Disease detectives: how maths can help us against disease outbreaks

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https://tinyurl.com/warwickCOVID

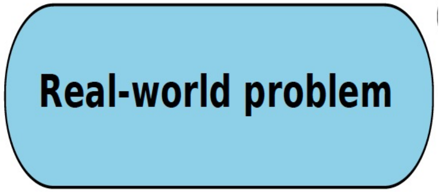
What are models?

Why use models?

What can models be used to estimate?

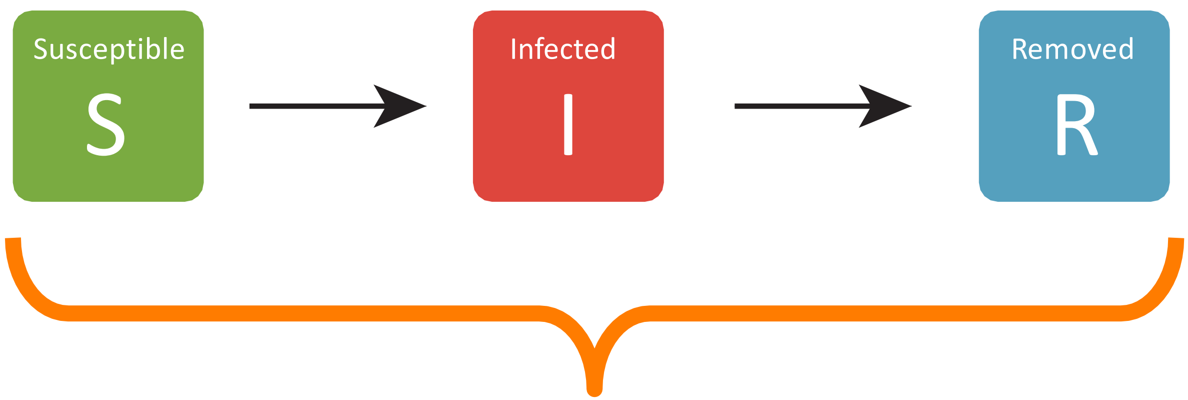
Decision making in uncertain times

What are models?



Infectious disease models

Example: SIR model



The population can be split into groups, which are referred to as 'compartments' or ‘disease states'

Infectious disease models

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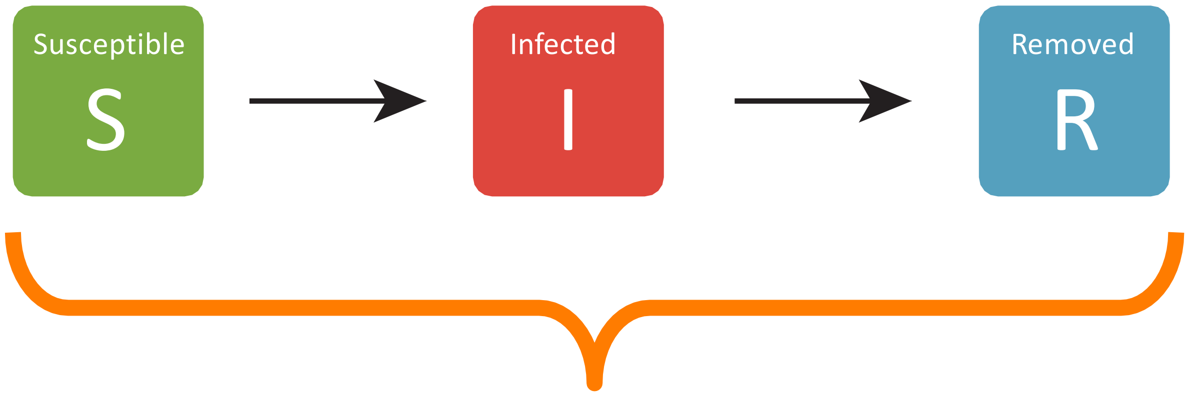

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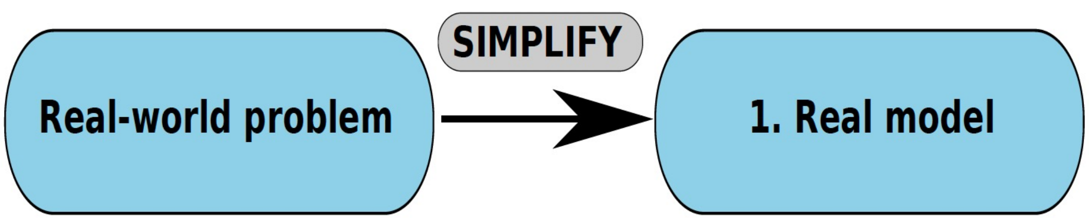

Infectious disease models

Choice of states depends on the disease

Examples: measles, rinderpest, rabies

Examples: influenza, STIs such as chlamydia

..and other groups may be included as required (e.g. groups by age, risk, vaccination)

Infectious disease models

Example: SIR model

Use mathematical equations to track:

- **how much of the population is in each group**
- the amount that move from one state to another

Infectious disease models

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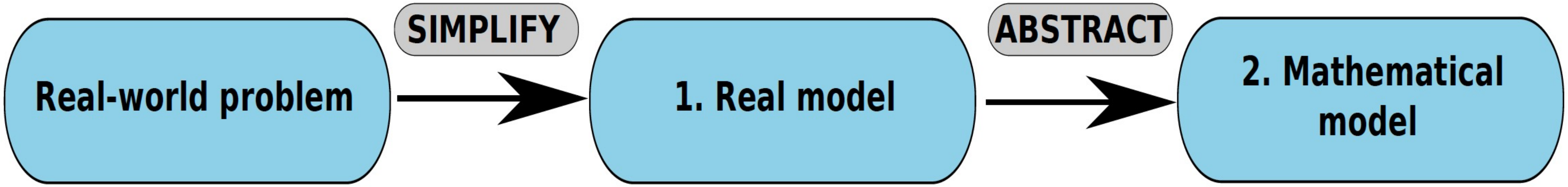
What are models?

A mathematical representation of a process
(such as disease spread)



Why use models?

Why use models?

To gather knowledge about the biological system

- Use different models to understand what transmission processes are most likely;
- Check whether the model includes all necessary biological features.

How are estimates made?

Model fitting: The process of estimating parameters from data

Important caveats!

- Limited by the available data and the models' outputs are only as good as the quality of the data that goes into them.

