

# UNIT 7: Infectious disease

# Outline

Introduction

Rate of spread

Single-epidemic model

Epidemic size

Recurrent epidemic models

Reproductive numbers and risk

# Infectious disease

- ▶ Extremely common

# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions

# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions
- ▶ A form of exploitation, but doesn't fit well into our previous modeling framework

# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions
- ▶ A form of exploitation, but doesn't fit well into our previous modeling framework
  - ▶ How many people are there?

# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions
- ▶ A form of exploitation, but doesn't fit well into our previous modeling framework
  - ▶ How many people are there?
  - ▶ How many influenza viruses are there?

# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions
- ▶ A form of exploitation, but doesn't fit well into our previous modeling framework
  - ▶ How many people are there?
  - ▶ How many influenza viruses are there?
  - ▶ How do they find each other?



# Infectious disease

- ▶ Extremely common
- ▶ Huge impacts on ecological interactions
- ▶ A form of exploitation, but doesn't fit well into our previous modeling framework
  - ▶ How many people are there?
  - ▶ How many influenza viruses are there?
  - ▶ How do they find each other?

# Disease agents

- ▶ **Poll:** Can you name an infectious agent that causes disease in humans?

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies



# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways





# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways
    - ▶ \* Tuberculosis, anthrax, pertussis

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways
    - ▶ \* Tuberculosis, anthrax, pertussis
  - ▶ **Eukaryotic** pathogens are nucleated cells who are more closely related to you than they are to bacteria

# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways
    - ▶ \* Tuberculosis, anthrax, pertussis
  - ▶ **Eukaryotic** pathogens are nucleated cells who are more closely related to you than they are to bacteria
    - ▶ \*

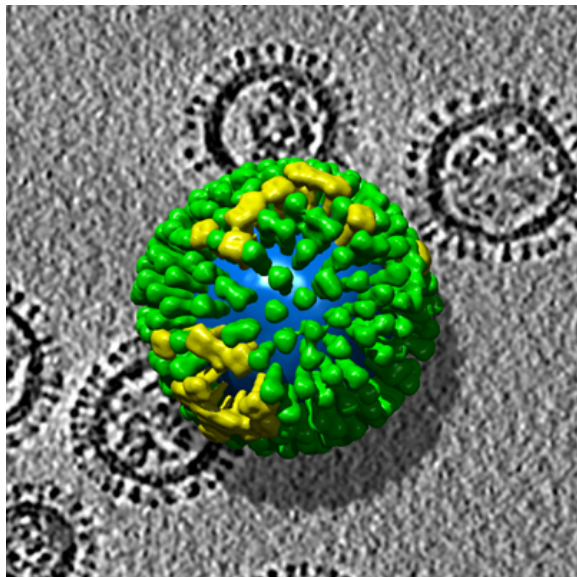
# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways
    - ▶ \* Tuberculosis, anthrax, pertussis
  - ▶ **Eukaryotic** pathogens are nucleated cells who are more closely related to you than they are to bacteria
    - ▶ \* Malaria, various worms

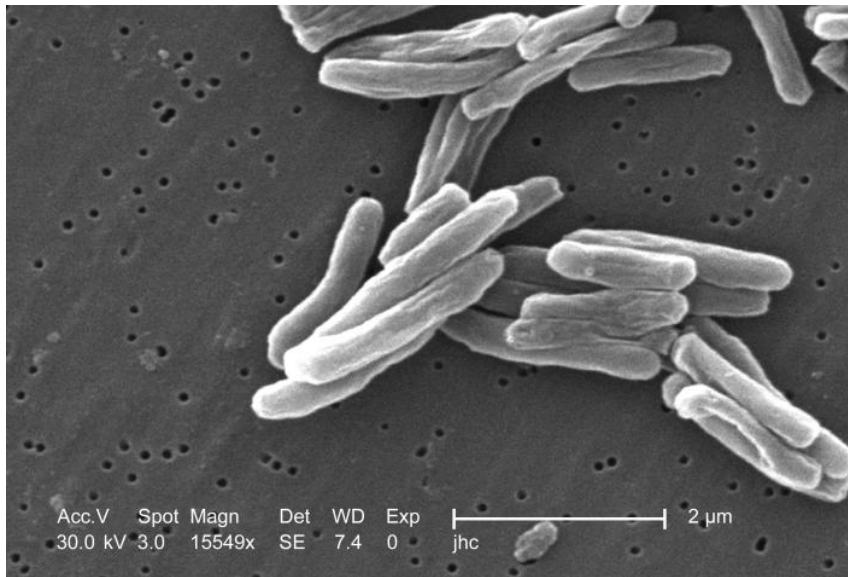
# Disease agents

- ▶ Poll: Can you name an infectious agent that causes disease in humans?
- ▶ Disease agents vary tremendously:
  - ▶ Most **viruses** have just a handful of genes that allow them to hijack a cell and get it to make virus copies
    - ▶ \* influenza virus, Ebola virus, HIV, measles
  - ▶ **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways
    - ▶ \* Tuberculosis, anthrax, pertussis
  - ▶ **Eukaryotic** pathogens are nucleated cells who are more closely related to you than they are to bacteria
    - ▶ \* Malaria, various worms

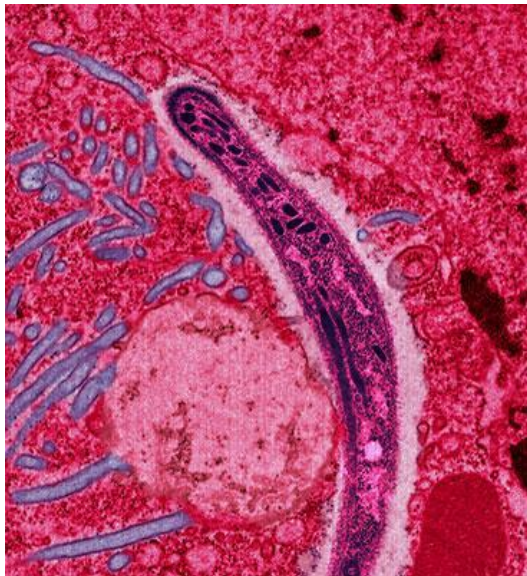
# Influenza virus



# Tuberculosis bacilli



# Malaria sporozoite





# Microparasites

- ▶ For infections with small pathogens (viruses and bacteria), we don't attempt to count pathogens, but instead divide disease into stages

# Microparasites

- ▶ For infections with small pathogens (viruses and bacteria), we don't attempt to count pathogens, but instead divide disease into stages
  - ▶ Latently infected

# Microparasites

- ▶ For infections with small pathogens (viruses and bacteria), we don't attempt to count pathogens, but instead divide disease into stages
  - ▶ Latently infected
  - ▶ **Productively infected**

# Microparasites

- ▶ For infections with small pathogens (viruses and bacteria), we don't attempt to count pathogens, but instead divide disease into stages
  - ▶ Latently infected
  - ▶ Productively infected
  - ▶ Recovered

# Microparasites

- ▶ For infections with small pathogens (viruses and bacteria), we don't attempt to count pathogens, but instead divide disease into stages
  - ▶ Latently infected
  - ▶ Productively infected
  - ▶ Recovered

# Microparasite models

- ▶ We model microparasites by counting the number of hosts in various **states**:

# Microparasite models

- ▶ We model microparasites by counting the number of hosts in various **states**:
  - ▶ **Susceptible** individuals can become infected

# Microparasite models

- ▶ We model microparasites by counting the number of hosts in various **states**:
  - ▶ **Susceptible** individuals can become infected
  - ▶ **Infectious** individuals are infected and can infect others



# Microparasite models

- ▶ We model microparasites by counting the number of hosts in various **states**:
  - ▶ **Susceptible** individuals can become infected
  - ▶ **Infectious** individuals are infected and can infect others
  - ▶ **Resistant** individuals are not infected and cannot become infected

# Microparasite models

- ▶ We model microparasites by counting the number of hosts in various **states**:
  - ▶ **Susceptible** individuals can become infected
  - ▶ **Infectious** individuals are infected and can infect others
  - ▶ **Resistant** individuals are not infected and cannot become infected
- ▶ More complicated models might include other states, such as latently infected hosts who are infected with the pathogen but cannot yet infect others

# Microparasite models

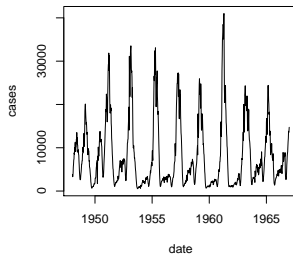
- ▶ We model microparasites by counting the number of hosts in various **states**:
  - ▶ **Susceptible** individuals can become infected
  - ▶ **Infectious** individuals are infected and can infect others
  - ▶ **Resistant** individuals are not infected and cannot become infected
- ▶ More complicated models might include other states, such as latently infected hosts who are infected with the pathogen but cannot yet infect others

