Week 1: Modeling Goals, Parameters, & Structures

Dr. Rachel Sippy
University of Cambridge

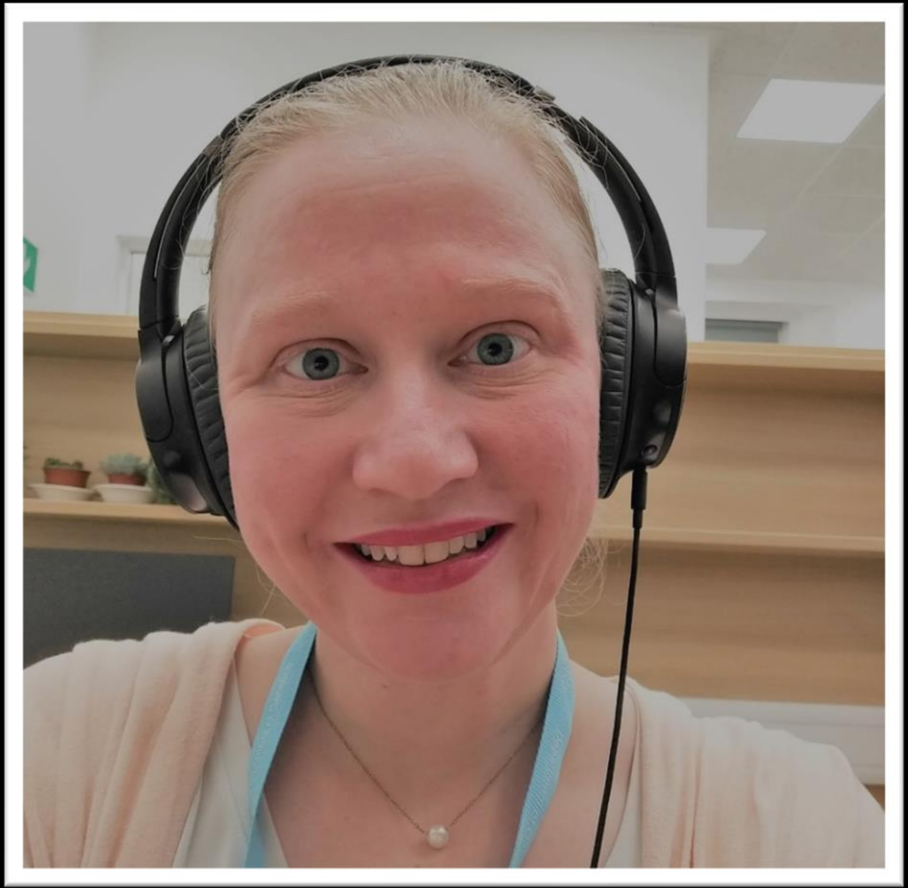
Objectives

- Add your first bullet point here
- Add your second bullet point here
- Add your third bullet point here

Post Questions in the Chat!

(we will have breaks to answer these during the workshop)

Week 1 Instructors



- Dr. Rachel Sippy

- Dr. Henrik Salje

Week 1 Overview

- Monday, July 26:
  - Introductory material, history of mathematical modeling
  - Introduction to R
- Tuesday, July 27:
  - Epidemic determinants & parameters
  - Guided practice in R
- Wednesday. July 28:
  - Model structures
  - Plots & compartmental models in R

Workshop Schedule

Time	Topics
2:00—2:10 pm	~~Outline & Introduction~~
2:10—3:00 pm	Defining Mathematical Models
3:00—3:30 pm	History of Mathematical Models
3:30—3:45 pm	Modern Modeling
3:40—3:50 pm	Break
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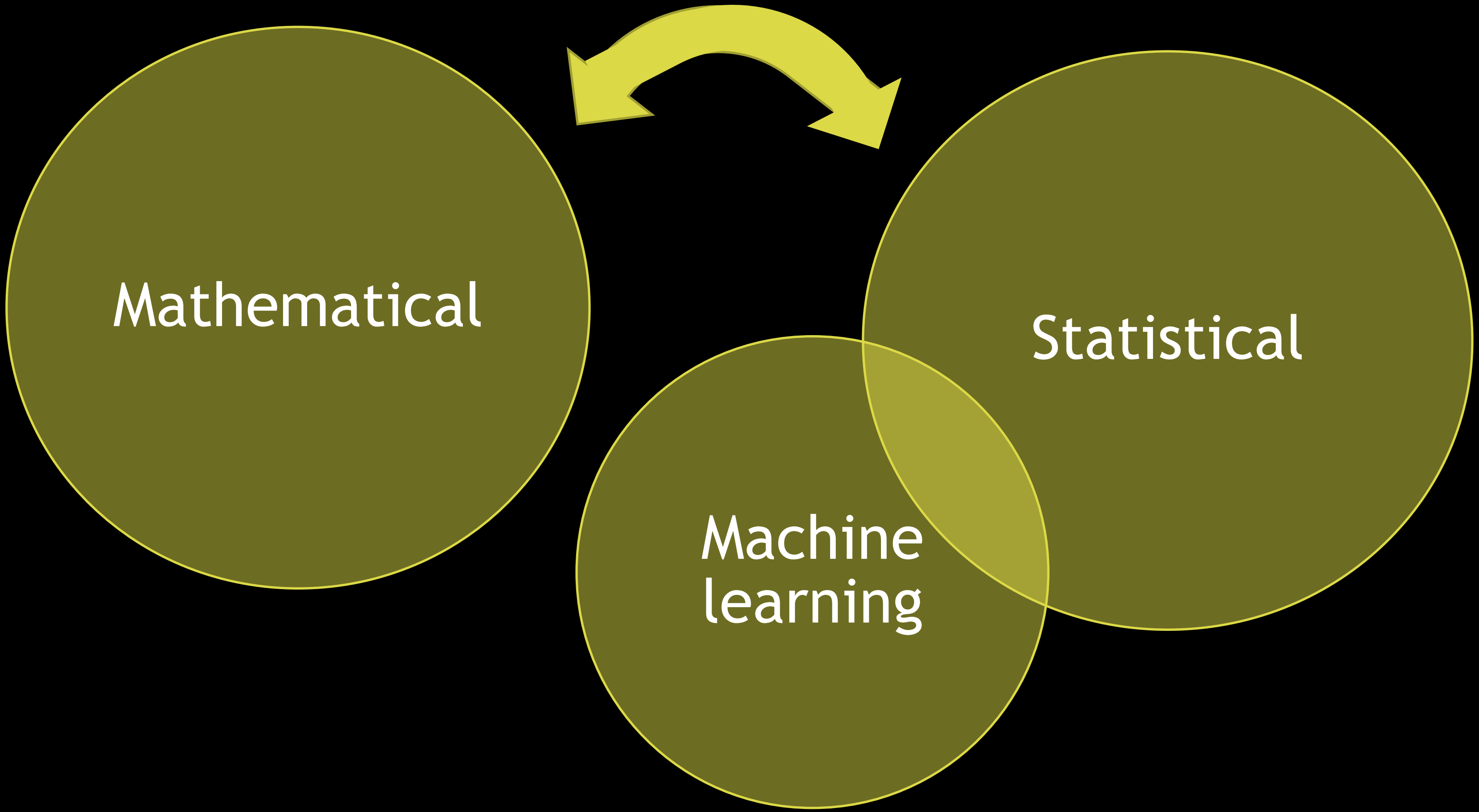
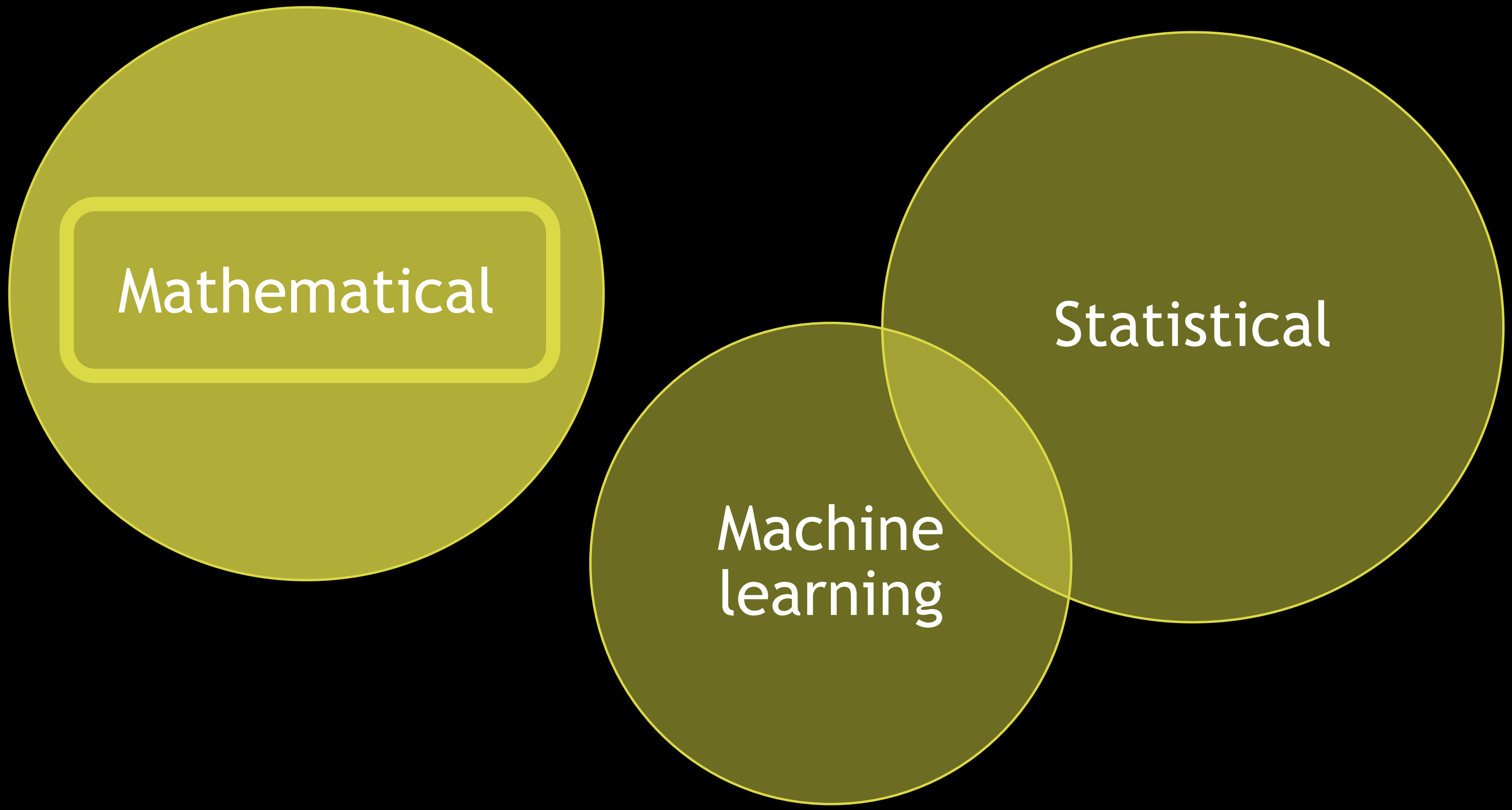
Three Major Model Types