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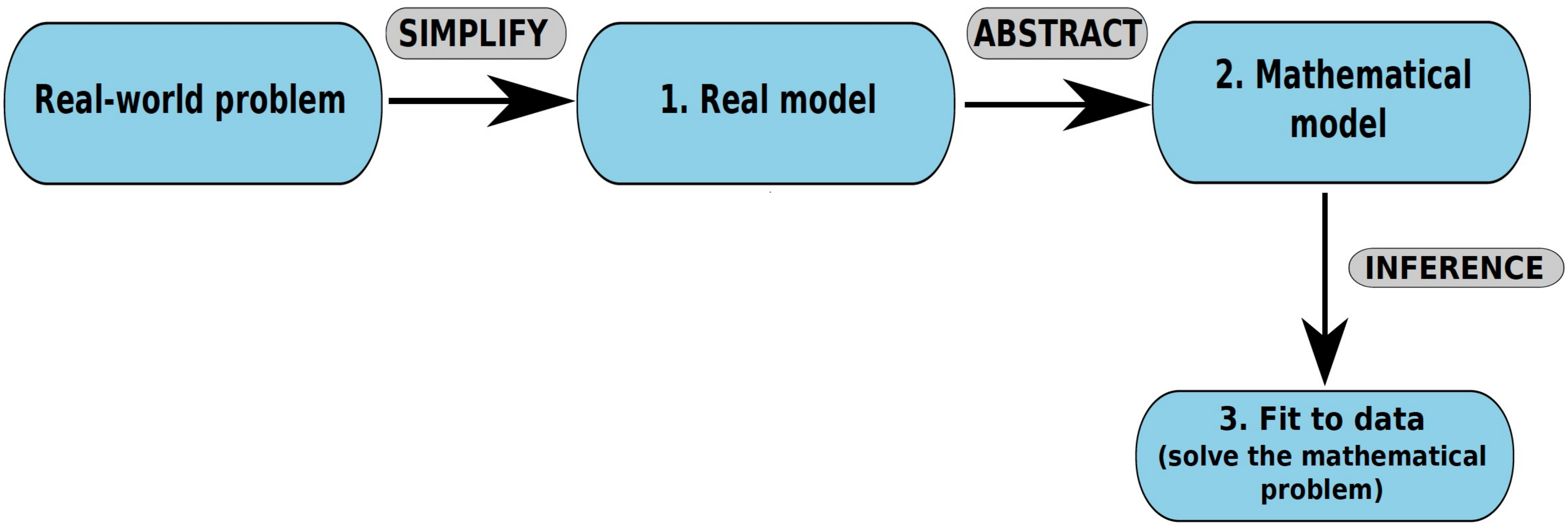


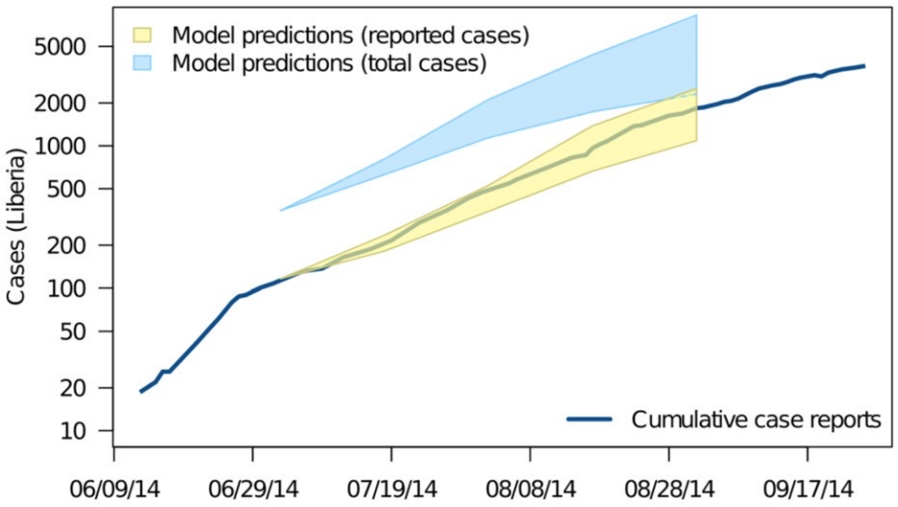
Why use models?

To produce estimates and/or make predictions

- Analyse disease burden in the future, given what has already occurred;
- Predict population size;
- Assess control interventions.

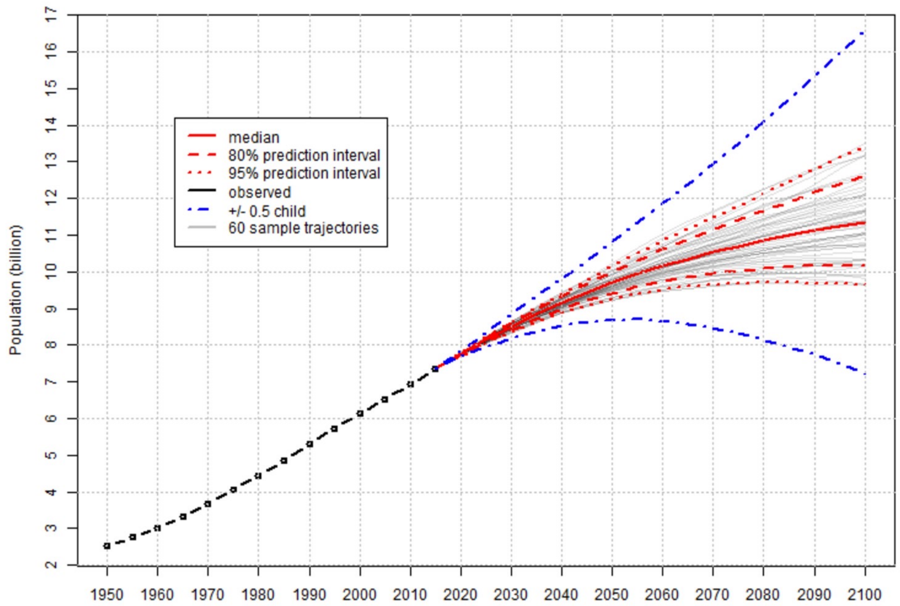
Projections of Ebola cases in Liberia in 2014

Drake et al. (2015) PLOS Biology



UN projections of world population size till 2100

https://esa.un.org/unpd/wpp/



What can models be used to estimate?

R_0

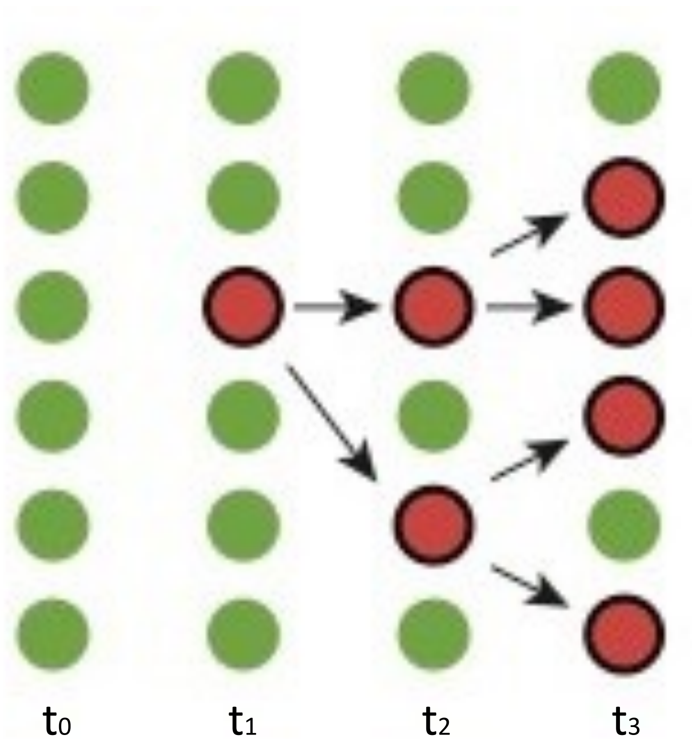
the expected number of secondary infections produced by a single infectious individual ***in an otherwise susceptible population***