# Models as tools

- Models are the tools that we use to connect scales:



**Measles reports from England and Wales**

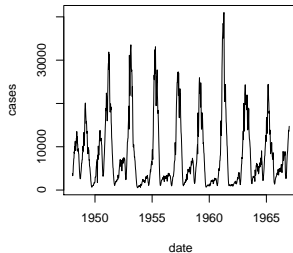


# Models as tools

- ▶ Models are the tools that we use to connect scales:
  - ▶ individuals to populations



Measles reports from England and Wales

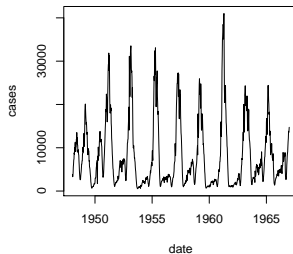


# Models as tools

- ▶ Models are the tools that we use to connect scales:
  - ▶ individuals to populations
  - ▶ single actions to trends through time



Measles reports from England and Wales

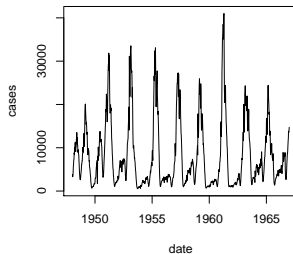


# Models as tools

- ▶ Models are the tools that we use to connect scales:
  - ▶ individuals to populations
  - ▶ single actions to trends through time



**Measles reports from England and Wales**



# Outline

Introduction

Rate of spread

Single-epidemic model

Epidemic size

Recurrent epidemic models

Reproductive numbers and risk



# Rate of spread

- ▶ **Poll:** For many diseases, especially new diseases, we can *observe* and *estimate*  $r$ .

# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe* and *estimate*  $r$ .



# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe and estimate  $r$* .
  - ▶ \* the exponential rate of spread

# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe and estimate*  $r$ .
  - ▶ \* the exponential rate of spread
- ▶ Poll: Want to know what factors contribute to that, and how it relates to  $\mathcal{R}$ .

# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe and estimate*  $r$ .
  - ▶ \* the exponential rate of spread
- ▶ Poll: Want to know what factors contribute to that, and how it relates to  $\mathcal{R}$ .
  - ▶ \*

# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe and estimate*  $r$ .
  - ▶ \* the exponential rate of spread
- ▶ Poll: Want to know what factors contribute to that, and how it relates to  $\mathcal{R}$ .
  - ▶ \* number of new cases per case

# Rate of spread

- ▶ Poll: For many diseases, especially new diseases, we can *observe and estimate*  $r$ .
  - ▶ \* the exponential rate of spread
- ▶ Poll: Want to know what factors contribute to that, and how it relates to  $\mathcal{R}$ .
  - ▶ \* number of new cases per case

# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$



# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:

# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:
  - ▶ Actual value of  $\mathcal{R}$  before an epidemic

# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:
  - ▶ Actual value of  $\mathcal{R}$  before an epidemic
  - ▶ Hypothetical value assuming no immunity

# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:
  - ▶ Actual value of  $\mathcal{R}$  before an epidemic
  - ▶ Hypothetical value assuming no immunity
  - ▶ Hypothetical value assuming no control efforts whatsoever

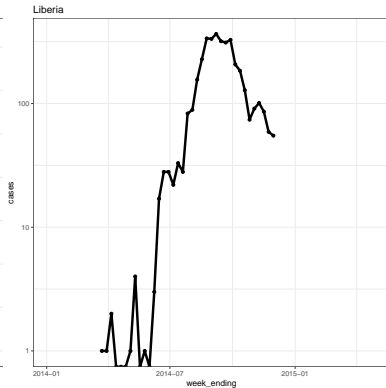
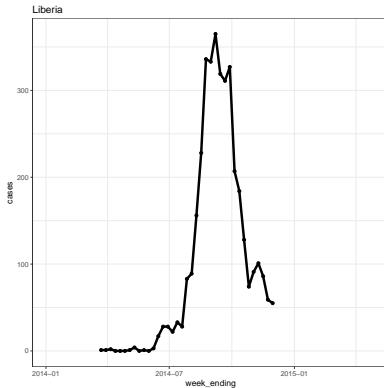
# Basic reproductive number

- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:
  - ▶ Actual value of  $\mathcal{R}$  before an epidemic
  - ▶ Hypothetical value assuming no immunity
  - ▶ Hypothetical value assuming no control efforts whatsoever
- ▶ Often easier to talk simply about  $\mathcal{R}$ .

# Basic reproductive number

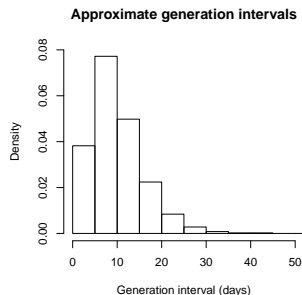
- ▶ People in the disease field love to talk specifically about  $\mathcal{R}_0$
- ▶ But they don't always mean the same thing:
  - ▶ Actual value of  $\mathcal{R}$  before an epidemic
  - ▶ Hypothetical value assuming no immunity
  - ▶ Hypothetical value assuming no control efforts whatsoever
- ▶ Often easier to talk simply about  $\mathcal{R}$ .

# Example: the West African Ebola epidemic



# Generation intervals

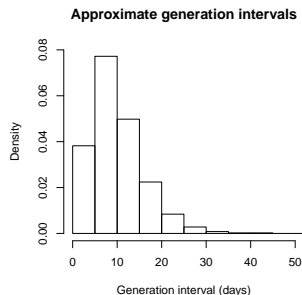
- Researchers try to estimate the *proportion* of transmission that happens for different **ages of infection**





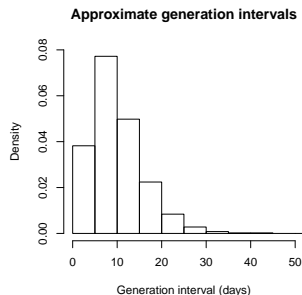
# Generation intervals

- ▶ Researchers try to estimate the *proportion* of transmission that happens for different **ages of infection**
- ▶ How long from the time you are *infected* to the time you *infect someone else*?



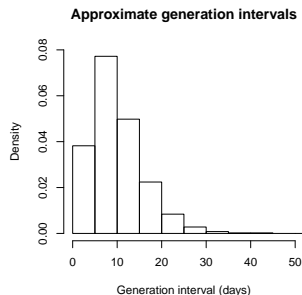
# Generation intervals

- ▶ Researchers try to estimate the *proportion* of transmission that happens for different **ages of infection**
- ▶ How long from the time you are *infected* to the time you *infect someone else*?
- ▶ Analogous to a life table



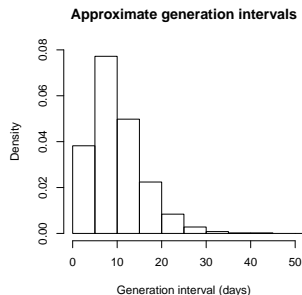
# Generation intervals

- ▶ Researchers try to estimate the *proportion* of transmission that happens for different **ages of infection**
- ▶ How long from the time you are *infected* to the time you *infect someone else*?
- ▶ Analogous to a life table
- ▶ The effective generation time  $\hat{G}$  has units of time



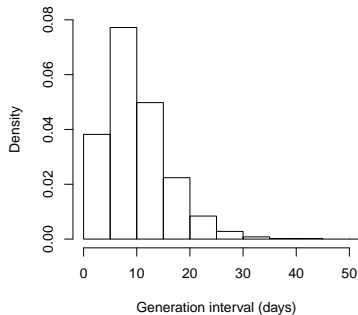
# Generation intervals

- ▶ Researchers try to estimate the *proportion* of transmission that happens for different **ages of infection**
- ▶ How long from the time you are *infected* to the time you *infect someone else*?
- ▶ Analogous to a life table
- ▶ The effective generation time  $\hat{G}$  has units of time

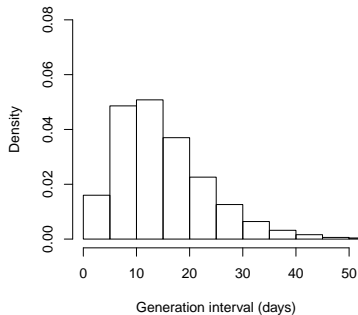


# Generation intervals

**Approximate generation intervals**

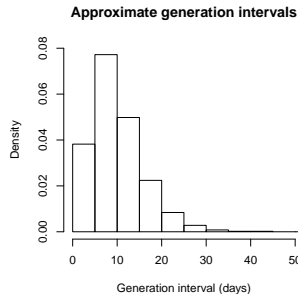


**Approximate generation intervals**



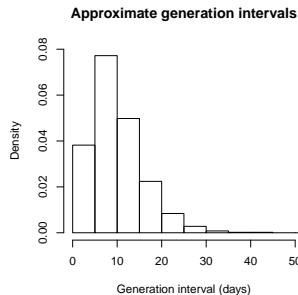
# Speed and risk

- Which is more dangerous, a fast disease, or a slow disease?