(used in epidemiology)
(general modeling approaches)

- Statistical models
  - Regression (many!), time series
- Mathematical models
  - Compartmental, mechanistic, agent-based
- Machine learning
  - Uses algorithms and statistical models

Model Types are Related




Mathematical
Statistical
Machine
learning

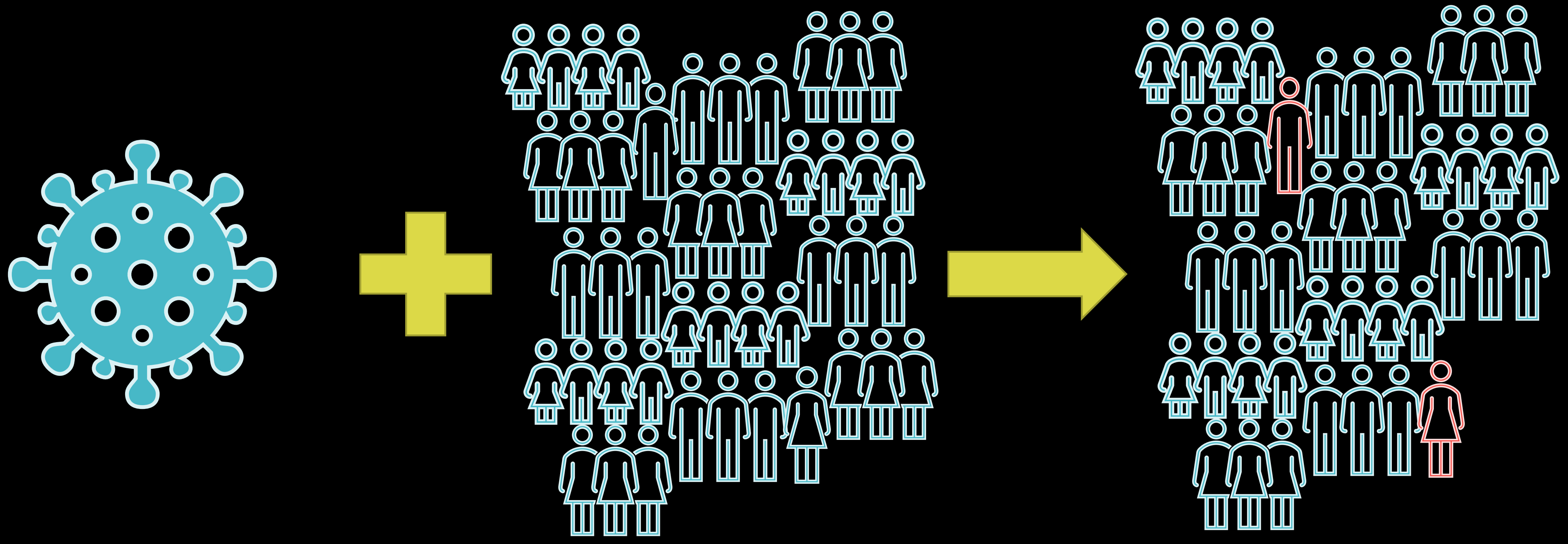
Mathematical Modeling

- Often called “mechanistic” modeling
- Used to assess explicit hypotheses about biological mechanisms of infection dynamics
- Model structure is critical first decision
- Models expressed as equations

Mathematical Modeling

- Used to estimate parameters/measures related to an epidemic
- Often, we use equations to create a scenario (set of conditions)
  - Example: population of city, level of interaction, certain disease, susceptibility of population
- If we can create a realistic model, then we can make changes to model and see what happens
  - Example: what happens when we vaccinate some people?
- This is similar to running an experiment and observing what happens
- Results from these observations can be compared to real data
  - Example: do model results match what happened in real life?

Epidemic Scenario



Public Health Applications

Mathematical Modeling

- Estimate transmission parameters from data
- Construct and build mechanistic models
- Build more realistic models

Public Health Questions

- How big will the final epidemic be?
- What is the R0 value?
- How will interventions impact the epidemic?

Public Health Applications: Example

Scenario

- Emergence of H5N1 (2006) and swine flu (2009)
- Vaccines take many months to develop
- Vaccines may improve during the pandemic
- Manu countries have no or low stockpiles of antivirals

Public Health Questions

Public Health Applications: Example

Scenario

- Emergence of H5N1 (2006) and swine flu (2009)
- Vaccines take many months to develop
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Public Health Questions

- How should we distribute vaccines?
- Should everyone use the first available vaccine or wait for a better one?
- Do travel restrictions impact spread?
- What is the impact of closing schools?
- How many cases would occur if we run out of antivirals?
- Is it better to use antivirals as prophylaxis or to treat cases?

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History of Mathematical Modeling of Infectious Disease

Early efforts & recent advances

History of Mathematical Models

1700 1800 1900 2000

History of Mathematical Models

1700 1800 1900 2000

- Daniel Bernoulli, 1760

It is, then, only the risk which is attributed to inoculation which should keep us undecided... 'What would be the state of the human race if, at the price of a certain number of victims, we could procure for it freedom from natural smallpox?' [**5**, p. 284]

History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli

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- What is the impact of inoculation against smallpox?

History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli

$$\text{Susceptible} \xrightarrow{s(a)\lambda(a)} \text{Immune}$$

Susceptible $\downarrow$ $\mu(a) + [1 - s(a)]\lambda(a)$

Immune $\downarrow$ $\mu(a)$

- s(a)=probability of surviving infection
- λ(a)=force of infection
- μ(a)=death rate

History of Mathematical Models

1700 — 1800 — 1900 — 2000

Bernoulli

Susceptible $\xrightarrow{s(a)\lambda(a)}$ Immune

Susceptible $\downarrow$ $\mu(a) + [1 - s(a)]\lambda(a)$

Immune $\downarrow$ $\mu(a)$

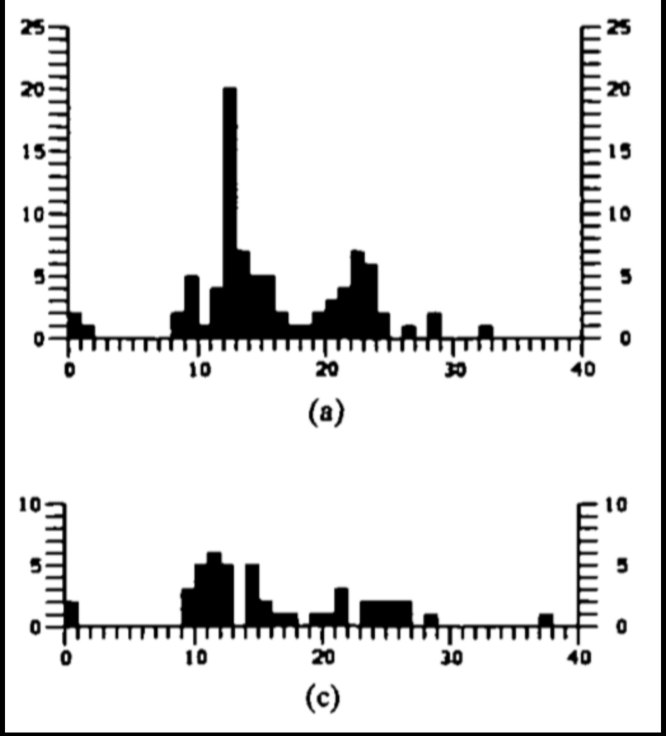
- Inoculation would increase life expectancy at birth by ~3 years

History of Mathematical Models

1700 1800 1900 2000

Bernoulli

- Pyotr En’ko, 1889
- How does contact between susceptible and infected people impact a measles epidemic?