- The 'basic reproductive number (ratio)'
- a measure of **initial spread** of a pathogen

$$R_0 = \text{Transmission rate} \times \text{Infectious period}$$

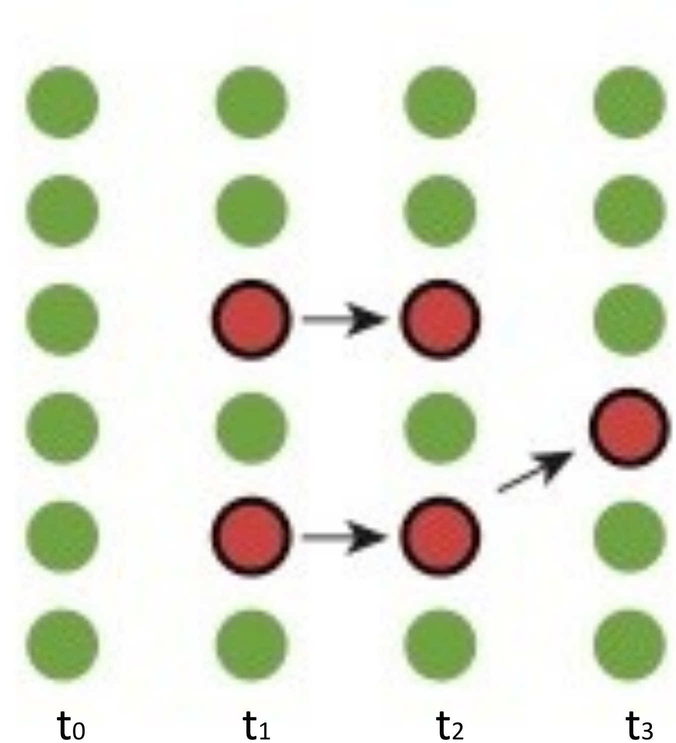
What can models be used to estimate?

$R_0 > 1$



Outbreak takes--off

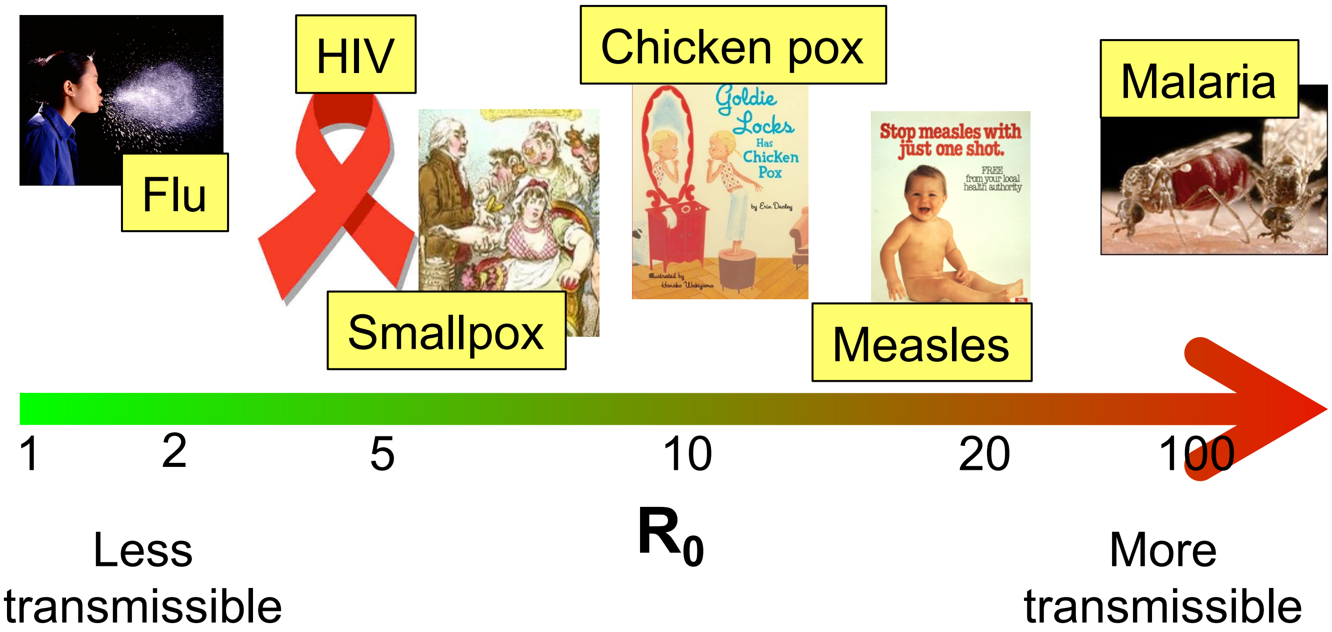
$R_0 < 1$



Outbreak dies out

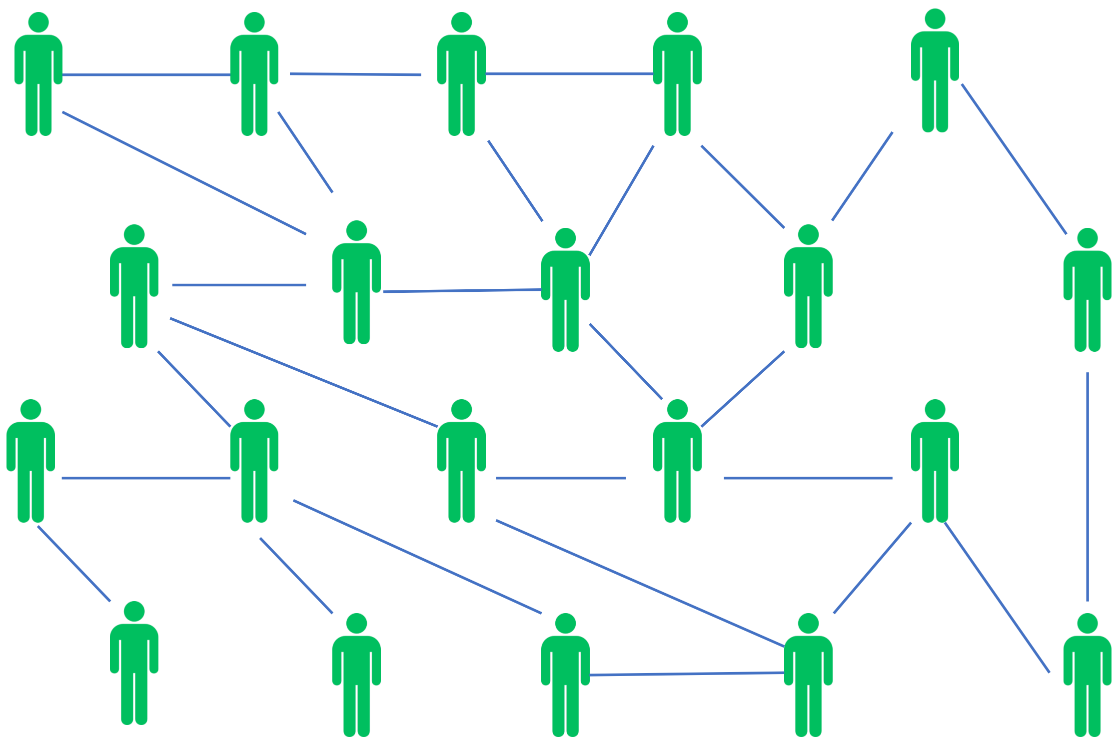
What can models be used to estimate?

