UNIT 7: Infectious disease

1 Introduction

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

- 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

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    – **Bacteria** are independent, free-living cells with hundreds or thousands of chemical pathways

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    – **Eukaryotic** pathogens are nucleated cells who are more closely related to you than they are to bacteria

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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**:

  - **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:

  - individuals to populations
 - single actions to trends through time

2 Rate of spread

- many diseases, especially new diseases, we can *observe* and *estimate* r.

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- to know what factors contribute to that, and how it relates to $\mathcal{R}$.

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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
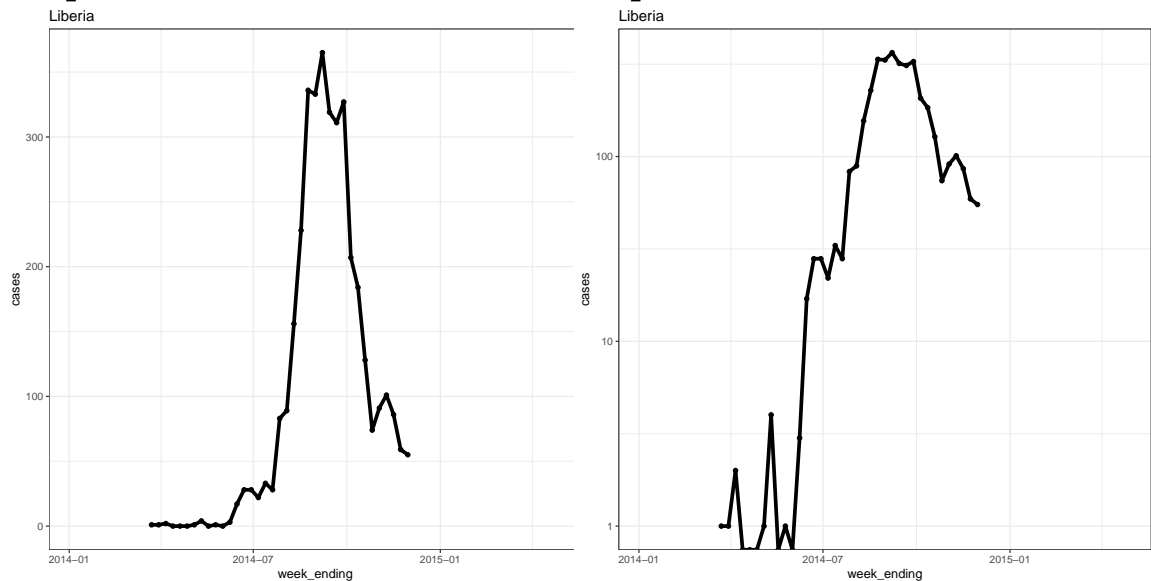
Generation intervals