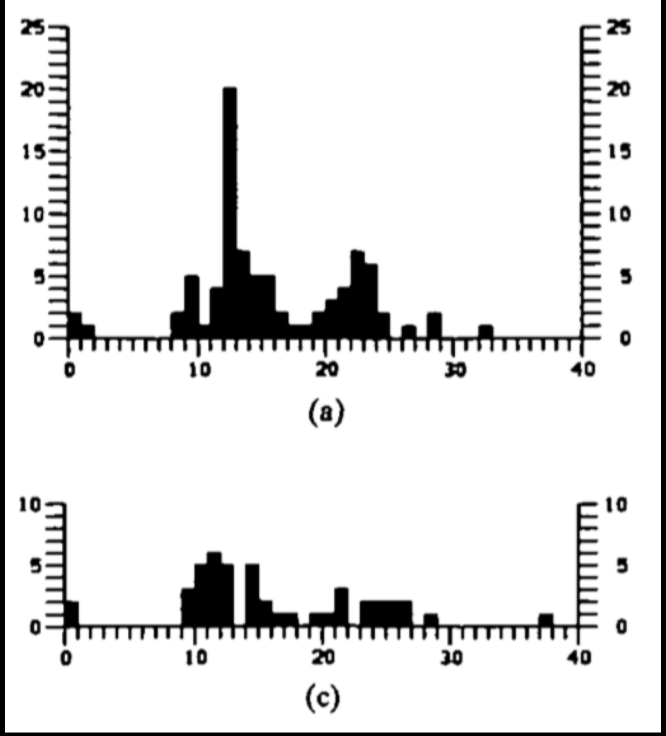
History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli | En'ko

- How does contact between susceptible and infected people impact a measles epidemic?

The number of contacts depends on the way of life. For a solitary way of life—one's home, one's servants, a selected circle of acquaintances—the number of contacts is less. In schools the patients are isolated at the first signs of the disease and can infect their schoolmates only as long as they appear completely healthy; therefore it is assumed that a patient has contact with the same number of individuals as a healthy individual.



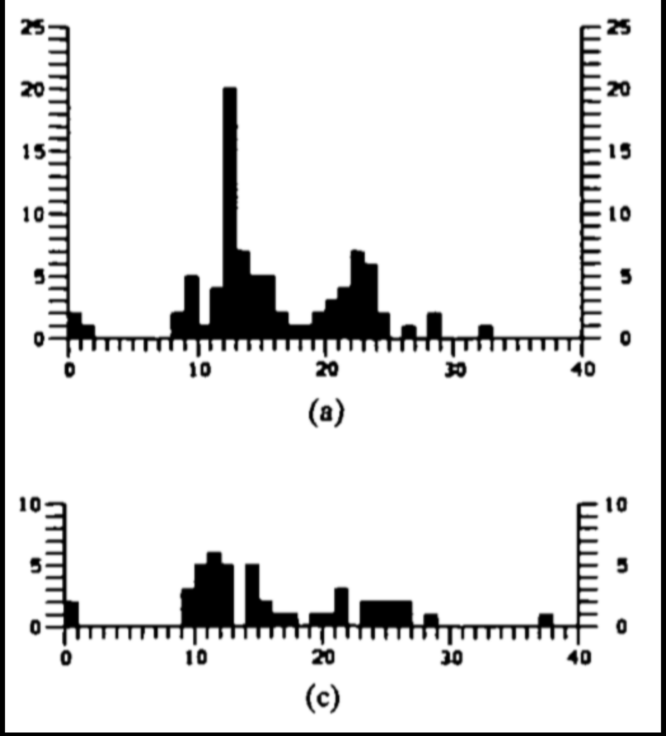
History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli | En'ko

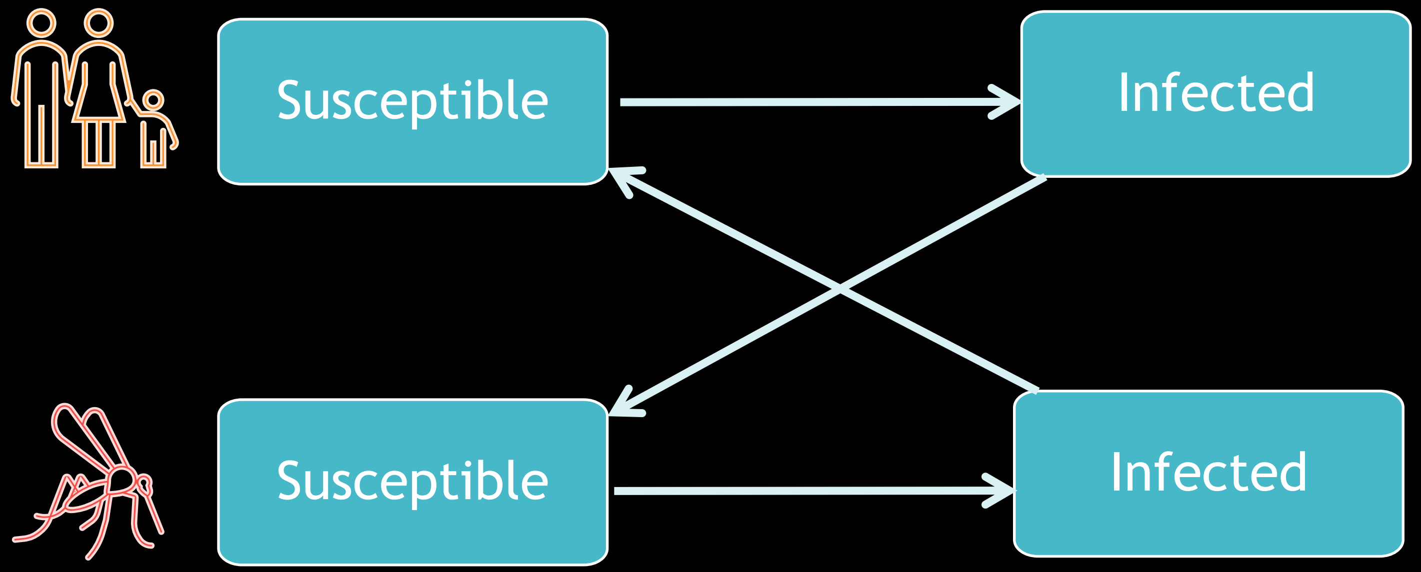
$$1 - ((N - 1 - x)/(N - 1))^A$$

- N=population size
- x=number of infected
- A=number of contacts



History of Mathematical Models

- Ronald Ross, 1911



History of Mathematical Models

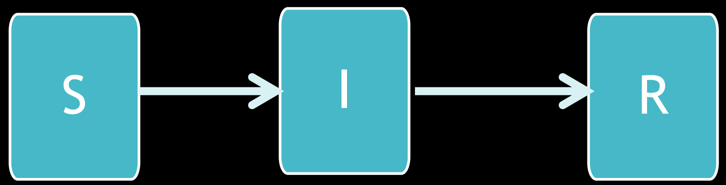
1700 | 1800 | 1900 | 2000

Bernoulli | En'ko | Ross

- How does vector control impact a malaria epidemic?
- If you increase mosquito mortality from 5% to 45% you could eradicate malaria in Africa
- Argued for establishment of new field of study, co-authored with Hilda Hudson

History of Mathematical Models

- Kermack and McKendrick, 1926



History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli | En'ko | Ross | Kermack & McKendrick