R_0 in the real world



Audience activity

Reality of disease spread



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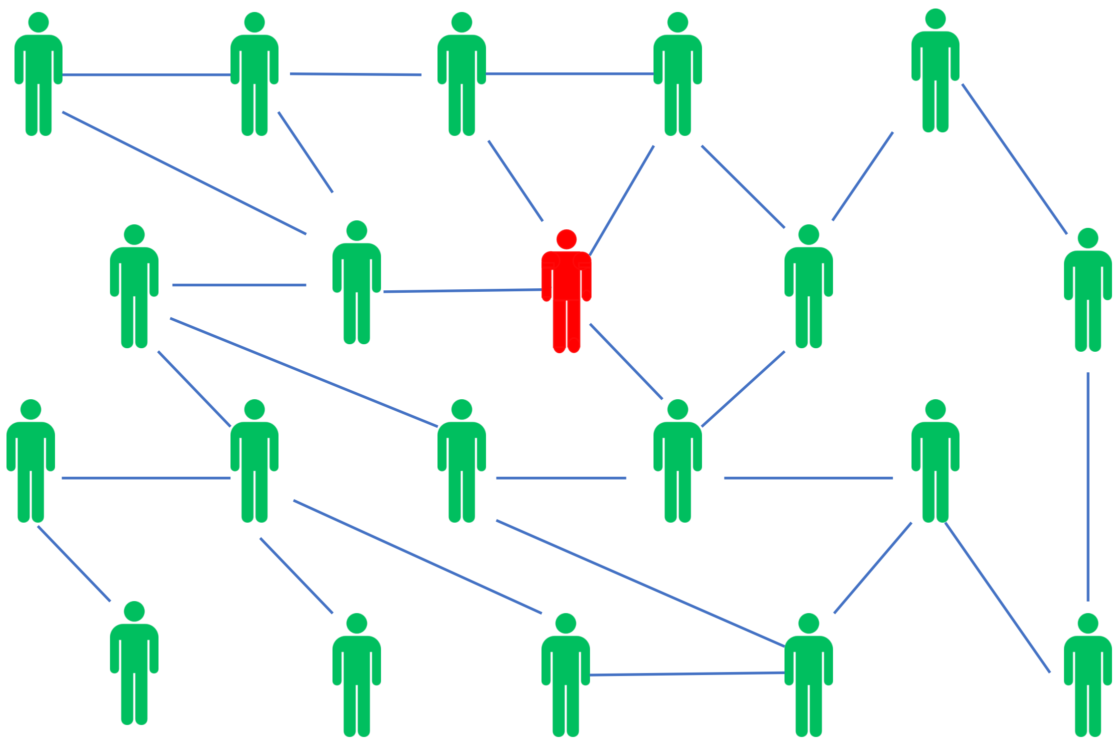

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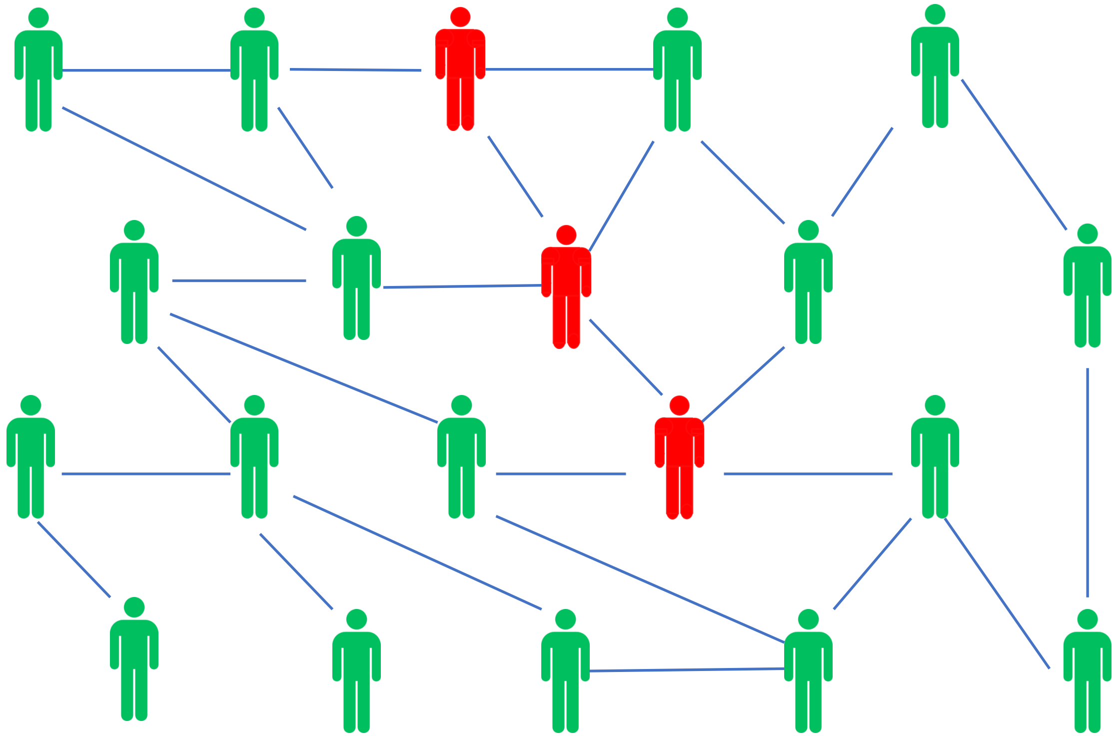

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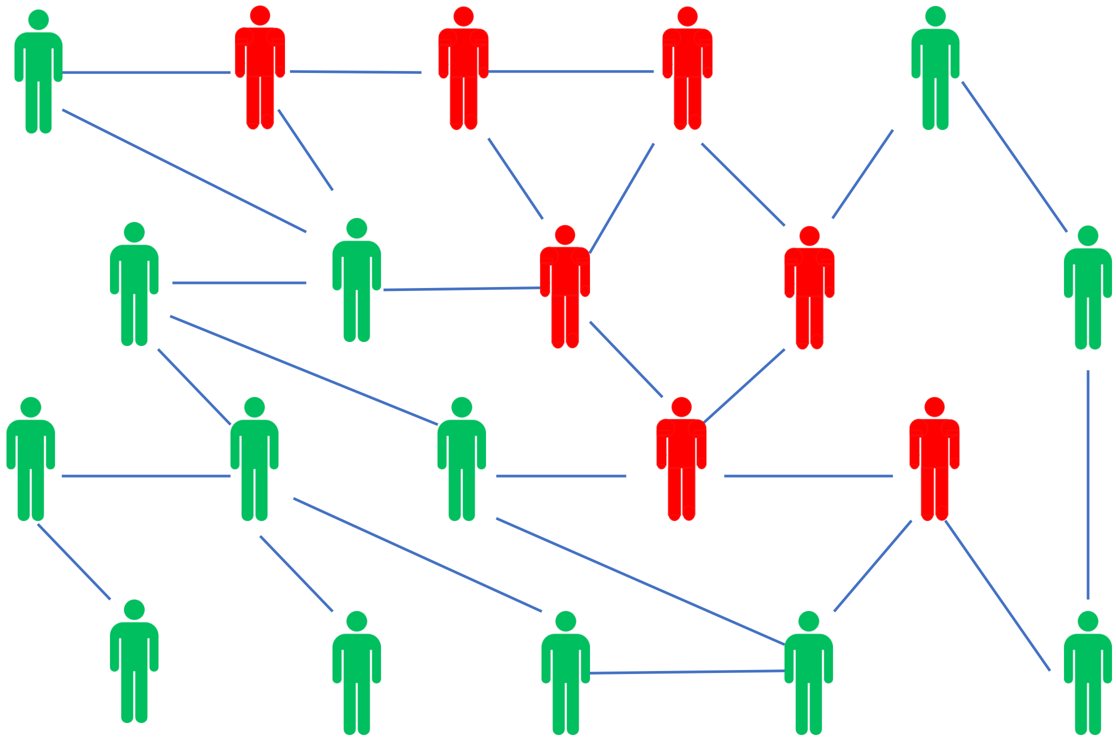