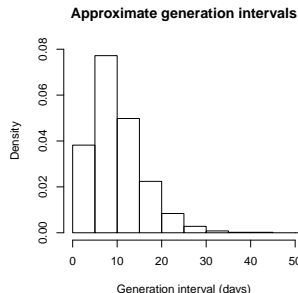
# Speed and risk

- ▶ Which is more dangerous, a fast disease, or a slow disease?
  - ▶ How are we measuring speed?



# Speed and risk

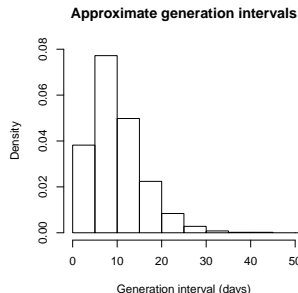
- ▶ Which is more dangerous, a fast disease, or a slow disease?
  - ▶ How are we measuring speed?
  - ▶ How are we measuring danger?





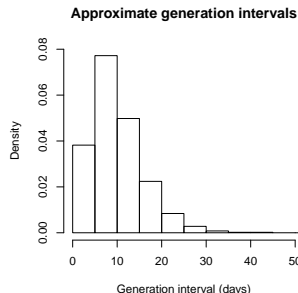
# Speed and risk

- ▶ Which is more dangerous, a fast disease, or a slow disease?
  - ▶ How are we measuring speed?
  - ▶ How are we measuring danger?
  - ▶ *What do we already know?*



# Speed and risk

- ▶ Which is more dangerous, a fast disease, or a slow disease?
  - ▶ How are we measuring speed?
  - ▶ How are we measuring danger?
  - ▶ *What do we already know?*



# Fighting Ebola



# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?

# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?



# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )

# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )
- ▶ If we know  $r$ , what does the generation time tell us about  $\mathcal{R}$ ?

# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )
- ▶ If we know  $r$ , what does the generation time tell us about  $\mathcal{R}$ ?
  - ▶ \*



# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )
- ▶ If we know  $r$ , what does the generation time tell us about  $\mathcal{R}$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the the *smaller* the strength of the epidemic (small reproductive number  $\mathcal{R}$ )

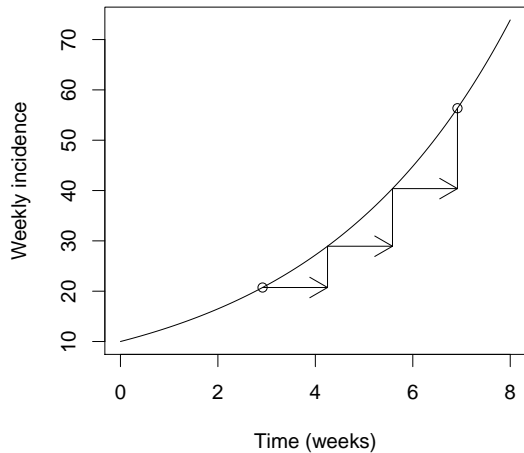
# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )
- ▶ If we know  $r$ , what does the generation time tell us about  $\mathcal{R}$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the the *smaller* the strength of the epidemic (small reproductive number  $\mathcal{R}$ )
- ▶  $\mathcal{R} = \exp(r\hat{G})$

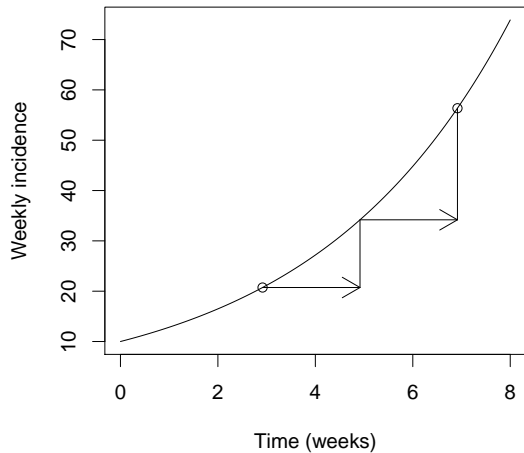
# Generation time and risk

- ▶ If we know  $\mathcal{R}$ , what does the generation time tell us about  $r$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the faster the exponential growth (large  $r$ )
- ▶ If we know  $r$ , what does the generation time tell us about  $\mathcal{R}$ ?
  - ▶ \* The faster the generations (small  $\hat{G}$ ), the the *smaller* the strength of the epidemic (small reproductive number  $\mathcal{R}$ )
- ▶  $\mathcal{R} = \exp(r\hat{G})$

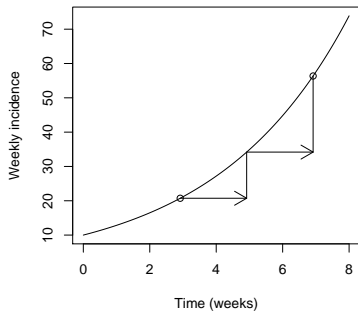
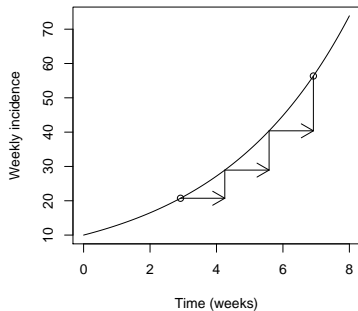
## Generation time and risk



## Generation time and risk



# Generation time and risk



# Generation time and risk

- ▶ An intuitive view:

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength



# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \*

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \* More strength required (greater  $\mathcal{R}$ )

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \* More strength required (greater  $\mathcal{R}$ )
- ▶ If we know epidemic speed, a faster generation speed means

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \* More strength required (greater  $\mathcal{R}$ )
- ▶ If we know epidemic speed, a faster generation speed means
  - ▶ \*

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \* More strength required (greater  $\mathcal{R}$ )
- ▶ If we know epidemic speed, a faster generation speed means
  - ▶ \* Less strength required (smaller  $\mathcal{R}$ )

# Generation time and risk

- ▶ An intuitive view:
  - ▶ Epidemic speed = Generation speed  $\times$  Generation strength
- ▶ If we know generation speed, then a faster epidemic speed means:
  - ▶ \* More strength required (greater  $\mathcal{R}$ )
- ▶ If we know epidemic speed, a faster generation speed means
  - ▶ \* Less strength required (smaller  $\mathcal{R}$ )

# Outline

Introduction

Rate of spread

Single-epidemic model

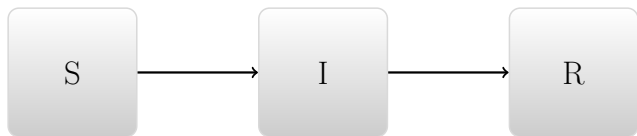
Epidemic size

Recurrent epidemic models

Reproductive numbers and risk

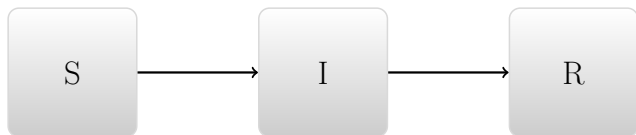


# Single-epidemic model



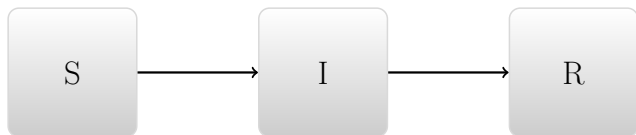
- Susceptible → Infectious → Recovered

# Single-epidemic model



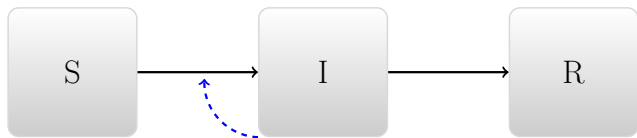
- ▶ Susceptible  $\rightarrow$  Infectious  $\rightarrow$  Recovered
- ▶ We also use  $N$  to mean the total population

# Single-epidemic model



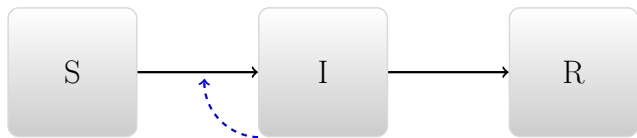
- ▶ Susceptible  $\rightarrow$  Infectious  $\rightarrow$  Recovered
- ▶ We also use  $N$  to mean the total population

# Transition rates



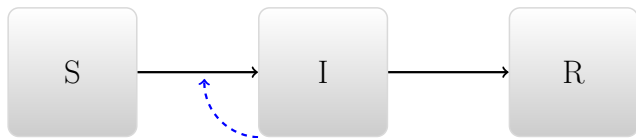
- What factors govern movement through the boxes?