- Evaluated plague and cholera epidemics
- Formalization of mechanistic models for epidemics

$$\frac{dS(t)}{dt} = -\beta S(t)I(t)$$

$$\frac{dI(t)}{dt} = \beta S(t)I(t) - \gamma I(t)$$

$$\frac{dR(t)}{dt} = \gamma I(t)$$

History of Mathematical Models

1700 | 1800 | 1900 | 2000

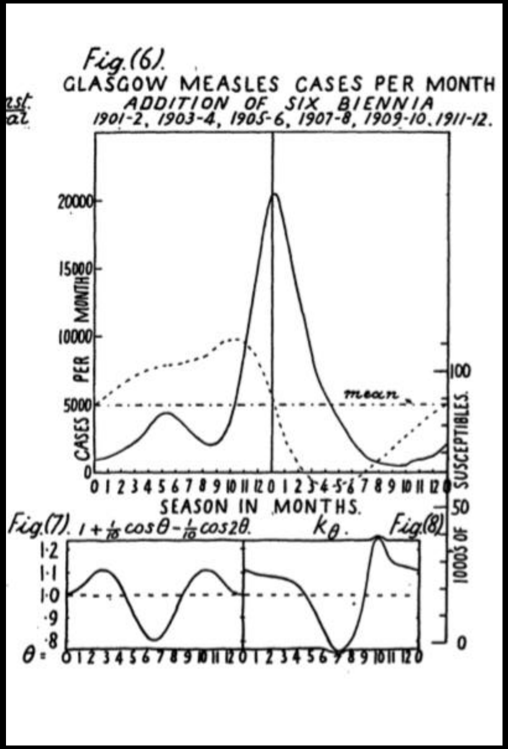
Bernoulli

En'ko

Ross

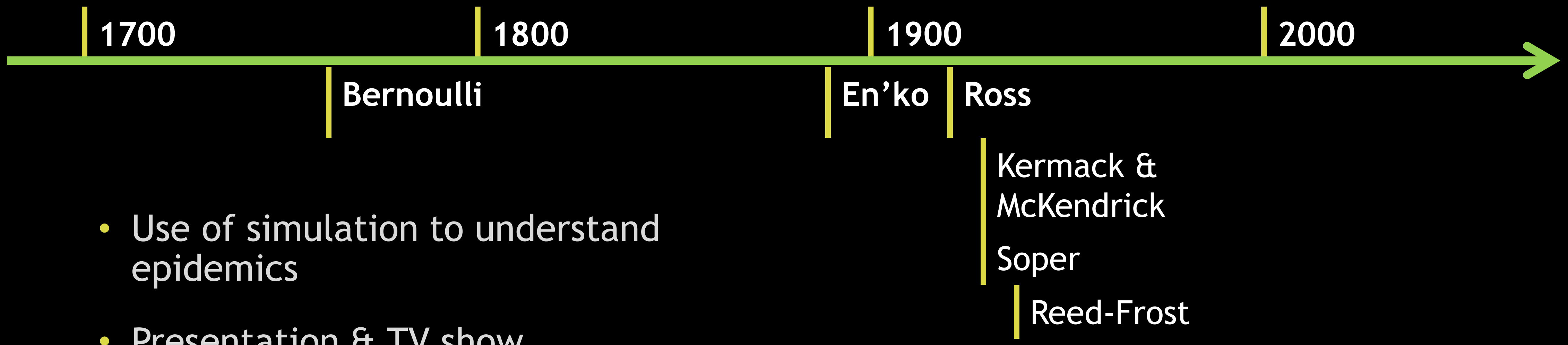
Kermack &
McKendrick

Soper



- Evaluated seasonality of measles epidemics

History of Mathematical Models



- Use of simulation to understand epidemics
- Presentation & TV show
- Formally published by Helen Abbey
- Basis for modern epidemic modeling

History of Mathematical Models

1700 | 1800 | 1900 | 2000

Bernoulli

En’ko

Ross

Kermack & McKendrick

Soper

Reed-Frost

MacDonald

- Extended Ross malaria models for use on computers
- Ross-MacDonald models, formalized by Smith & McKenzie, Aron & May, and Anderson & May

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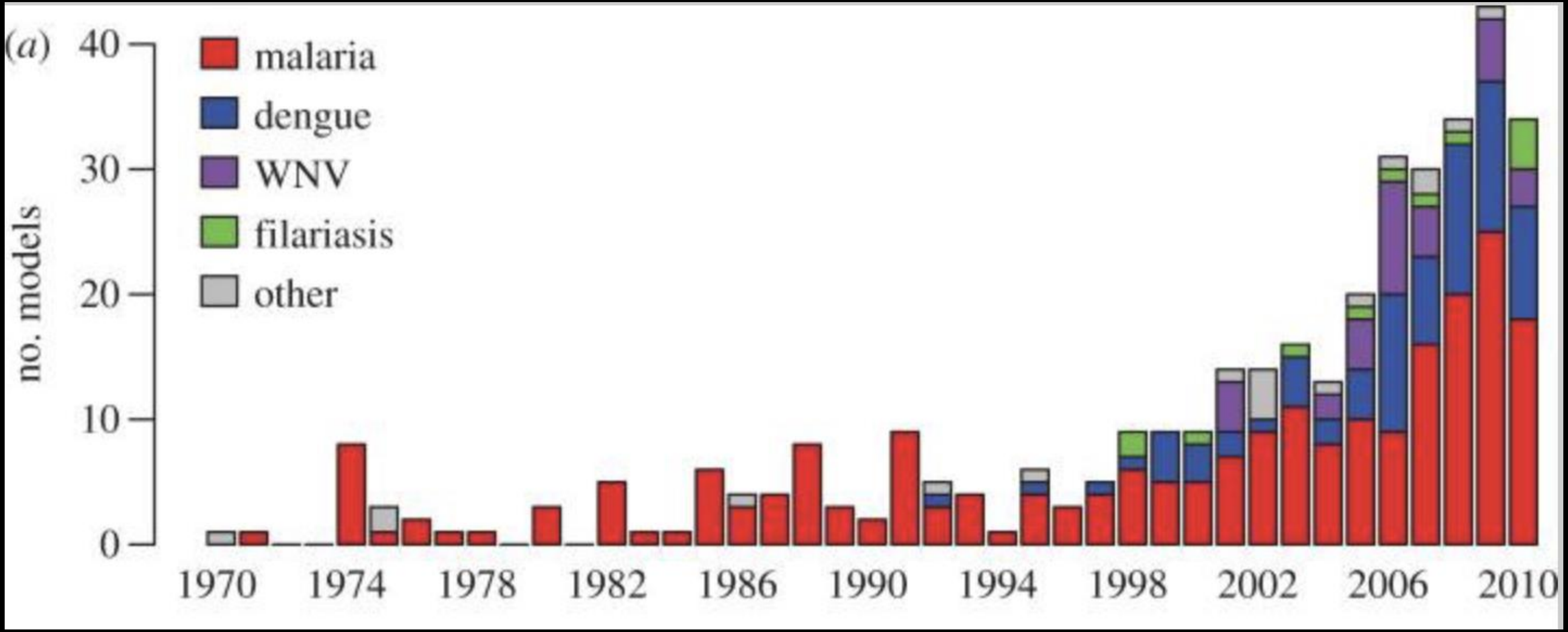
Modern Modeling