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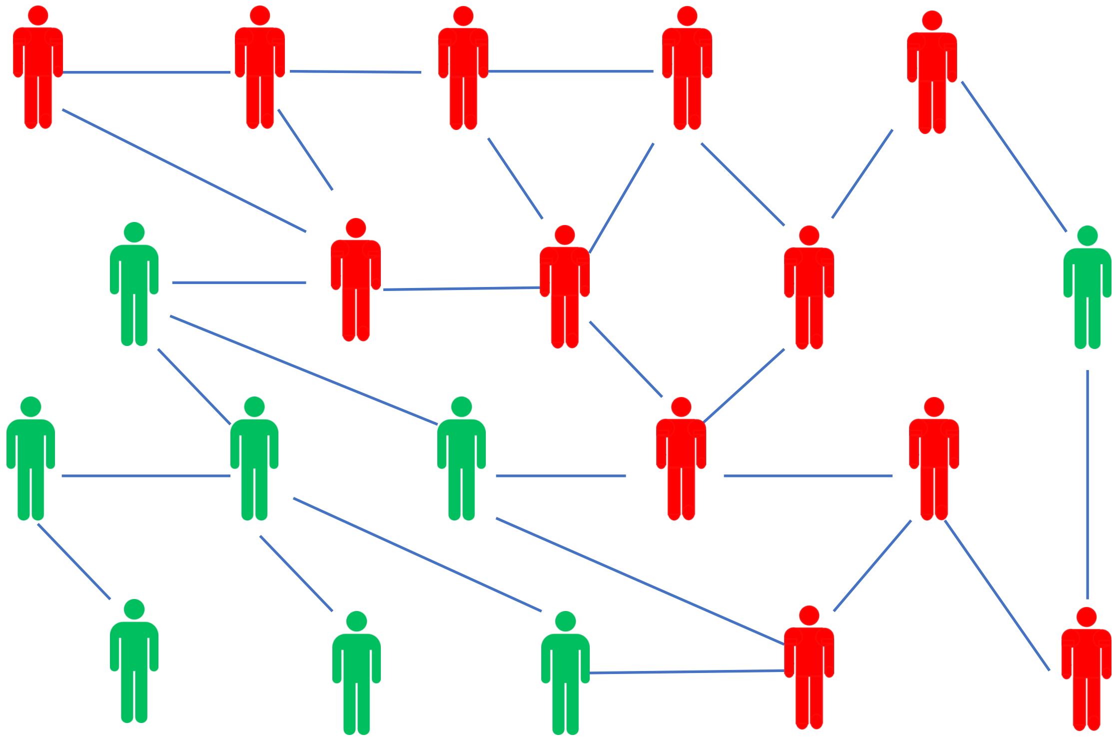

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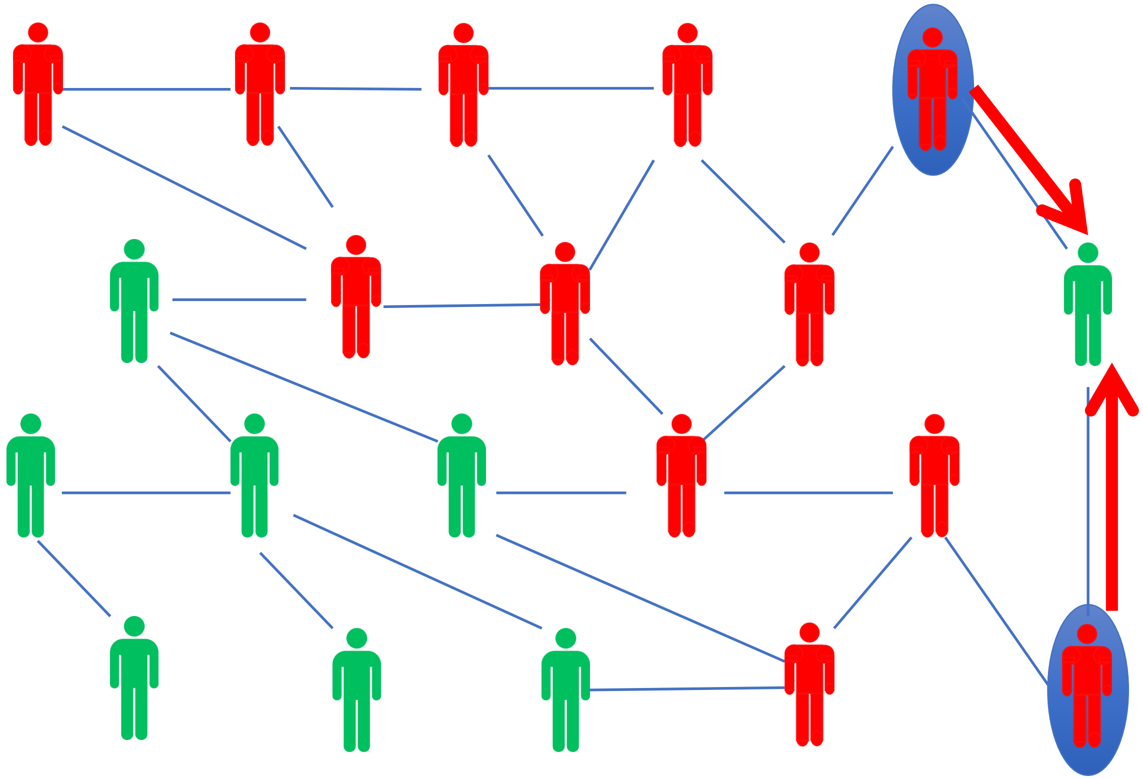


- So R_0 only really has any meaning at the start of an outbreak, when everyone is susceptible.