# Transition rates



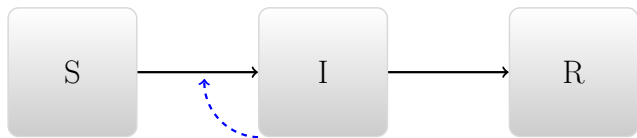
- ▶ What factors govern movement through the boxes?
  - ▶ People get better independently

# Transition rates



- ▶ What factors govern movement through the boxes?
  - ▶ People get better independently
  - ▶ People get infected by infectious people

# Transition rates



- ▶ What factors govern movement through the boxes?
  - ▶ People get better independently
  - ▶ People get infected by infectious people

# Conceptual modeling

- Poll: What happens in the long term if we introduce an infectious individual?





# Conceptual modeling

- Poll: What happens in the long term if we introduce an infectious individual?



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic** – an outbreak of disease



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic**
    - an outbreak of disease
  - ▶ \*



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic**
    - an outbreak of disease
  - ▶ \* Disease burns out



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic**
    - an outbreak of disease
  - ▶ \* Disease burns out
  - ▶ \*



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic**
    - an outbreak of disease
  - ▶ \* Disease burns out
  - ▶ \* Everyone winds up either recovered or susceptible



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic**
    - an outbreak of disease
  - ▶ \* Disease burns out
  - ▶ \* Everyone winds up either recovered or susceptible
- ▶ \*



# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic** – an outbreak of disease
  - ▶ \* Disease burns out
  - ▶ \* Everyone winds up either recovered or susceptible
  - ▶ \* Not everyone gets infected!





# Conceptual modeling

- ▶ Poll: What happens in the long term if we introduce an infectious individual?
  - ▶ \* The *may be* an **epidemic** – an outbreak of disease
  - ▶ \* Disease burns out
  - ▶ \* Everyone winds up either recovered or susceptible
  - ▶ \* Not everyone gets infected!



# Interpreting

- ▶ Why might there not be an epidemic?

# Interpreting

- ▶ Why might there not be an epidemic?



# Interpreting

- ▶ Why might there not be an epidemic?
  - ▶ \* If the disease can't spread well enough in the population

# Interpreting

- ▶ Why might there not be an epidemic?
  - ▶ \* If the disease can't spread well enough in the population
  - ▶ \*

# Interpreting

- ▶ Why might there not be an epidemic?
  - ▶ \* If the disease can't spread well enough in the population
  - ▶ \* Demographic stochasticity: if we only start with one individual, we expect an element of chance

# Interpreting

- ▶ Why might there not be an epidemic?
  - ▶ \* If the disease can't spread well enough in the population
  - ▶ \* Demographic stochasticity: if we only start with one individual, we expect an element of chance
- ▶ Why doesn't everyone get infected?

# Interpreting

- ▶ Why might there not be an epidemic?
  - ▶ \* If the disease can't spread well enough in the population
  - ▶ \* Demographic stochasticity: if we only start with one individual, we expect an element of chance
- ▶ Why doesn't everyone get infected?



# Implementing the model

- The simplest way to implement this conceptual model is with differential equations:



# Implementing the model

- ▶ The simplest way to implement this conceptual model is with differential equations:

▶

$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$



# Implementing the model

- ▶ The simplest way to implement this conceptual model is with differential equations:

- ▶ 
$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I$$



# Implementing the model

- ▶ The simplest way to implement this conceptual model is with differential equations:

- ▶ 
$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I$$

- ▶ 
$$\frac{dR}{dt} = \gamma I$$



# Implementing the model

- ▶ The simplest way to implement this conceptual model is with differential equations:

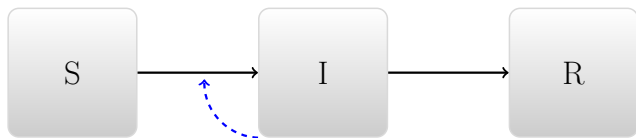
- ▶ 
$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I$$

- ▶ 
$$\frac{dR}{dt} = \gamma I$$



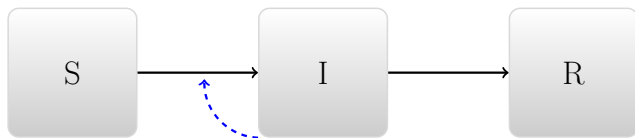
# Quantities



## State variables

- ▶  $S, I, R, N$ : [people] or [people/ha]

# Quantities



State variables

- ▶  $S, I, R, N$ : [people] or [people/ha]

# Quantities

## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])



# Quantities

## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious

# Quantities

## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious
  - ▶ Total infection rate is  $\beta I/N$ , because  $I/N$  is the proportion of the population infectious

# Quantities

## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious
  - ▶ Total infection rate is  $\beta I/N$ , because  $I/N$  is the proportion of the population infectious
- ▶ Infectious people recover at *per capita* rate  $\gamma$  (units [1/time])

# Quantities

## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious
  - ▶ Total infection rate is  $\beta I/N$ , because  $I/N$  is the proportion of the population infectious
- ▶ Infectious people recover at *per capita* rate  $\gamma$  (units [1/time])
  - ▶ Total recovery rate is  $\gamma I$

# Quantities

## Parameters

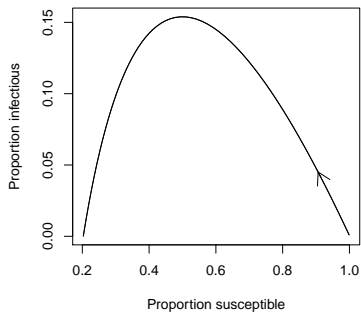
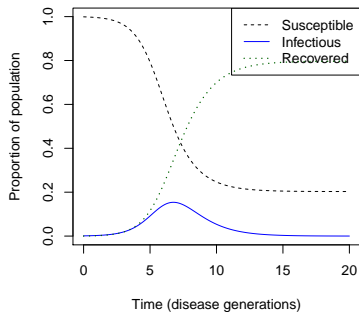
- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious
  - ▶ Total infection rate is  $\beta I/N$ , because  $I/N$  is the proportion of the population infectious
- ▶ Infectious people recover at *per capita* rate  $\gamma$  (units [1/time])
  - ▶ Total recovery rate is  $\gamma I$
  - ▶ Mean time infectious is  $D = 1/\gamma$  (units [time])

# Quantities

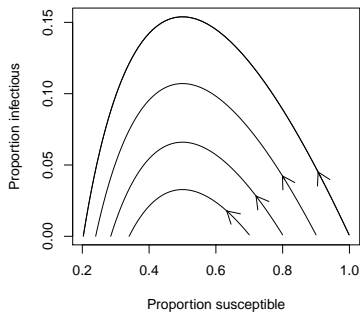
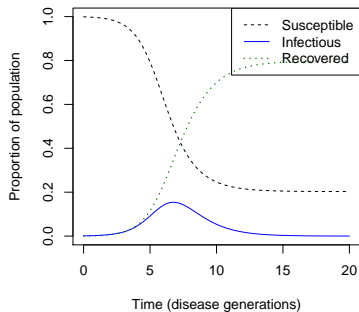
## Parameters

- ▶ Susceptible people have **potentially effective** contacts at rate  $\beta$  (units [1/time])
  - ▶ These are contacts that would lead to infection if the person contacted is infectious
  - ▶ Total infection rate is  $\beta I/N$ , because  $I/N$  is the proportion of the population infectious
- ▶ Infectious people recover at *per capita* rate  $\gamma$  (units [1/time])
  - ▶ Total recovery rate is  $\gamma I$
  - ▶ Mean time infectious is  $D = 1/\gamma$  (units [time])

# Simulating the model



# Simulating the model





# Basic reproductive number

- ▶ **Poll:** What *unitless* parameter can you make from the model above?

# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?



# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**

# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**
  - ▶ \*

# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**
  - ▶ \* The *potential* number of infections caused by an average infectious individual

# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**
  - ▶ \* The *potential* number of infections caused by an average infectious individual



# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**
  - ▶ \* The *potential* number of infections caused by an average infectious individual
    - ▶ \* That is: the number they would cause on average if everyone else were susceptible

# Basic reproductive number

- ▶ Poll: What *unitless* parameter can you make from the model above?
  - ▶ \*  $\mathcal{R}_0 = \beta D = \beta/\gamma$  is the **basic reproductive number**
  - ▶ \* The *potential* number of infections caused by an average infectious individual
    - ▶ \* That is: the number they would cause on average if everyone else were susceptible



# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?

# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?



# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?
  - ▶ \* Number of infected individuals grows exponentially

# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?
  - ▶ \* Number of infected individuals grows exponentially
- ▶ What happens early in the epidemic if  $\mathcal{R}_0 < 1$ ?

# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?
  - ▶ \* Number of infected individuals grows exponentially
- ▶ What happens early in the epidemic if  $\mathcal{R}_0 < 1$ ?
  - ▶ \*

# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?
  - ▶ \* Number of infected individuals grows exponentially
- ▶ What happens early in the epidemic if  $\mathcal{R}_0 < 1$ ?
  - ▶ \* Number of infected individuals cannot grow (disease cannot invade)

# Basic reproductive number implications

- ▶ Poll: What happens early in the epidemic if  $\mathcal{R}_0 > 1$ ?
  - ▶ \* Number of infected individuals grows exponentially
- ▶ What happens early in the epidemic if  $\mathcal{R}_0 < 1$ ?
  - ▶ \* Number of infected individuals cannot grow (disease cannot invade)

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:



# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:



# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?



# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \*

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?



# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?

▶ \*

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?
  - ▶ \* When susceptibles are low enough  $\mathcal{R}_e < 1$

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?
  - ▶ \* When susceptibles are low enough  $\mathcal{R}_e < 1$
  - ▶ \*

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?
  - ▶ \* When susceptibles are low enough  $\mathcal{R}_e < 1$
  - ▶ \* When  $\mathcal{R}_e < 1$ , the disease dies out on its own (less than one case per case)

# Effective reproductive number

- ▶ The effective reproductive number gives the number of new infections per infectious individual in a partially susceptible population:
  - ▶ \*  $\mathcal{R}_e = \mathcal{R}_0 S/N$
- ▶ Is the disease increasing or decreasing?
  - ▶ \* It will increase when  $\mathcal{R}_e > 1$  (more than one case per case)
  - ▶ \* This happens when  $S/N > 1/\mathcal{R}_0$
- ▶ Why doesn't everyone get infected?
  - ▶ \* When susceptibles are low enough  $\mathcal{R}_e < 1$
  - ▶ \* When  $\mathcal{R}_e < 1$ , the disease dies out on its own (less than one case per case)

## Subsection 1

Epidemic size

# Epidemic size

- ▶ In this model, the epidemic always burns out

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles



# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \*

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \* The number of susceptibles at the beginning of the epidemic

# Epidemic size

- ▶ In this model, the epidemic always burns out
    - ▶ No source of new susceptibles
  - ▶ Epidemic size is determined by:
    - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
    - ▶ \* The number of susceptibles at the beginning of the epidemic
- ▶ \*

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \* The number of susceptibles at the beginning of the epidemic
    - ▶ \* More susceptibles leads to a bigger epidemic

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \* The number of susceptibles at the beginning of the epidemic
    - ▶ \* More susceptibles leads to a bigger epidemic
    - ▶ \*



# Epidemic size

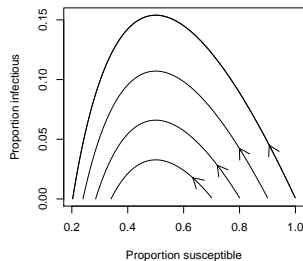
- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \* The number of susceptibles at the beginning of the epidemic
    - ▶ \* More susceptibles leads to a bigger epidemic
    - ▶ \* ... and *fewer* susceptibles at the end

# Epidemic size

- ▶ In this model, the epidemic always burns out
  - ▶ No source of new susceptibles
- ▶ Epidemic size is determined by:
  - ▶ \*  $\mathcal{R}_0$ — larger  $\mathcal{R}_0$  leads to a bigger epidemic
  - ▶ \* The number of susceptibles at the beginning of the epidemic
    - ▶ \* More susceptibles leads to a bigger epidemic
    - ▶ \* ... and *fewer* susceptibles at the end

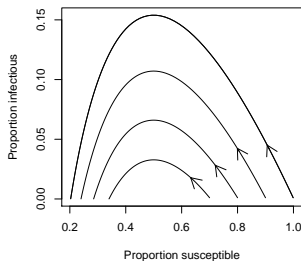
# Overshoot

- Why does more susceptibles at the beginning mean fewer susceptibles at the end?



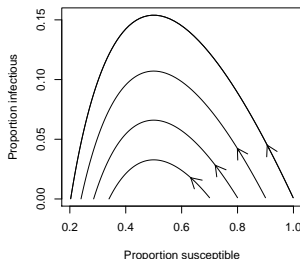
# Overshoot

- Why does more susceptibles at the beginning mean fewer susceptibles at the end?



# Overshoot

- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?
  - ▶ \* Bigger epidemic  $\Rightarrow$

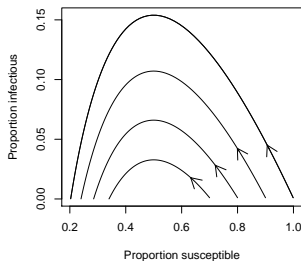


# Overshoot

- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?

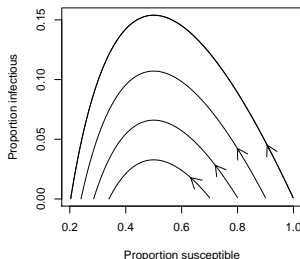
▶ \* Bigger epidemic  $\Rightarrow$

▶ \*



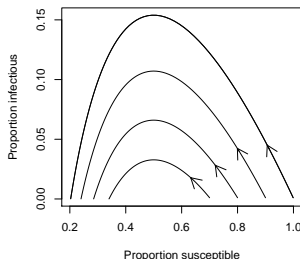
# Overshoot

- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?
  - ▶ \* Bigger epidemic  $\Rightarrow$
  - ▶ \* More infections at peak (same number of susceptibles)  $\Rightarrow$



# Overshoot

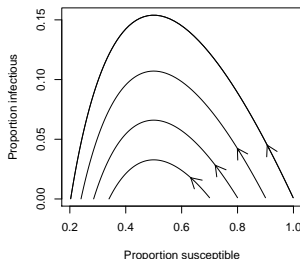
- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?
  - ▶ \* Bigger epidemic  $\Rightarrow$
  - ▶ \* More infections at peak (same number of susceptibles)  $\Rightarrow$
- ▶ \*





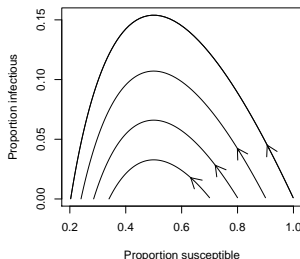
# Overshoot

- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?
  - ▶ \* Bigger epidemic  $\Rightarrow$
  - ▶ \* More infections at peak (same number of susceptibles)  $\Rightarrow$
  - ▶ \* More infections after peak
  - ...



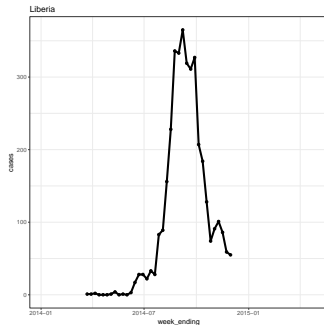
# Overshoot

- ▶ Why does more susceptibles at the beginning mean fewer susceptibles at the end?
  - ▶ \* Bigger epidemic  $\Rightarrow$
  - ▶ \* More infections at peak (same number of susceptibles)  $\Rightarrow$
  - ▶ \* More infections after peak
  - ...



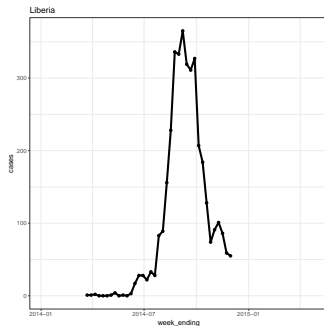
# Ebola example

- In September, the US CDC predicted “as many as” 1.5 million Ebola cases in Liberia by January



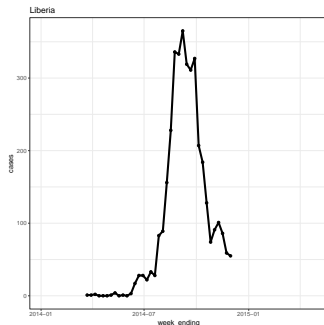
# Ebola example

- ▶ In September, the US CDC predicted “as many as” 1.5 million Ebola cases in Liberia by January
- ▶ In fact, their model predicted many *more* cases than that by April



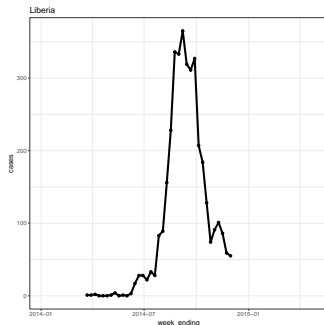
# Ebola example

- ▶ In September, the US CDC predicted “as many as” 1.5 million Ebola cases in Liberia by January
- ▶ In fact, their model predicted many *more* cases than that by April
- ▶ What happened?



