Intro to infectious disease modeling (in R)

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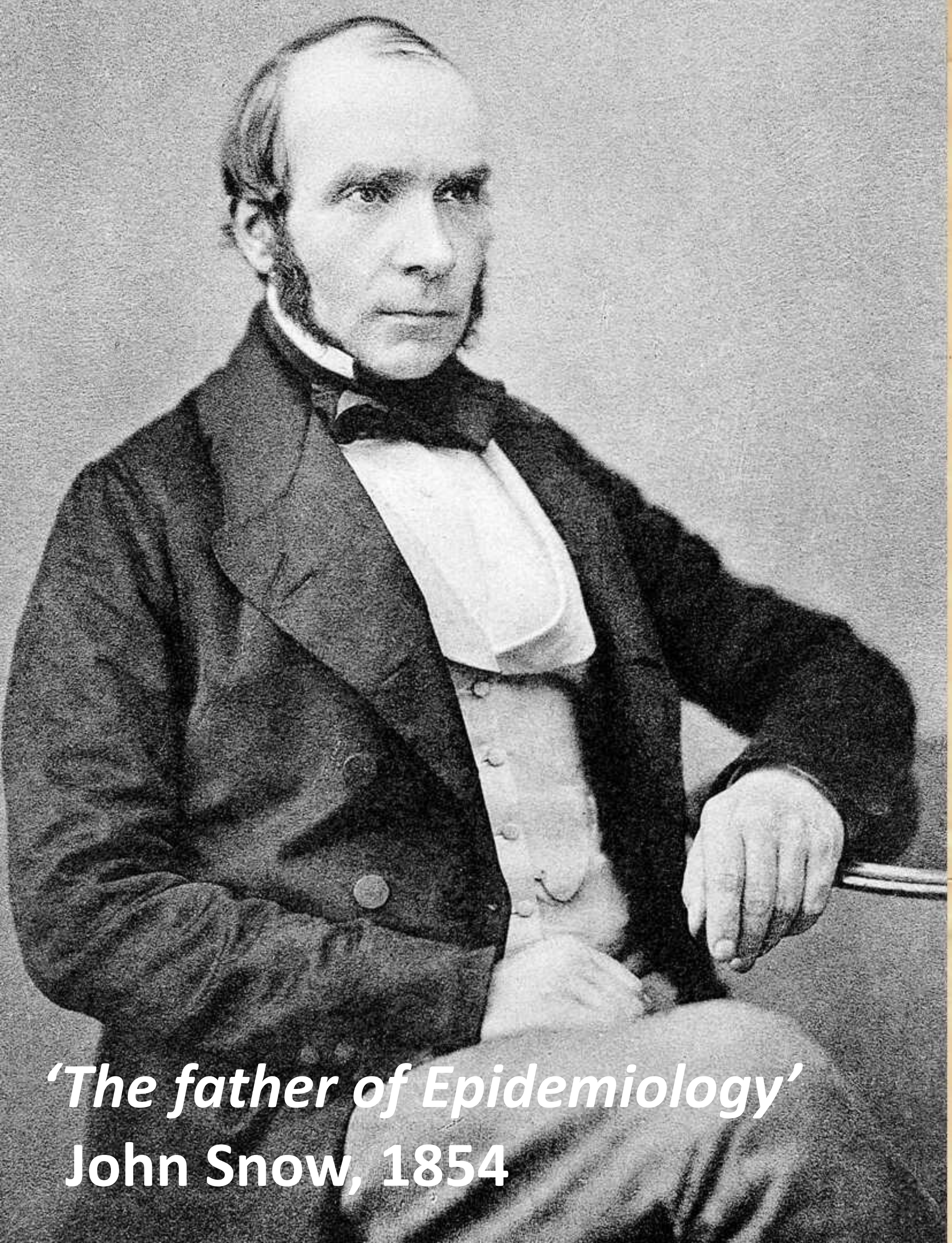
All materials at: github.com/SineadMorris/trainings