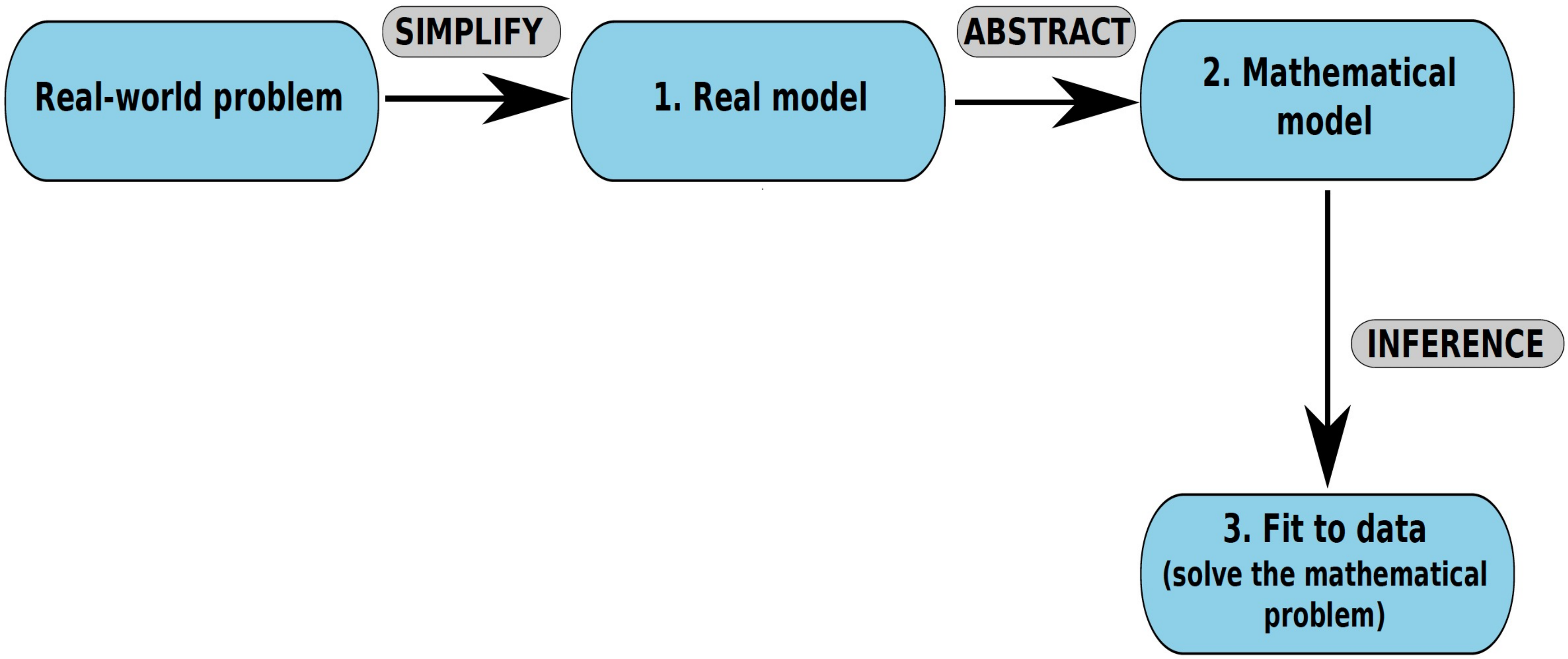
What can models be used to estimate?

R (or R_t)

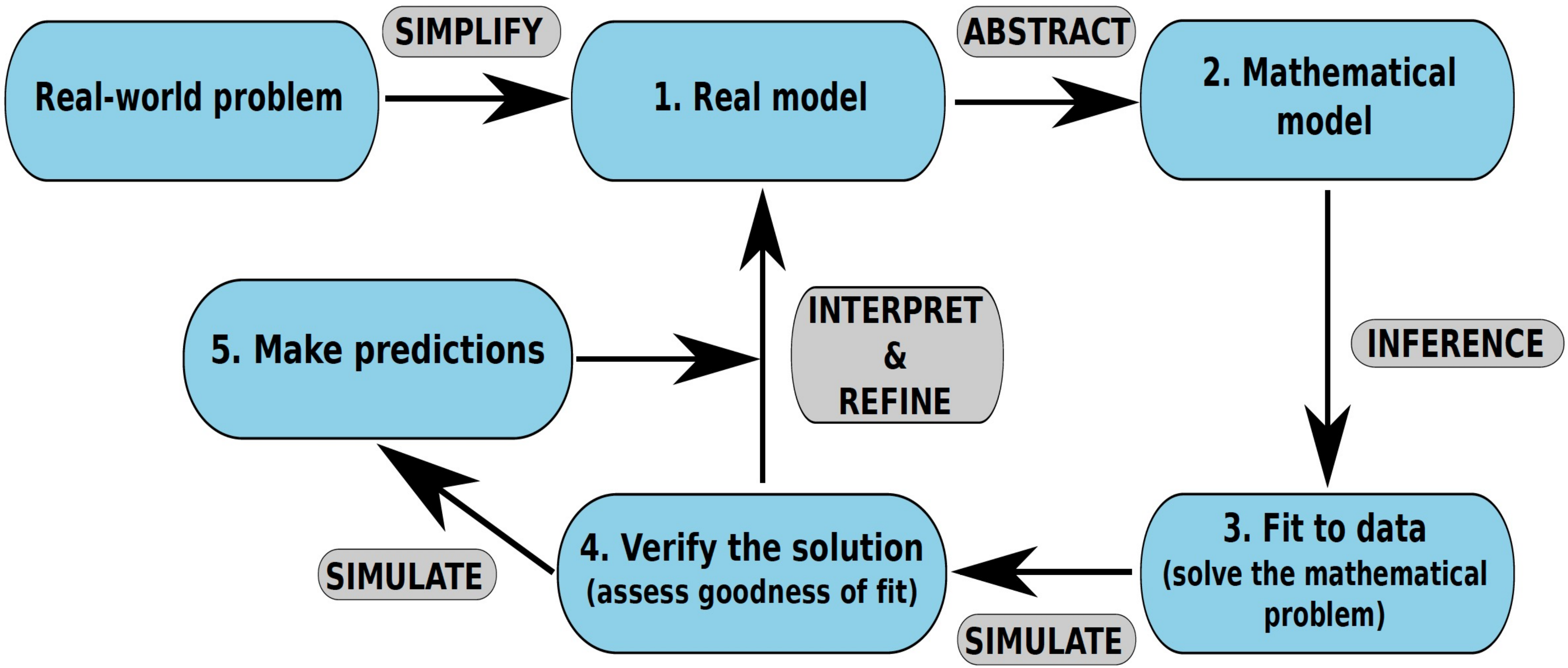
the number of people each currently infected person, on average, passes infection onto

- The effective reproduction number
- a measure of **current potential of pathogen spread** of a pathogen

Modelling cycle



Modelling cycle



What can models be used to estimate?

- Note of caution: **The R number is only a single measure** and so cannot be used as a sole indicator of the current threat posed by an epidemic.

What other information may we want to know about?

What can models be used to estimate?

- Note of caution: **The R number is only a single measure** and so cannot be used as a sole indicator of the current threat posed by an epidemic.
    - the rate of occurrence of new infections (incidence rate)
    - the prevalence of infection across communities
    - the current burden faced by the healthcare system (e.g. ICU occupancy)

What is our objective?

In the event of an outbreak of infectious disease, policy makers usually want the answer to one specific question

What should we do?

~~What should we have done?~~

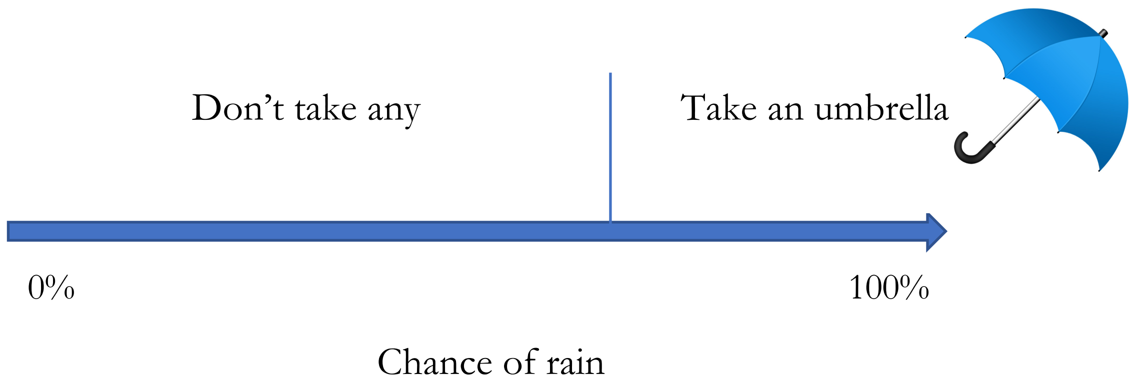
Retrospective analysis → Prediction

Example: A rainy day?