# Ebola example

- ▶ In September, the US CDC predicted “as many as” 1.5 million Ebola cases in Liberia by January
- ▶ In fact, their model predicted many *more* cases than that by April
- ▶ What happened?



# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?





# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \*

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions
  - ▶ \*

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions
  - ▶ \* Behaviour change

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions
  - ▶ \* Behaviour change
  - ▶ \*

# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions
  - ▶ \* Behaviour change
  - ▶ \* Heterogeneity (differences between hosts, locations, etc.)



# What limits epidemics?

- ▶ Poll: What limits epidemics in our simple models?
  - ▶ \* Depletion of susceptibles
- ▶ Poll: What else limits epidemics in real life?
  - ▶ \* Interventions
  - ▶ \* Behaviour change
  - ▶ \* Heterogeneity (differences between hosts, locations, etc.)

# Outline

Introduction

Rate of spread

Single-epidemic model

Epidemic size

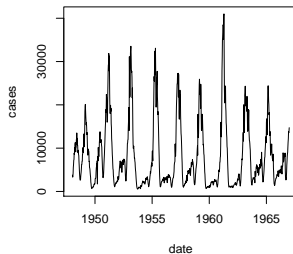
Recurrent epidemic models

Reproductive numbers and risk

# Recurrent epidemic models

- Poll: If epidemics tend to burn out, why do we often see repeated epidemics?

Measles reports from England and Wales

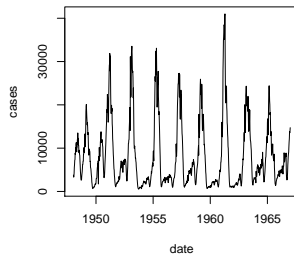


# Recurrent epidemic models

- Poll: If epidemics tend to burn out, why do we often see repeated epidemics?



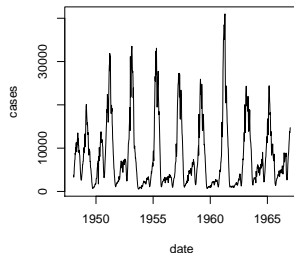
Measles reports from England and Wales



# Recurrent epidemic models

- ▶ Poll: If epidemics tend to burn out, why do we often see repeated epidemics?
  - ▶ \* People might lose immunity

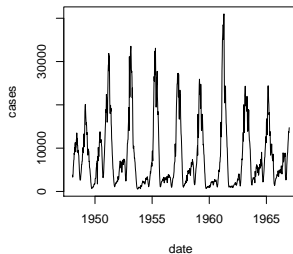
Measles reports from England and Wales



# Recurrent epidemic models

- ▶ Poll: If epidemics tend to burn out, why do we often see repeated epidemics?
  - ▶ \* People might lose immunity
  - ▶ \*

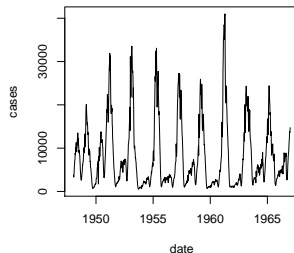
Measles reports from England and Wales



# Recurrent epidemic models

- ▶ Poll: If epidemics tend to burn out, why do we often see repeated epidemics?
  - ▶ \* People might lose immunity
  - ▶ \* Births and deaths

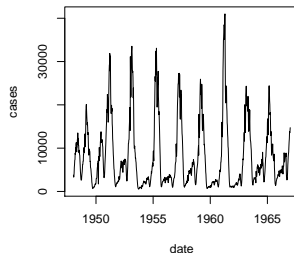
Measles reports from England and Wales



# Recurrent epidemic models

- ▶ Poll: If epidemics tend to burn out, why do we often see repeated epidemics?
  - ▶ \* People might lose immunity
  - ▶ \* Births and deaths

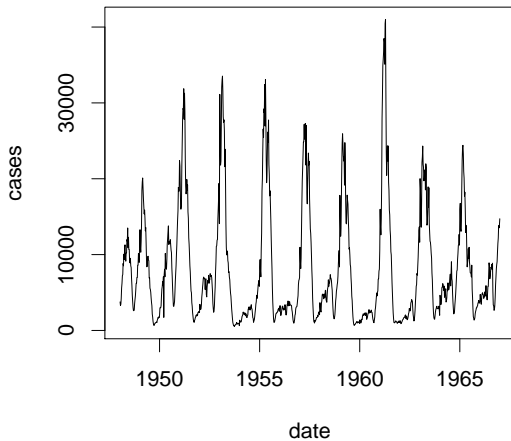
Measles reports from England and Wales



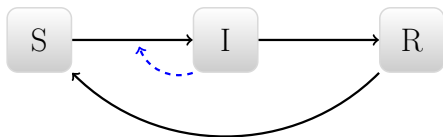


# Recurrent epidemics

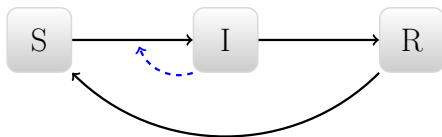
## Measles reports from England and Wales



## Closing the circle

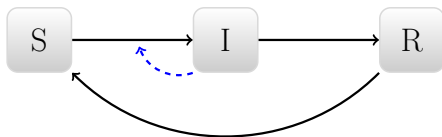


# Closing the circle



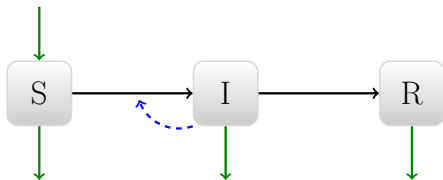
- \* Loss of immunity

# Closing the circle

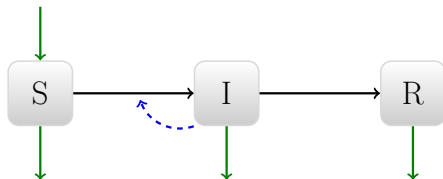


- \* Loss of immunity

# Closing the circle

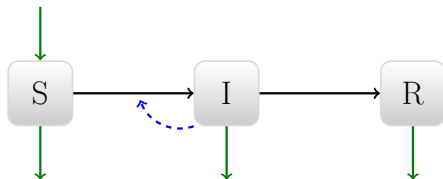


# Closing the circle



- \* Births and deaths

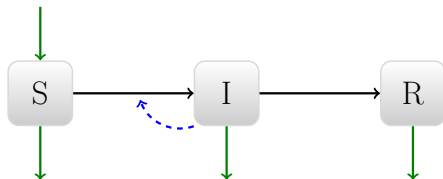
# Closing the circle



- \* Births and deaths



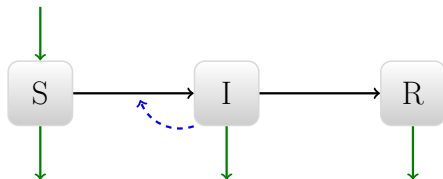
# Closing the circle



- ▶ \* Births and deaths
  - ▶ \* Effect on dynamics is similar to loss of immunity



# Closing the circle

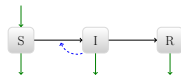


- ▶ \* Births and deaths
  - ▶ \* Effect on dynamics is similar to loss of immunity

# Births and deaths



$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$



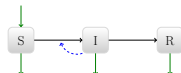
# Births and deaths



$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$



$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I - dI$$



# Births and deaths

►

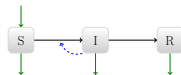
$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$

►

$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I - dI$$

►

$$\frac{dR}{dt} = \gamma I - dR$$



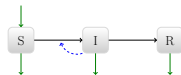
# Births and deaths

- ▶ 
$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I - dI$$

- ▶ 
$$\frac{dR}{dt} = \gamma I - dR$$

▶ We often assume  $b = d$



# Births and deaths

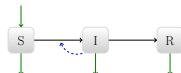
- ▶ 
$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I - dI$$

- ▶ 
$$\frac{dR}{dt} = \gamma I - dR$$

- ▶ We often assume  $b = d$

- ▶  $\implies$  population is constant



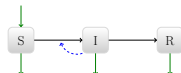
# Births and deaths

- ▶ 
$$\frac{dS}{dt} = bN - \beta \frac{SI}{N} - dS$$

- ▶ 
$$\frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I - dI$$

- ▶ 
$$\frac{dR}{dt} = \gamma I - dR$$

- ▶ We often assume  $b = d$ 
  - ▶  $\implies$  population is constant



# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$



# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case

# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case
  - ▶ Number of susceptibles at equilibrium determined by the number required to keep infection in balance

# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case
  - ▶ Number of susceptibles at equilibrium determined by the number required to keep infection in balance
    - ▶  $S/N = 1/\mathcal{R}_0$

# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case
  - ▶ Number of susceptibles at equilibrium determined by the number required to keep infection in balance
    - ▶  $S/N = 1/\mathcal{R}_0$

▶ \*

# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case
  - ▶ Number of susceptibles at equilibrium determined by the number required to keep infection in balance
    - ▶  $S/N = 1/\mathcal{R}_0$
  - ▶ \* Reciprocal control!