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

- 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
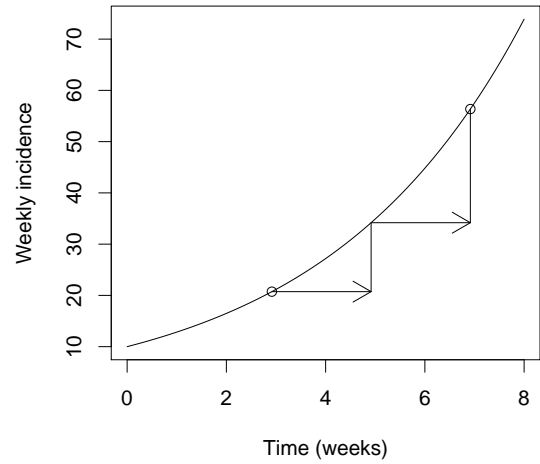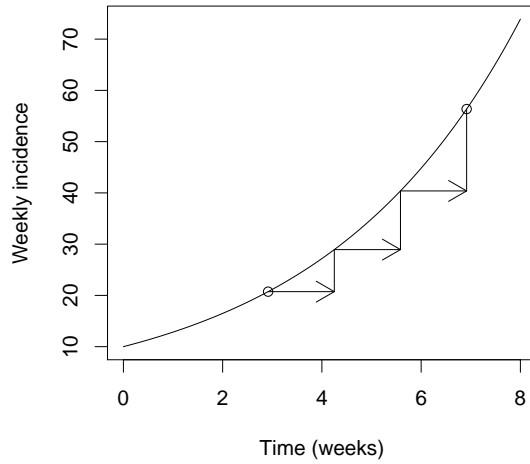
Generation intervals
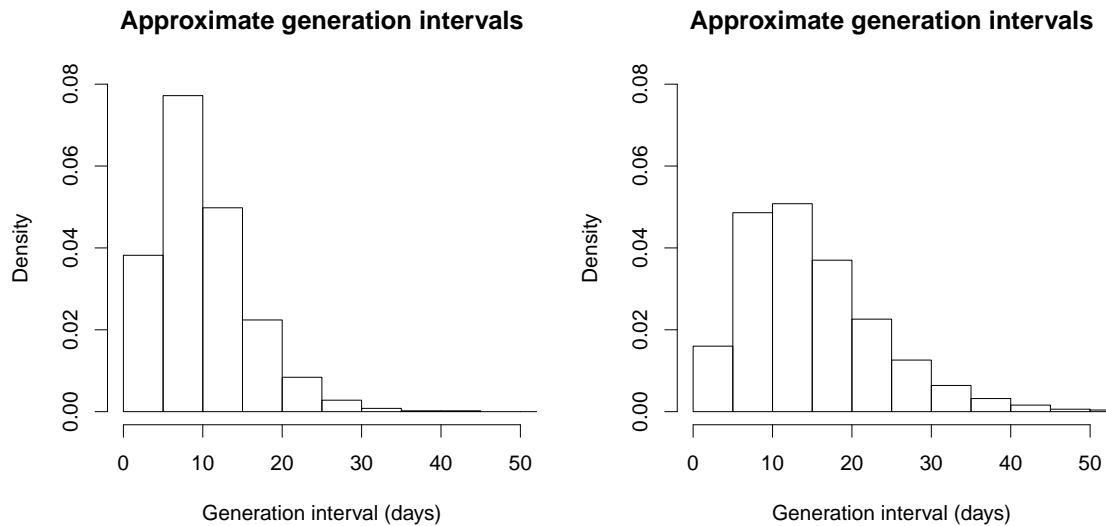
Speed and risk

- 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?*

Generation time and risk

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

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

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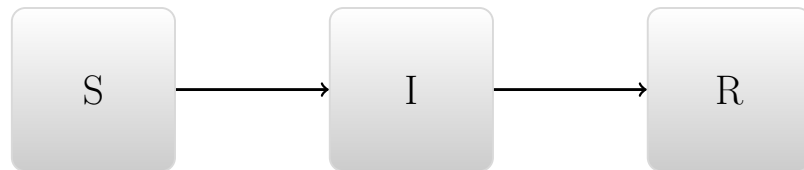
- $\mathcal{R} = \exp(r\hat{G})$

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Generation time and risk
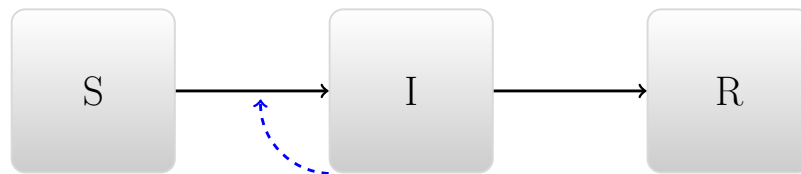

Generation time and risk

- An intuitive view:

    - Epidemic speed = Generation speed $\times$ Generation strength

- If we know generation speed, then a faster epidemic speed means:

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- If we know epidemic speed, a faster generation speed means

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3 Single-epidemic model

- Susceptible → Infectious → Recovered
- We also use N to mean the total population

Transition rates

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

Conceptual modeling

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

- Why might there not be an epidemic?

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- Why doesn't everyone get infected?