What wet weather gear should I take today?

It depends!

On what?



Example: A rainy day?

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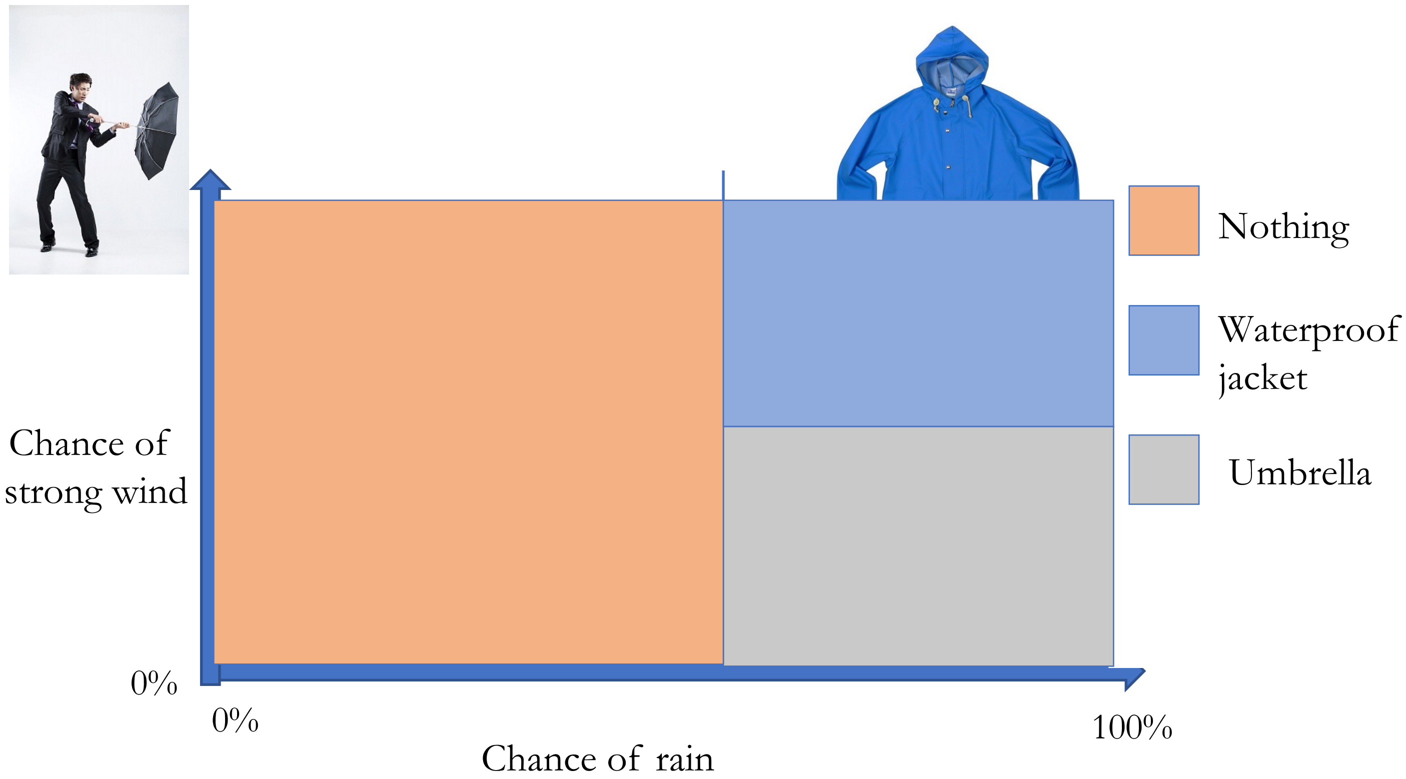


What is our objective?

In this simple example, we may think that the objective is not to get wet.

However, uncertainty in whether it is going to rain means we also have to consider:

- Will we get cold?
- Will we have to carry an umbrella or a raincoat all day?

So our ***objective function*** that influences our decision may be to minimise the risk across all of this potential impacts.

Decision making & uncertainty

Day 1 of a foot-and-mouth disease outbreak

Useful Cumbria facts

- 8000 farms, high density farming region
- 892 farms infected in 2001
- 3000 farms had their livestock culled
- Vaccination was not used in 2001

Choice A
Just cull animals on infected and "high risk" farms

Choice B
Same as A but also vaccinate all farms within 10km of infected farms

Decision making & uncertainty

Day 1 of a foot-and-mouth disease outbreak

Useful Vaccination facts

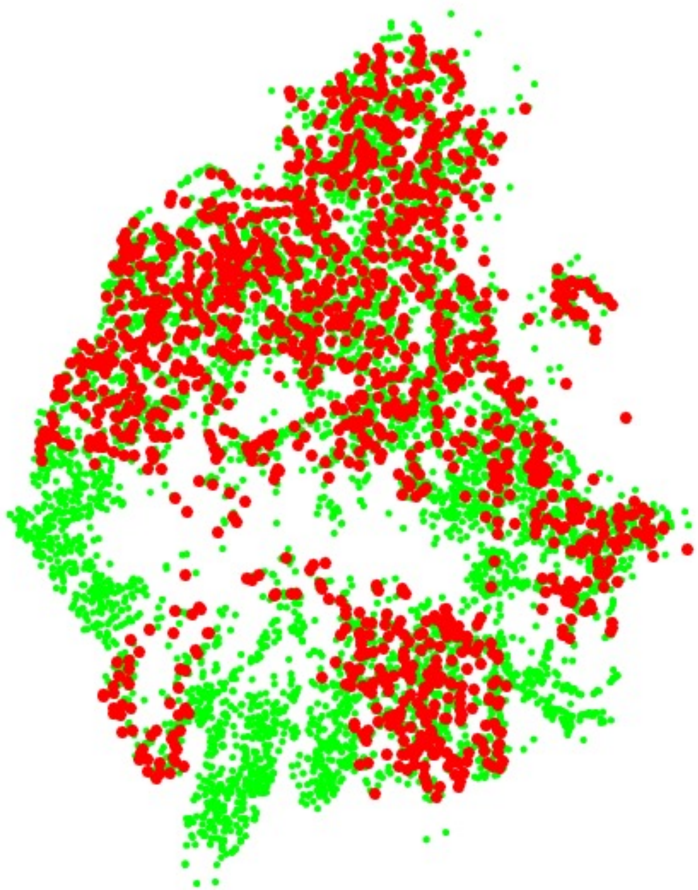
- If vaccination is used anywhere, livestock export ban will be extended from 3 months to 6 months after last farm culled.
- Vaccinated animals can remain susceptible for several days before becoming immune.

