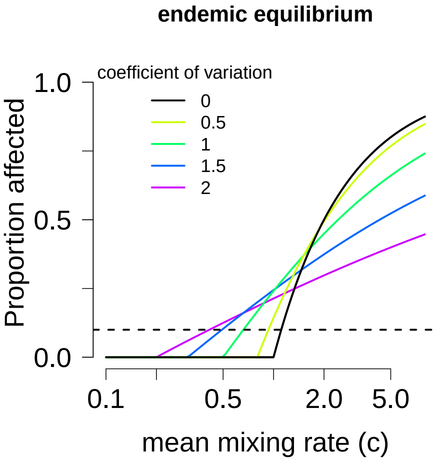
Equilibrium analysis

- As disease prevalence goes up:
  - Susceptible pool is the most resistant, or least exposed group
  - Infectious pool moves looks more like the general population.
- $\rightarrow$ lower proportion affected *for a given value of* $\mathcal{R}_0$*.*

Homogeneous endemic curve



Heterogeneous endemic curves



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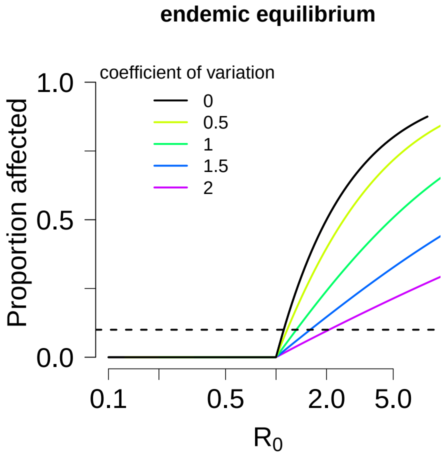
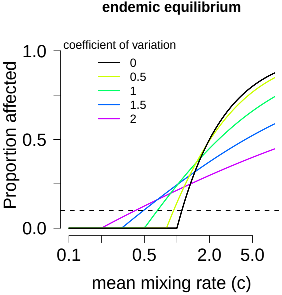


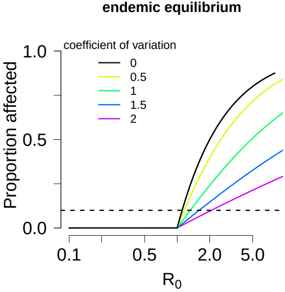
Heterogeneity and disease

- Heterogeneity has a double-edged effect
  - Effects of disease are *lower* for a given value of $\mathcal{R}_0$.
  - But $\mathcal{R}_0$ is *higher* for given mean values of factors underlying transmission



Heterogeneous endemic curves

- Heterogeneity makes the endemic curve flatter
- Disease levels are more resistant to change



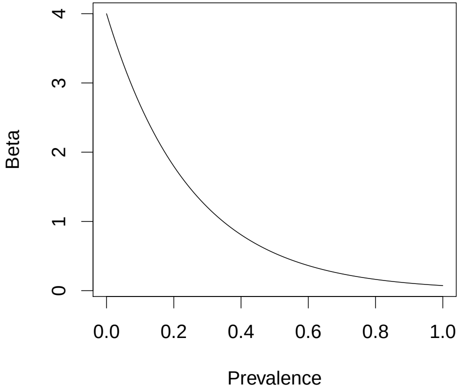
How diseases reach equilibrium

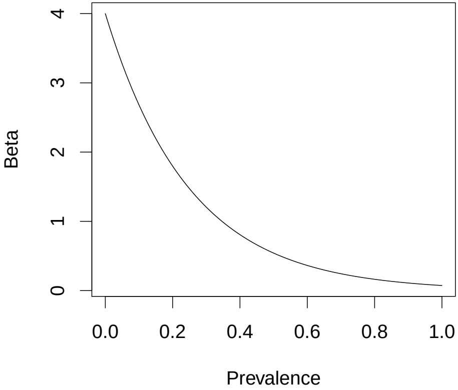
- Diseases that invade have high values of $\mathcal{R}_0$
- $\mathcal{R}_{\mathrm{eff}}$ must be 1 at equilibrium
  - Potentially infectious contacts are wasted
    - Many potential contacts are not susceptible (affected by disease)
    - Those not affected less susceptible than average
  - Infectious pool less infectious

Spatial and network models

- Individual-level, or spatial, heterogeneity also usually increases wasted contacts
- Infectious people meet:
  - people with similar social backgrounds
  - people with similar behaviours
  - people who are nearby geographically or in the contact network
- More wasted contacts further flatten the endemic curve

Phenomenological



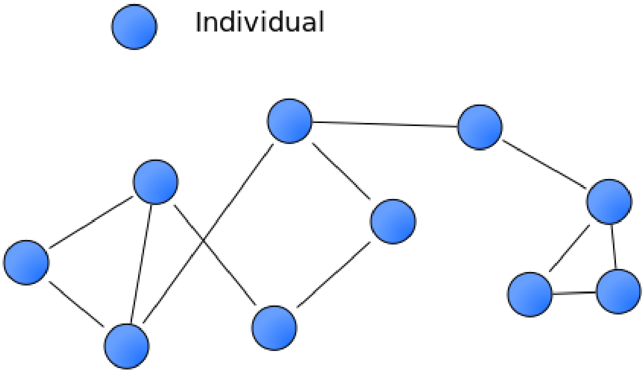


- Simply *make* β go down with prevalence, $\beta = B \times$:
  - $e^{-\alpha P}$
  - $(1 - P)^s$
  - $(1 - P/s)^{\alpha s}$

Multi-group models

- Divide the population into groups.
  - cities and villages
  - rich and poor
  - high and low sexual activity
  - age, gender
  - ...

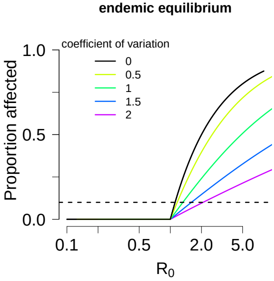
Individual-based models

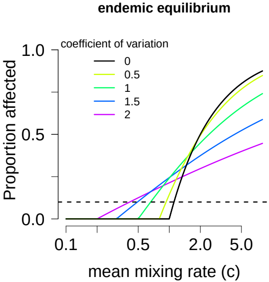


- Allow many possibilities:
  - vary individual characteristics
  - add a network of interactions
  - let the network change
- Individual-based approaches require stochastic models

Summary


Exit
Madison Avenue
& 42 Street
Open M-F 6:30am-7:30pm


endemic equilibrium
coefficient of variation
0
0.5
1
1.5
2
Proportion affected
1.0
0.5
0.0
0.1
0.5
2.0
5.0
R_0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mean mixing rate (c)

Summary

- People are heterogeneous in many ways
  - . . . and on many scales
- Simple models give us important qualitative insights
  - Diseases in heterogeneous populations are likely to be more robust to change than expected from homogeneous models
- More complicated models can help address relevant detail

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