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Implementing the model

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

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

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

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

Quantities

State variables

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

Parameters

- Susceptible people have **potentially effective** contacts at rate β (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 γ (units [1/time])

  – Total recovery rate is γI

  – Mean time infectious is $D = 1/\gamma$ (units [time])

Simulating the model
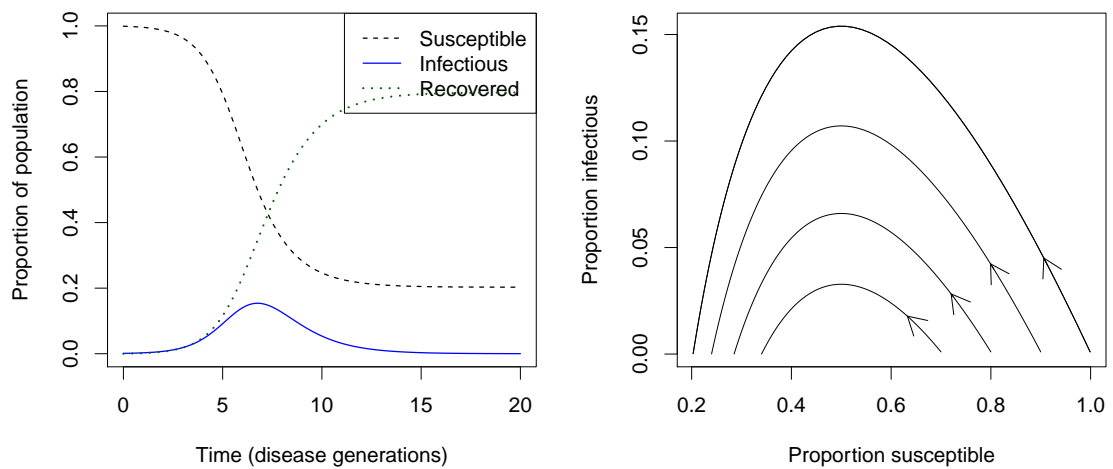
Basic reproductive number

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

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Basic reproductive number implications

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

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- What happens early in the epidemic if $\mathcal{R}_0 < 1$?

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Effective reproductive number

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

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- Is the disease increasing or decreasing?

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- Why doesn't everyone get infected?

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3.1 Epidemic size

- In this model, the epidemic always burns out

    – No source of new susceptibles

- Epidemic size is determined by:

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Overshoot

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

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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?

- What limits epidemics in our simple models?

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- What else limits epidemics in real life?
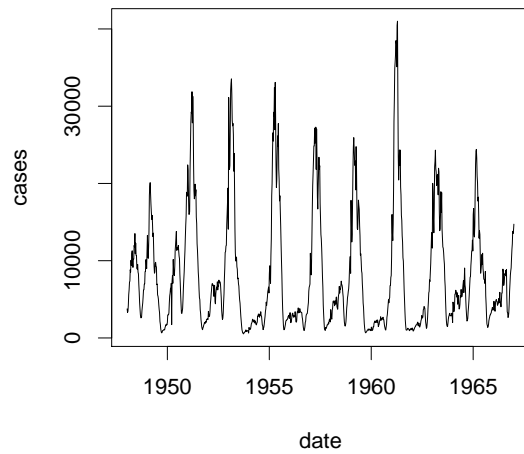
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4 Recurrent epidemic models

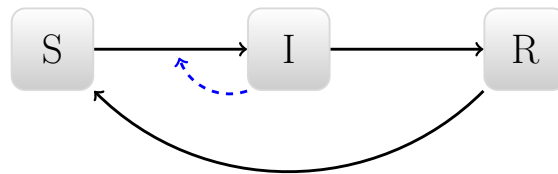- If epidemics tend to burn out, why do we often see repeated epidemics?

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Recurrent epidemics
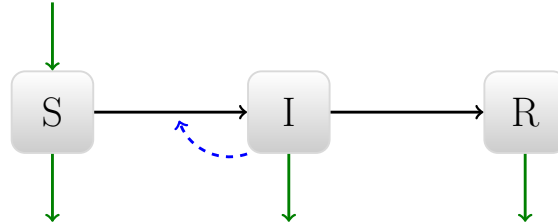
Measles reports from England and Wales

Closing the circle

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Closing the circle

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Births and deaths

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

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

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

- We often assume $b = d$

    - population is constant

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

        * $S/N = 1/\mathcal{R}_0$

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

- As susceptibles go up, what happens?