Modern Modeling

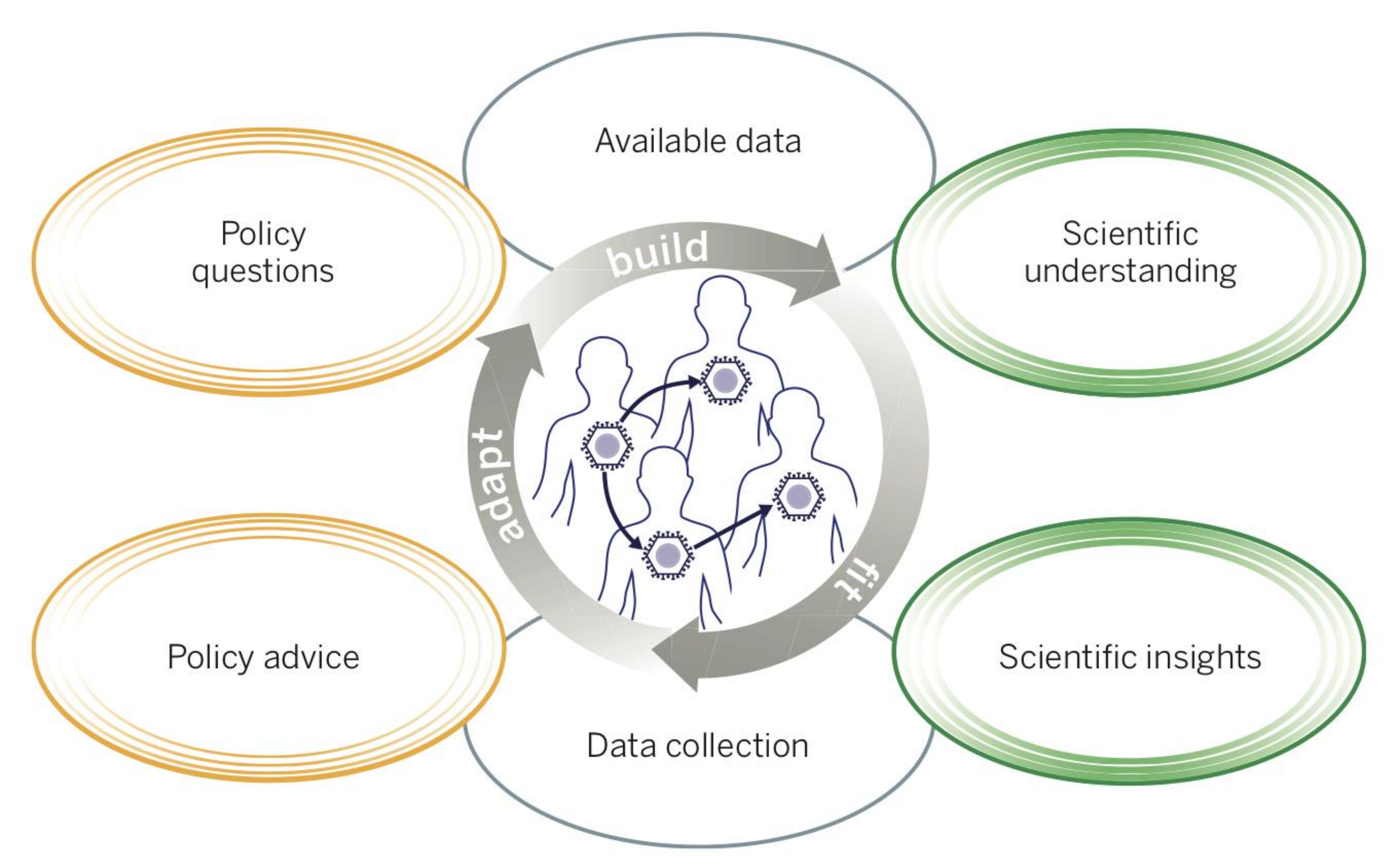


Reiner et al. 2013

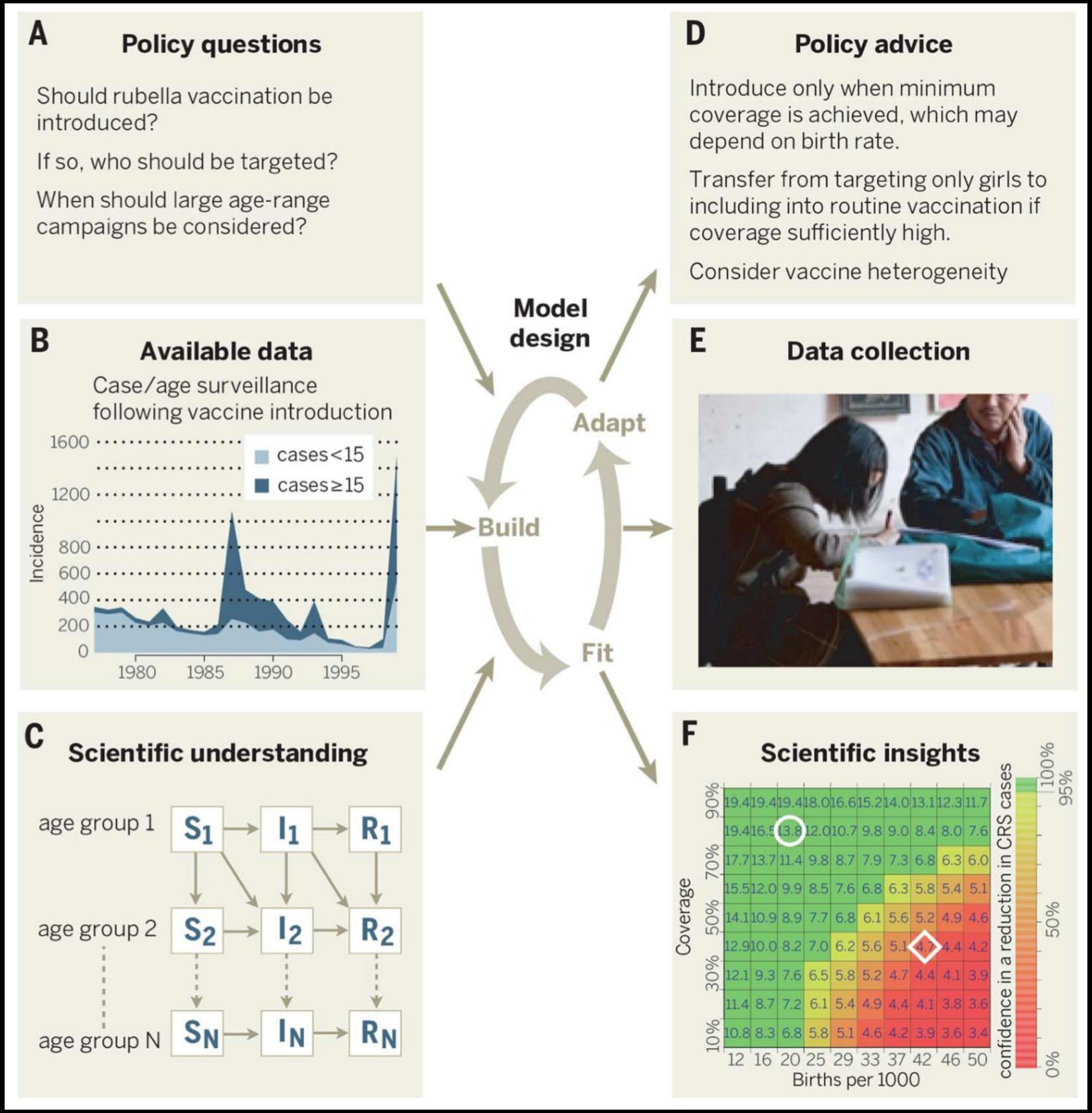
- Early models have been expanded and developed for a wide variety of scenarios and applications