<u>Choice A</u>
Just cull animals on infected and "high risk" farms

<u>Choice B</u>
Same as A but also vaccinate all farms within 10km of infected farms

Decision making & uncertainty

Day 121 of the outbreak

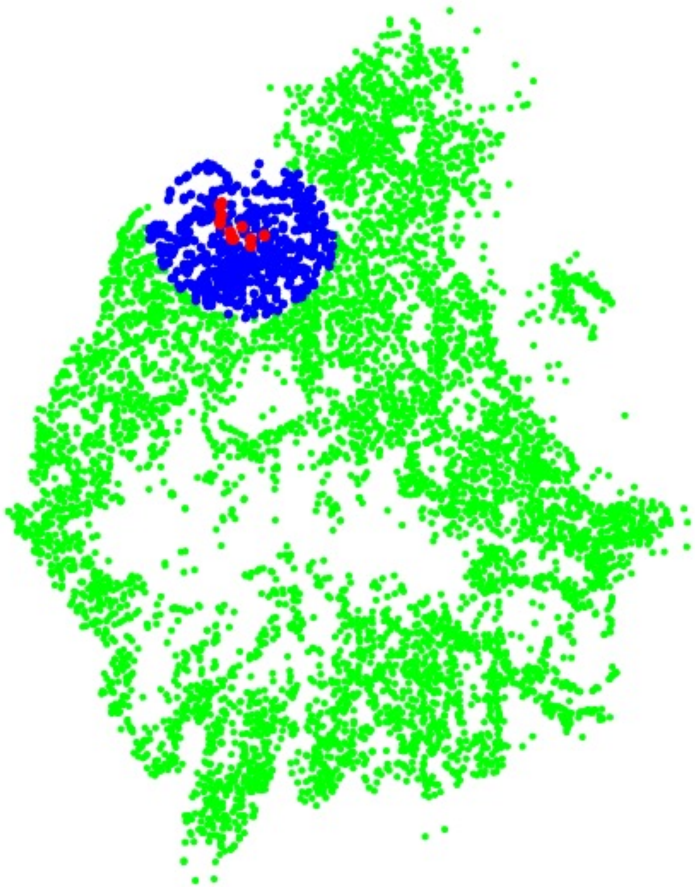


- 1231 infected/culled farms.
- Outbreak classified as "out of control" and spread to other counties.
- You, the policy makers, are "slammed" in the press.
- The media state that vaccination should have been considered.

What could we have done better?

Decision making & uncertainty

Day 45 of the outbreak



- 28 infected/culled farms
- No spread outside Cumbria
- 1237 vaccinated farms
- You, the policy makers, are “slammed” in the press:
  - The outbreak was small.
  - Vaccination should not have been used.
  - UK now has a lengthy export ban.
  - Supermarkets refuse to accept vaccinated meat.

What could we have done better?

Decision making & uncertainty

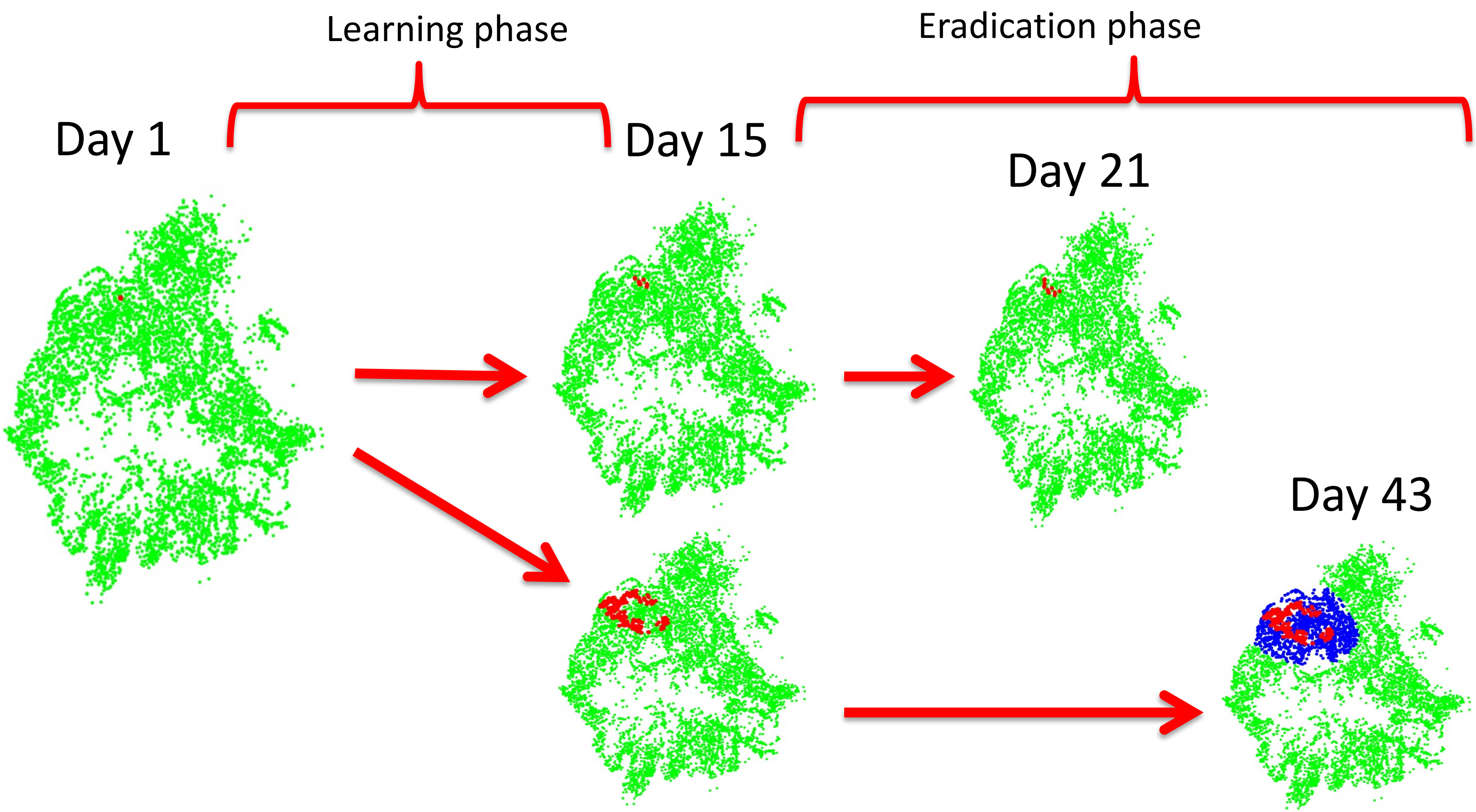
Day 1 of a foot-and-mouth disease outbreak

We're now going to consider an adaptive strategy.

- Make a control decision on day 1.
- Observe the outbreak and "learn" about the behaviour of the epidemic.
- Once uncertainty is sufficiently resolved, "switch" control strategies if necessary.

Decision making & uncertainty

Start with culling – the bet hedging strategy



Decision making & uncertainty

By managing an epidemic adaptively, we can reduce the overall “cost” of an outbreak.

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Acknowledgements

UK Research and Innovation

JUNIPER

https://maths.org/juniper/ @JuniperConsort1

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https://warwick.ac.uk/fac/cross_fac/zeeman_institute/ @WarwickSBIDER

Webpages:
https://edmhill.github.io;
https://warwick.ac.uk/fac/sci/lifesci/people/mtildesley/

Contact patterns & human behaviour

- To understand how a disease may spread in the human population, we need to have a good understanding of human behaviour.
- Of course, it is impossible to know exactly who contacts whom and the risk of disease spread.
- So we need a way to approximate contact behaviour to provide data for mathematical models.
- One way to do this is to use ***contact networks***.

The Warwick Contact Survey

- In the 1990s, academics at Warwick University kept a diary over the summer of everyone they came into contact with.
- At the end of the experiment, all participants and their contacts were built into a network, to highlight the risk of a disease spreading in the population.
- **Some interesting trends emerged…**
- People are clearly not randomly connected and are observed to form into clusters with some "very connected" people.