# Equilibrium

- ▶ At equilibrium, we know that  $\mathcal{R}_e = 1$ 
  - ▶ One case per case
  - ▶ Number of susceptibles at equilibrium determined by the number required to keep infection in balance
    - ▶  $S/N = 1/\mathcal{R}_0$
  - ▶ \* Reciprocal control!

# *Equilibrium*

- ▶ Number of infectious individuals determined by number required to keep susceptibles in balance.

# Equilibrium

- ▶ Number of infectious individuals determined by number required to keep susceptibles in balance.
- ▶ As susceptibles go up, what happens?



# Equilibrium

- ▶ Number of infectious individuals determined by number required to keep susceptibles in balance.
- ▶ As susceptibles go up, what happens?
  - ▶ Per capita replenishment goes down

# Equilibrium

- ▶ Number of infectious individuals determined by number required to keep susceptibles in balance.
- ▶ As susceptibles go up, what happens?
  - ▶ Per capita replenishment goes down
  - ▶ Infections required goes down

# Equilibrium

- ▶ Number of infectious individuals determined by number required to keep susceptibles in balance.
- ▶ As susceptibles go up, what happens?
  - ▶ Per capita replenishment goes down
  - ▶ Infections required goes down

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?



# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \*

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change



# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \*

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dI/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \*

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \*

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct
  - ▶ \*



# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct
  - ▶ \* If we keep increasing the rate ...

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct
  - ▶ \* If we keep increasing the rate ...
    - ▶ \*

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct
  - ▶ \* If we keep increasing the rate ...
    - ▶ \* Number of susceptibles goes down

# Reciprocal control

- ▶ What happens if we protect susceptibles (move them to  $R$  class)?
  - ▶ \* Equation for  $dl/dt$  does not change
  - ▶ \* Number of susceptibles does not change
  - ▶ \* Fewer susceptibles need to be removed by infection (some are removed by us)
  - ▶ \* Number of infectious individuals goes down
- ▶ What else could happen?
  - ▶ \* If we remove susceptibles fast enough, infection could go extinct
  - ▶ \* If we keep increasing the rate ...
    - ▶ \* Number of susceptibles goes down

# Reciprocal control

- ▶ **Poll:** What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?

# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?



# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$

# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \*



# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down

# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down



# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down
    - ▶ \* So the number of infectious individuals goes down

# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down
    - ▶ \* So the number of infectious individuals goes down
- ▶ \*

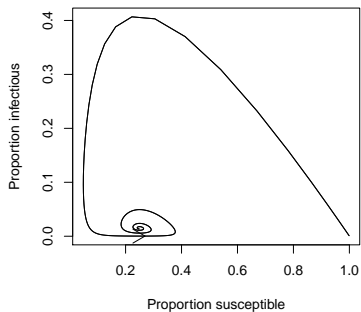
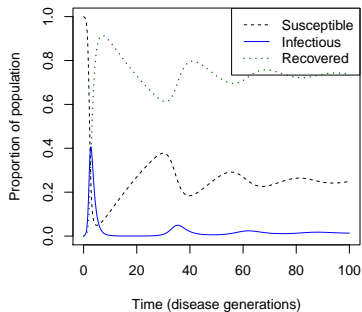
# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down
    - ▶ \* So the number of infectious individuals goes down
  - ▶ \* If we remove infectious individuals fast enough, the infection could go extinct

# Reciprocal control

- ▶ Poll: What happens if we remove infectious individuals at a constant rate (find them and cure them or isolate them)?
  - ▶ \* We need more susceptibles to balance  $dl/dt$
  - ▶ \* If we have more susceptibles, then per capita replenishment goes down
    - ▶ \* So the number of infectious individuals goes down
  - ▶ \* If we remove infectious individuals fast enough, the infection could go extinct

# Tendency to oscillate



# Tendency to oscillate

- ▶ “Closed-loop” SIR models (ie., with births or loss of immunity):



# Tendency to oscillate

- ▶ “Closed-loop” SIR models (ie., with births or loss of immunity):
  - ▶ Tend to oscillate

# Tendency to oscillate

- ▶ “Closed-loop” SIR models (ie., with births or loss of immunity):
  - ▶ Tend to oscillate
  - ▶ Oscillations tend to be damped

# Tendency to oscillate

- ▶ “Closed-loop” SIR models (ie., with births or loss of immunity):
  - ▶ Tend to oscillate
  - ▶ Oscillations tend to be damped
    - ▶ System reaches an **endemic** equilibrium – disease persists

# Tendency to oscillate

- ▶ “Closed-loop” SIR models (ie., with births or loss of immunity):
  - ▶ Tend to oscillate
  - ▶ Oscillations tend to be damped
    - ▶ System reaches an **endemic** equilibrium – disease persists

# Source of oscillations

- ▶ Similar to predator-prey systems

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?



# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic



# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \*

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ... then a very low number of susceptibles

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ... then a very low number of susceptibles
  - ▶ \*

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ...then a very low number of susceptibles
  - ▶ \* ...then a very low level of disease

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ... then a very low number of susceptibles
  - ▶ \* ... then a very low level of disease
  - ▶ \*

# Source of oscillations

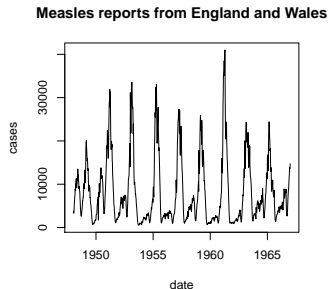
- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ... then a very low number of susceptibles
  - ▶ \* ... then a very low level of disease
  - ▶ \* ... then an increase in the number of susceptibles

# Source of oscillations

- ▶ Similar to predator-prey systems
- ▶ What happens if we start with too many susceptibles?
  - ▶ \* There will be a big epidemic
  - ▶ \* ...then a very low number of susceptibles
  - ▶ \* ...then a very low level of disease
  - ▶ \* ...then an increase in the number of susceptibles

# Persistent oscillations

- **Poll:** If oscillations tend to be damped in simple models, why do they persist in real life?



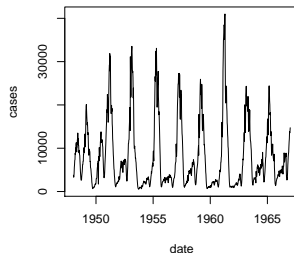


# Persistent oscillations

- Poll: If oscillations tend to be damped in simple models, why do they persist in real life?



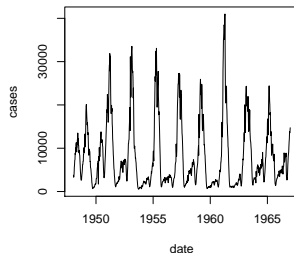
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather

Measles reports from England and Wales



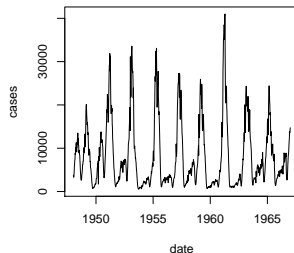
# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?

- ▶ \* Weather

- ▶ \*

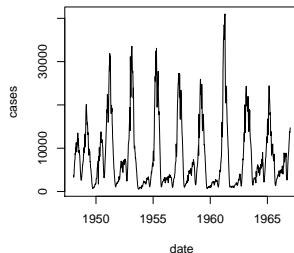
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms

Measles reports from England and Wales

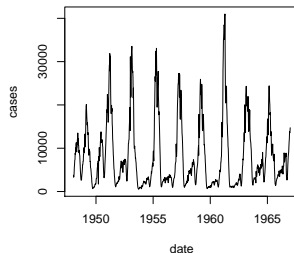


# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?

- ▶ \* Weather
- ▶ \* School terms
- ▶ \*

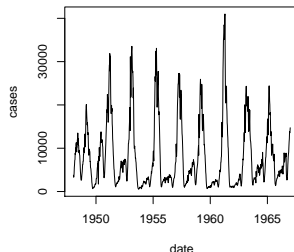
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms
  - ▶ \* Demographic stochasticity

Measles reports from England and Wales



# Persistent oscillations

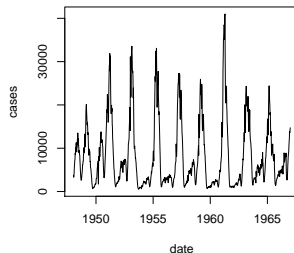
- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?