Modern Modeling

- Modeling is used to fit and answer policy questions



Heesterbeek et al. 2015



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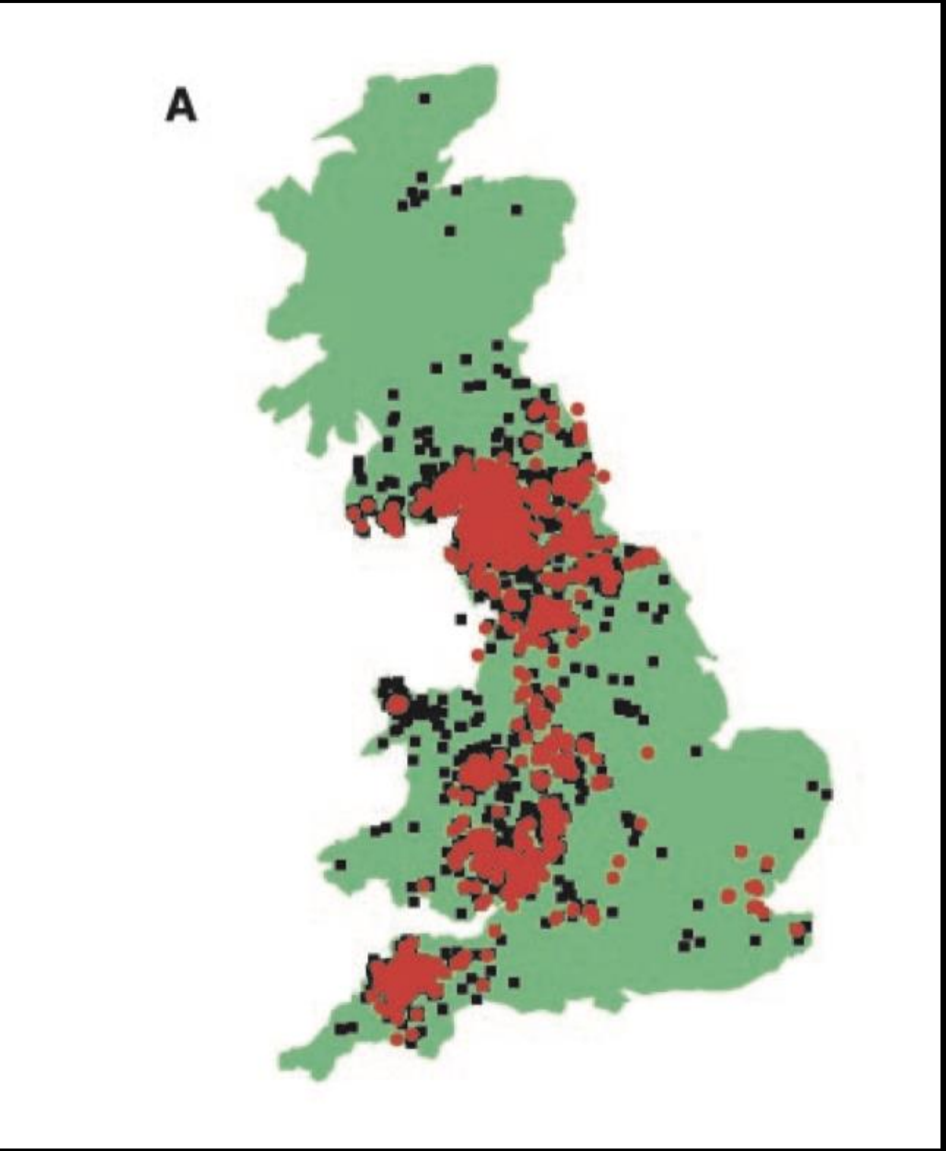
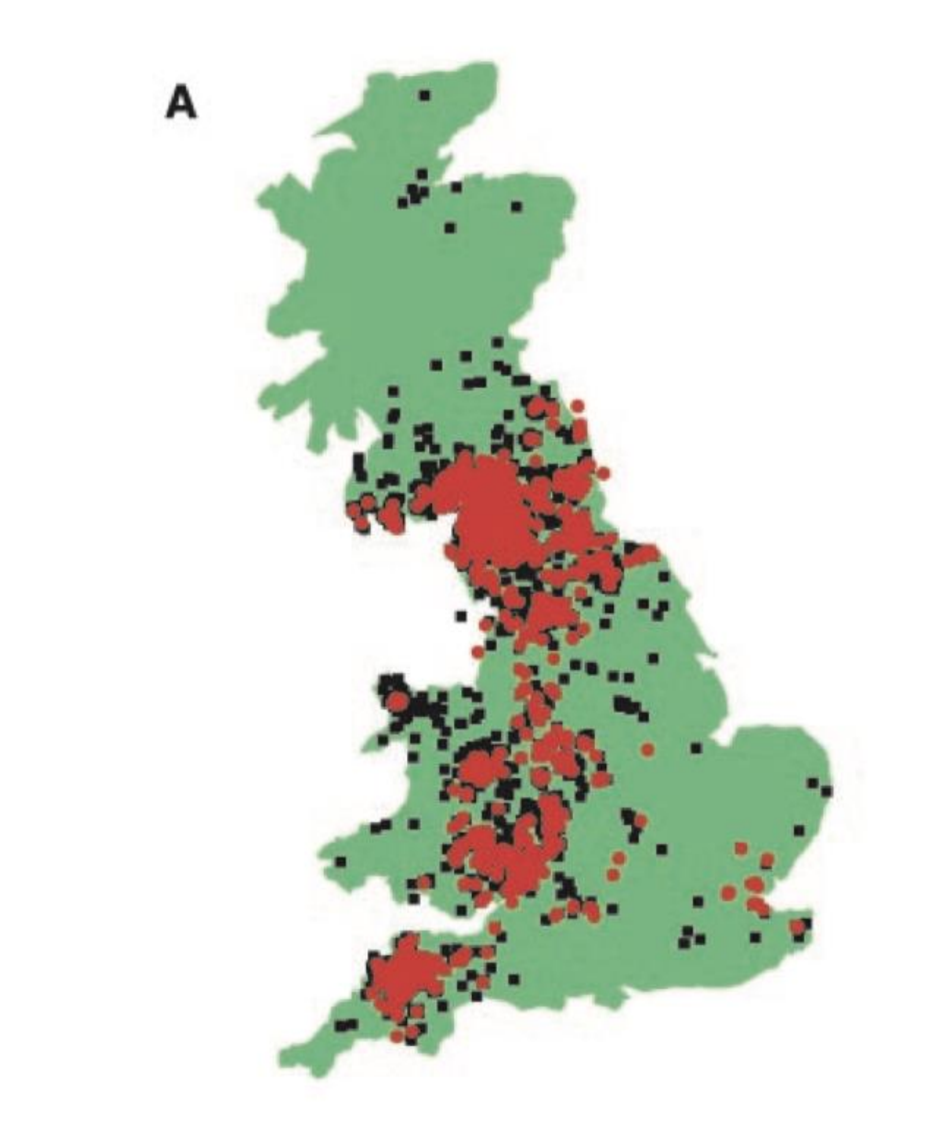
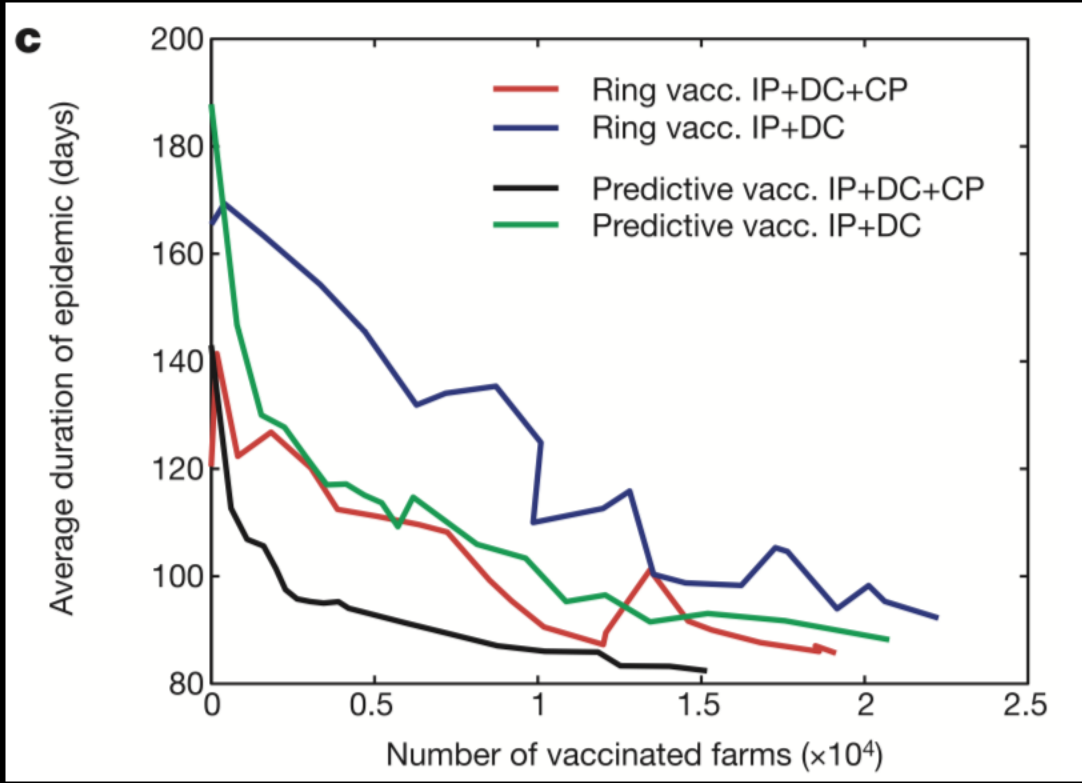


Foot & Mouth Disease, UK 2001

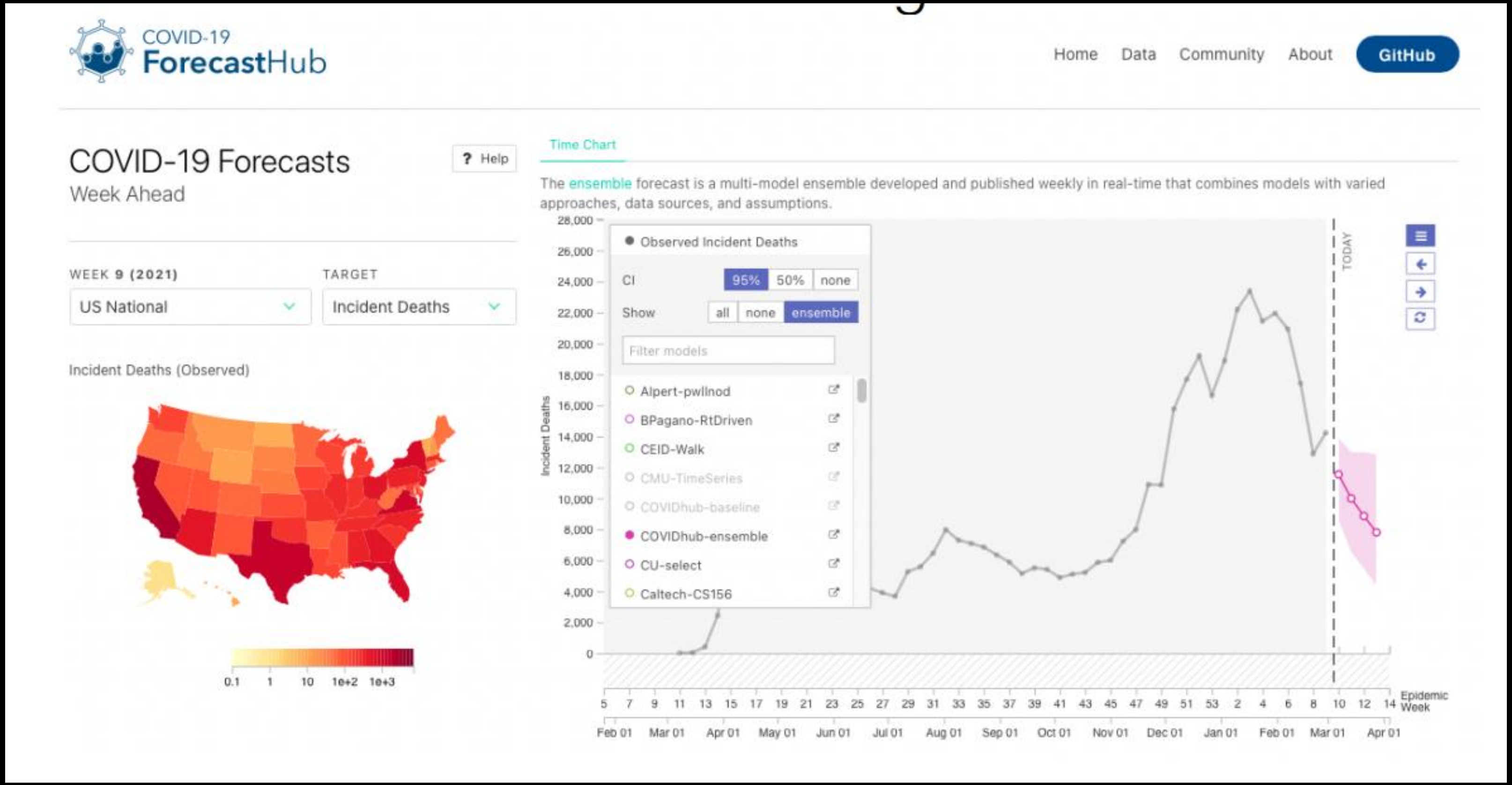
- Series of outbreaks among farms
- Questions around severity of control and which controls to implement
- Test the impacts of different control scenarios