  - Per capita replenishment goes down
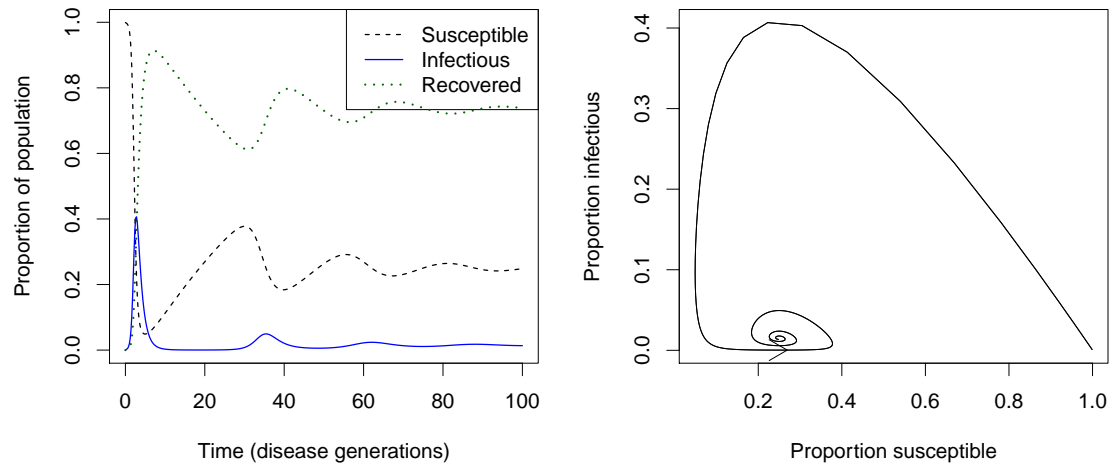 - Infections required goes down

Reciprocal control

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

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- What else could happen?

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Reciprocal control

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

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Tendency to oscillate

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

- What happens if we start with too many susceptibles?

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Persistent oscillations

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

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5   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

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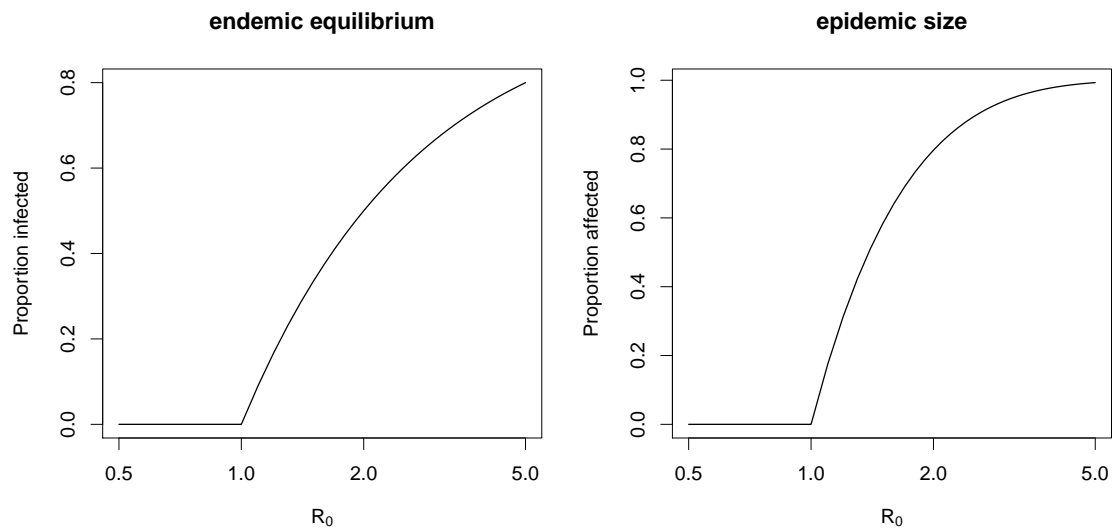
Examples

- 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?

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Examples:

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

- What proportion of the population should be vaccinated to eliminate polio?

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- Measles has an $\mathcal{R}_0$ of about 20. What proportion of the population should be vaccinated to eliminate measles?

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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* $\mathcal{R}_0$

    - 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