- ▶ \* Weather
- ▶ \* School terms
- ▶ \* Demographic stochasticity



\*

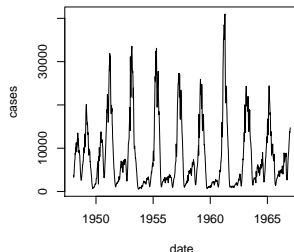
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms
  - ▶ \* Demographic stochasticity
  - ▶ \* Changes in Behaviour

Measles reports from England and Wales



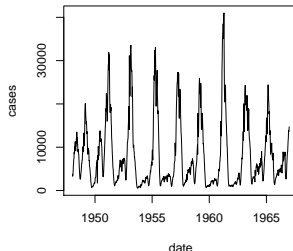


# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms
  - ▶ \* Demographic stochasticity
  - ▶ \* Changes in Behaviour



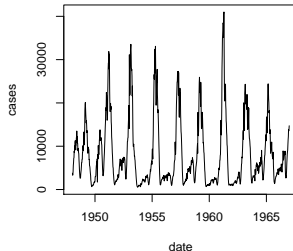
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms
  - ▶ \* Demographic stochasticity
  - ▶ \* Changes in Behaviour
    - ▶ \* People are more careful when disease levels are high

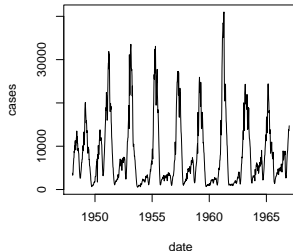
Measles reports from England and Wales



# Persistent oscillations

- ▶ Poll: If oscillations tend to be damped in simple models, why do they persist in real life?
  - ▶ \* Weather
  - ▶ \* School terms
  - ▶ \* Demographic stochasticity
  - ▶ \* Changes in Behaviour
    - ▶ \* People are more careful when disease levels are high

Measles reports from England and Wales



# Outline

Introduction

Rate of spread

Single-epidemic model

Epidemic size

Recurrent epidemic models

Reproductive numbers and risk

# Reproductive numbers and risk

- ▶ At equilibrium, the proportion of people who are susceptible to disease should be approximately  $S/N = 1/\mathcal{R}_0$

# Reproductive numbers and risk

- ▶ At equilibrium, the proportion of people who are susceptible to disease should be approximately  $S/N = 1/\mathcal{R}_0$
- ▶ Proportion “affected” (infectious or immune) should be approximately  $V/N = 1 - 1/\mathcal{R}_0$

# Reproductive numbers and risk

- ▶ At equilibrium, the proportion of people who are susceptible to disease should be approximately  $S/N = 1/\mathcal{R}_0$
- ▶ Proportion “affected” (infectious or immune) should be approximately  $V/N = 1 - 1/\mathcal{R}_0$
- ▶ If you have a single, fast epidemic, the size is also predicted by  $\mathcal{R}_0$ .

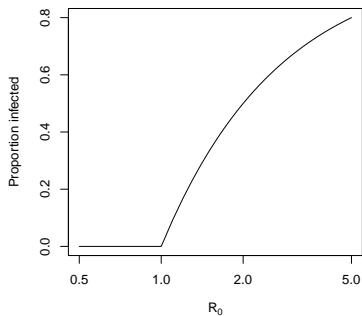
# Reproductive numbers and risk

- ▶ At equilibrium, the proportion of people who are susceptible to disease should be approximately  $S/N = 1/\mathcal{R}_0$
- ▶ Proportion “affected” (infectious or immune) should be approximately  $V/N = 1 - 1/\mathcal{R}_0$
- ▶ If you have a single, fast epidemic, the size is also predicted by  $\mathcal{R}_0$ .

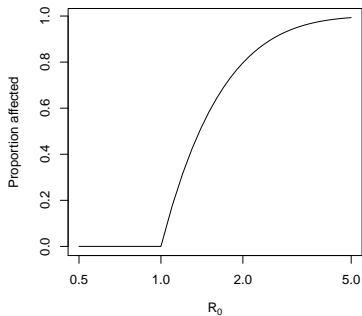


# Reproductive numbers and risk

**endemic equilibrium**



**epidemic size**



# Examples

- ▶ Ronald Ross predicted 100 years ago that reducing mosquito densities by a factor of 5 or so would *eliminate* malaria

# Examples

- ▶ Ronald Ross predicted 100 years ago that reducing mosquito densities by a factor of 5 or so would *eliminate* malaria
- ▶ Gradual disappearance of polio, typhoid, etc., without risk factors going to zero

# Examples

- ▶ Ronald Ross predicted 100 years ago that reducing mosquito densities by a factor of 5 or so would *eliminate* malaria
- ▶ Gradual disappearance of polio, typhoid, etc., without risk factors going to zero
- ▶ Eradication of smallpox!

# Examples

- ▶ Ronald Ross predicted 100 years ago that reducing mosquito densities by a factor of 5 or so would *eliminate* malaria
- ▶ Gradual disappearance of polio, typhoid, etc., without risk factors going to zero
- ▶ Eradication of smallpox!

# Threshold for elimination

- ▶ What proportion of the population should be vaccinated to eliminate a disease?

# Threshold for elimination

- ▶ What proportion of the population should be vaccinated to eliminate a disease?



# Threshold for elimination

- ▶ What proportion of the population should be vaccinated to eliminate a disease?
  - ▶ \* Transmission should be reduced by a factor of  $\mathcal{R}$ , so a fraction  $1 - 1/\mathcal{R}$  should be vaccinated



# Threshold for elimination

- ▶ What proportion of the population should be vaccinated to eliminate a disease?
  - ▶ \* Transmission should be reduced by a factor of  $\mathcal{R}$ , so a fraction  $1 - 1/\mathcal{R}$  should be vaccinated

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ **Poll:** What proportion of the population should be vaccinated to eliminate polio?

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?



# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?
  - ▶ \* At least  $1 - 1/5 = 80\%$

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?
  - ▶ \* At least  $1 - 1/5 = 80\%$
- ▶ Measles has an  $\mathcal{R}_0$  of about 20. What proportion of the population should be vaccinated to eliminate measles?

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?
  - ▶ \* At least  $1 - 1/5 = 80\%$
- ▶ Measles has an  $\mathcal{R}_0$  of about 20. What proportion of the population should be vaccinated to eliminate measles?
  - ▶ \*

# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?
  - ▶ \* At least  $1 - 1/5 = 80\%$
- ▶ Measles has an  $\mathcal{R}_0$  of about 20. What proportion of the population should be vaccinated to eliminate measles?
  - ▶ \* At least  $1 - 1/20 = 95\%$



# Examples:

- ▶ Polio has an  $\mathcal{R}_0$  of about 5.
- ▶ Poll: What proportion of the population should be vaccinated to eliminate polio?
  - ▶ \* At least  $1 - 1/5 = 80\%$
- ▶ Measles has an  $\mathcal{R}_0$  of about 20. What proportion of the population should be vaccinated to eliminate measles?
  - ▶ \* At least  $1 - 1/20 = 95\%$

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*
  - ▶ Human populations are **heterogeneous**

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*
  - ▶ Human populations are **heterogeneous**
    - ▶ People differ in: nutrition, exposure, access to care

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*
  - ▶ Human populations are **heterogeneous**
    - ▶ People differ in: nutrition, exposure, access to care
  - ▶ Information and misinformation

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*
  - ▶ Human populations are **heterogeneous**
    - ▶ People differ in: nutrition, exposure, access to care
  - ▶ Information and misinformation
    - ▶ Vaccine scares, trust in health care in general

# Persistence of infectious disease

- ▶ Why have infectious diseases persisted?
  - ▶ The pathogens *evolve*
  - ▶ Human populations are **heterogeneous**
    - ▶ People differ in: nutrition, exposure, access to care
  - ▶ Information and misinformation
    - ▶ Vaccine scares, trust in health care in general



# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high
    - ▶ Elimination is harder

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high
    - ▶ Elimination is harder
- ▶ Marginal populations

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high
    - ▶ Elimination is harder
- ▶ Marginal populations
  - ▶ Heterogeneity could make it easier to concentrate on the most vulnerable populations and eliminate disease

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high
    - ▶ Elimination is harder
- ▶ Marginal populations
  - ▶ Heterogeneity could make it easier to concentrate on the most vulnerable populations and eliminate disease
  - ▶ Humans rarely do this, however: the populations that need the most support typically have the least access

# Heterogeneity and persistence

- ▶ Heterogeneity *increases*  $\mathcal{R}_0$ 
  - ▶ When disease is rare, it is concentrated in the most vulnerable populations
    - ▶ Cases per case is high
    - ▶ Elimination is harder
- ▶ Marginal populations
  - ▶ Heterogeneity could make it easier to concentrate on the most vulnerable populations and eliminate disease
  - ▶ Humans rarely do this, however: the populations that need the most support typically have the least access