Keeling et al. 2001, 2003





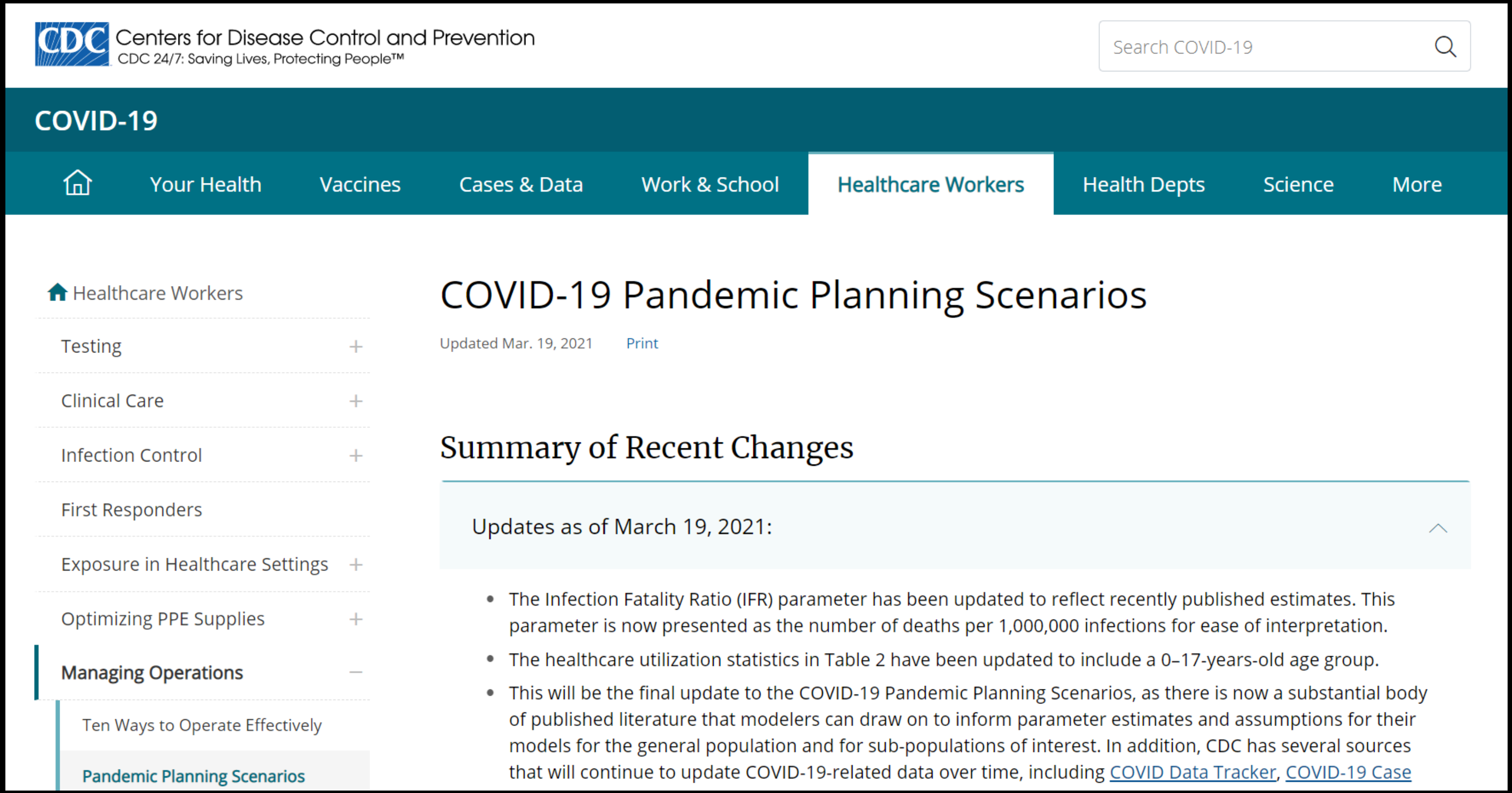
Keeling et al. 2001, 2003



COVID-19, Global 2020—2021

- Efforts to forecast disease incidence and deaths for different locations on a weekly basis

https://viz.covid19forecasthub.org



CDC Centers for Disease Control and Prevention
CDC 24/7: Saving Lives, Protecting People™

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Healthcare Workers
- Testing
- Clinical Care
- Infection Control
- First Responders
- Exposure in Healthcare Settings
- Optimizing PPE Supplies
- Managing Operations
  - Ten Ways to Operate Effectively
  - Pandemic Planning Scenarios

COVID-19 Pandemic Planning Scenarios

Updated Mar. 19, 2021 Print

Summary of Recent Changes

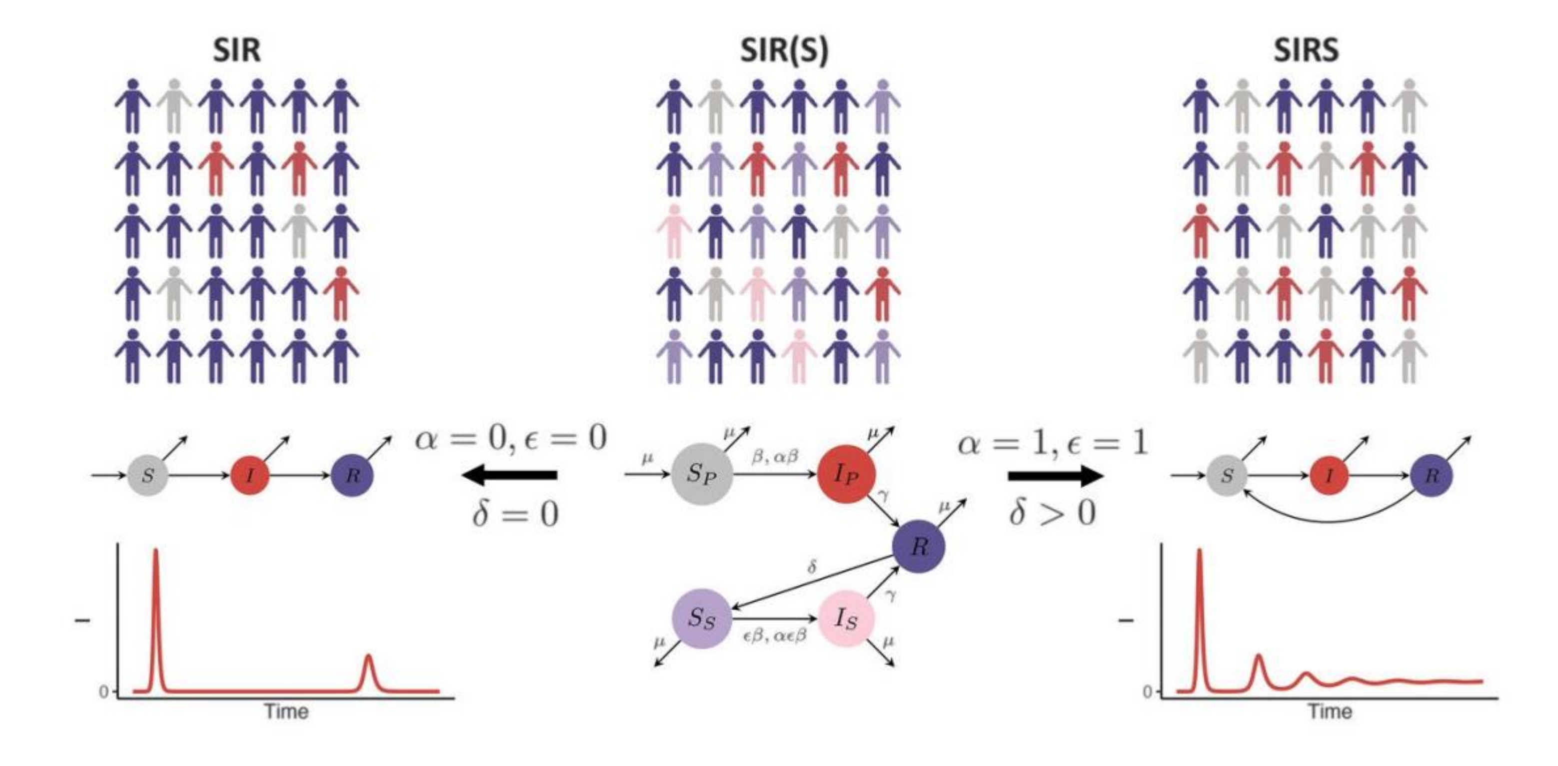
Updates as of March 19, 2021:

- The Infection Fatality Ratio (IFR) parameter has been updated to reflect recently published estimates. This parameter is now presented as the number of deaths per 1,000,000 infections for ease of interpretation.
- The healthcare utilization statistics in Table 2 have been updated to include a 0–17-years-old age group.
- This will be the final update to the COVID-19 Pandemic Planning Scenarios, as there is now a substantial body of published literature that modelers can draw on to inform parameter estimates and assumptions for their models for the general population and for sub-populations of interest. In addition, CDC has several sources that will continue to update COVID-19-related data over time, including COVID Data Tracker, COVID-19 Case

COVID-19, Global 2020—2021

- Scenario planning: estimates of outcomes using best-case, worst-case, and most-likely parameters for disease transmission and severity
- Based on biological and epidemiologic characteristics of SARS-CoV-2

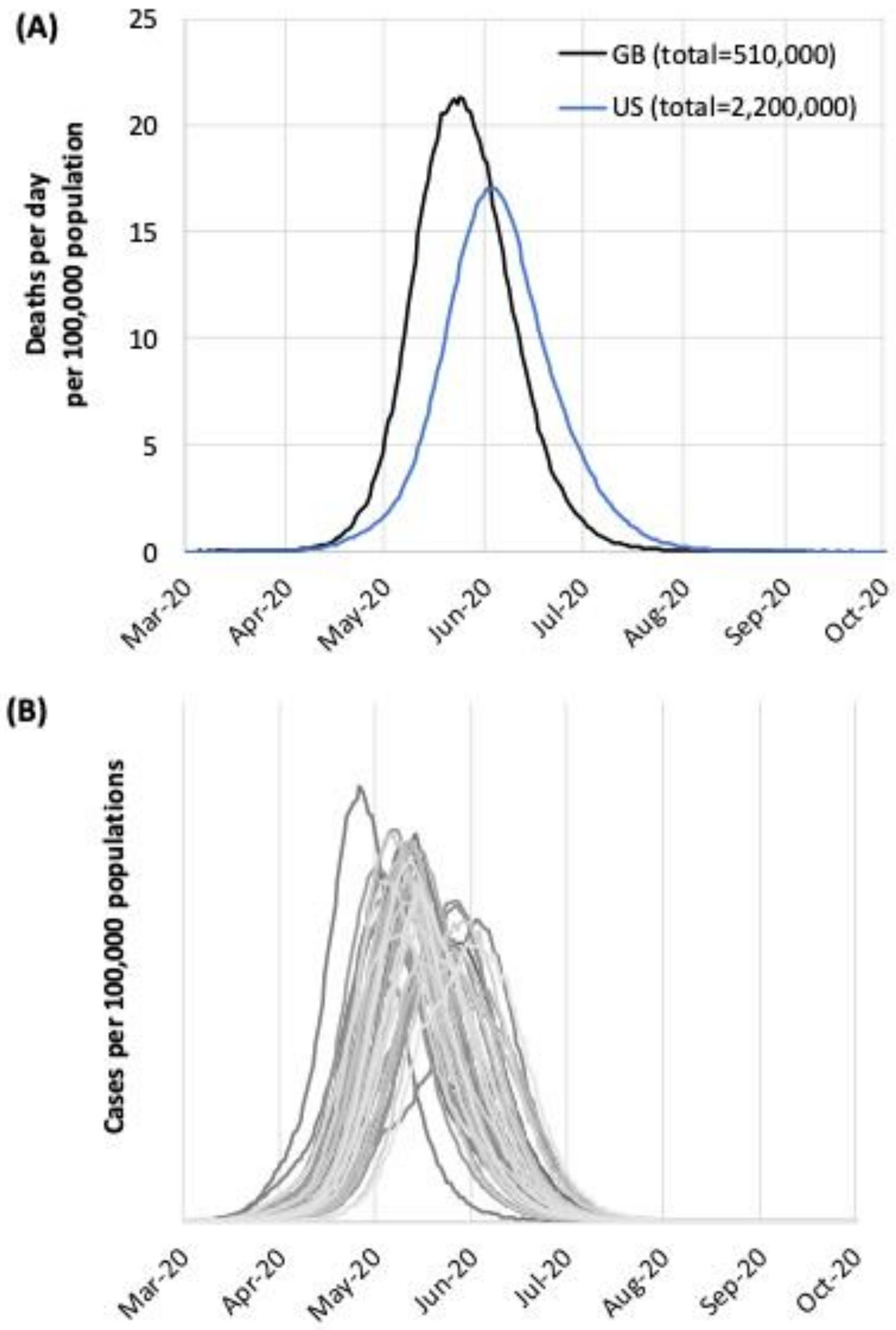
https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html



COVID-19, Global 2020—2021

- Understanding immunity, vaccination, and long-term dynamics

Saad-Roy et al. 2020



Ferguson et al. 2020

COVID-19, Global 2020—2021

- Questions around severity of control and which controls to implement
- Test the impacts of different control scenarios

Figure 1: Unmitigated epidemic scenarios for GB and the US.

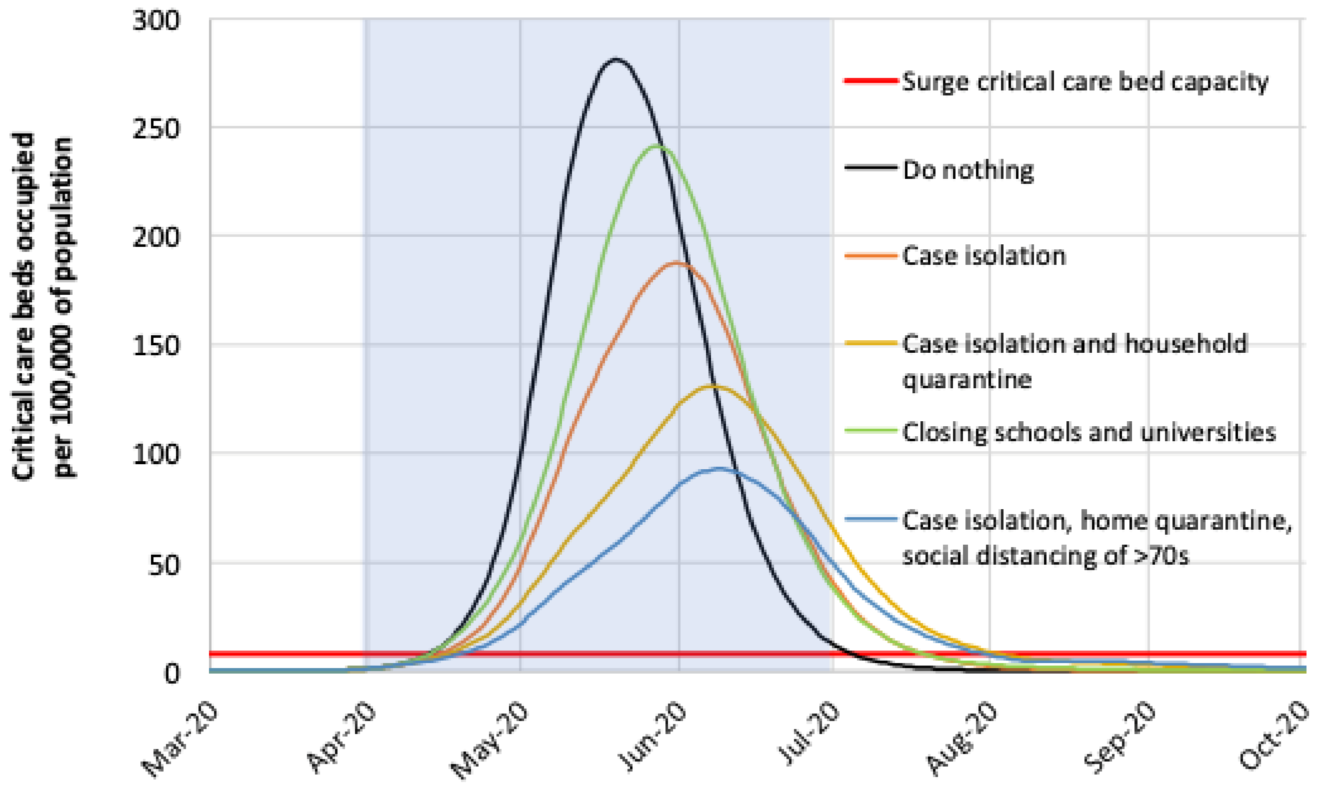


Figure 2: Mitigation strategy scenarios for GB showing critical care (ICU) bed requirements. The black line shows the unmitigated epidemic. The green line shows a mitigation strategy incorporating closure of schools and universities; orange line shows case isolation; yellow line shows case isolation and household quarantine; and the blue line shows case isolation, home quarantine and social distancing of those aged over 70. The blue shading shows the 3-month period in which these interventions are assumed to remain in place.

COVID-19, Global 2020—2021

- Questions around severity of control and which controls to implement
- Test the impacts of different control scenarios

Ferguson et al. 2020

“All models are wrong, but some are useful.”

-George Box

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