Objectives

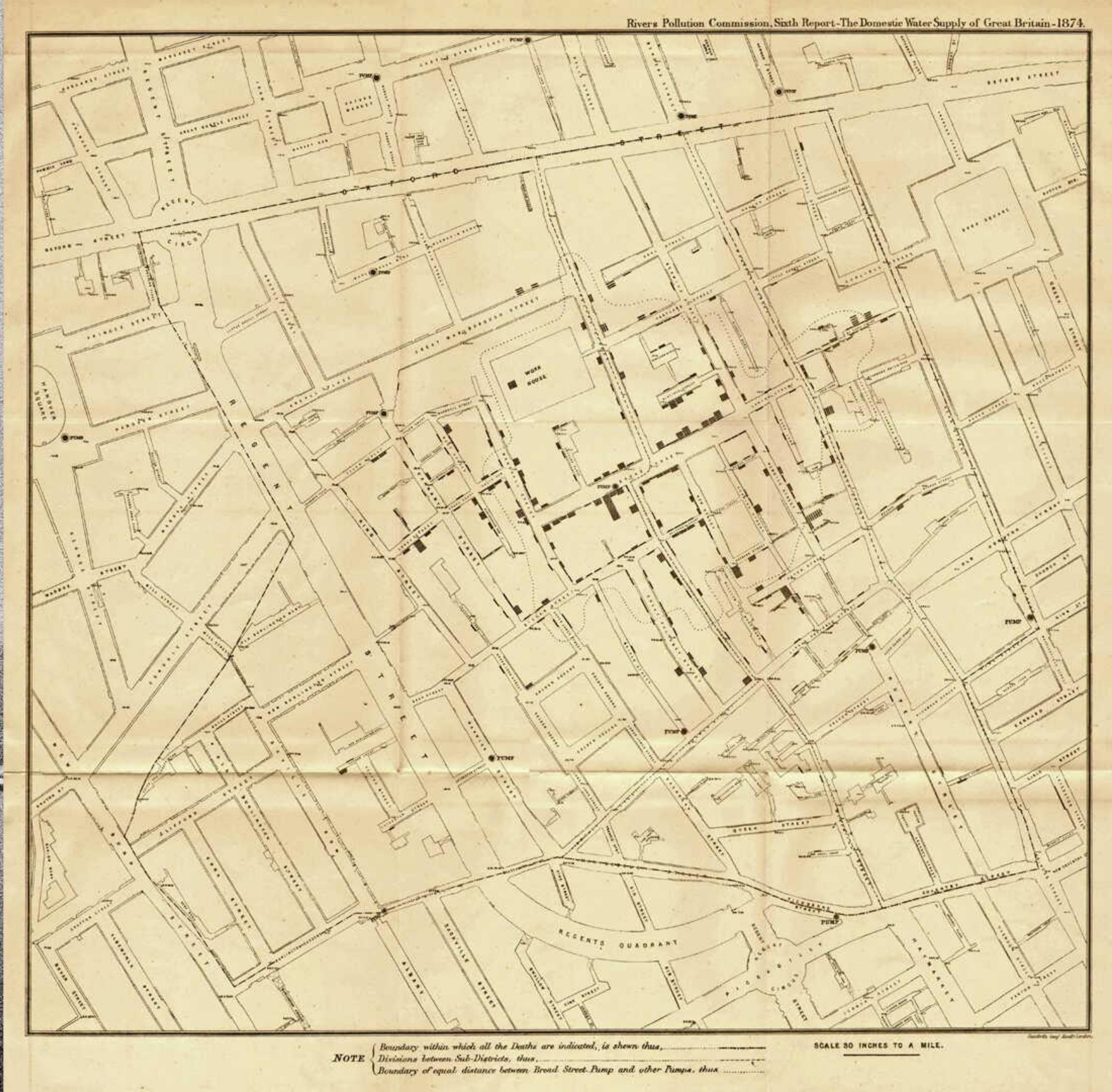
- Background & practical concepts
- Construct a simple disease model: SIR example
- Extend this model to fit a particular need
- Code a model in R
- Time for Qs & additional resources

Background & practical concepts



‘The father of Epidemiology’

John Snow, 1854



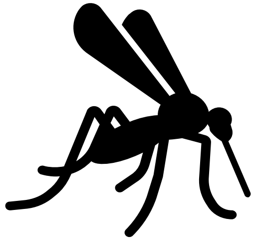
The parents of Infectious Disease Modeling

Hilda
Hudson

Ronald
Ross

Anderson
McKendrick

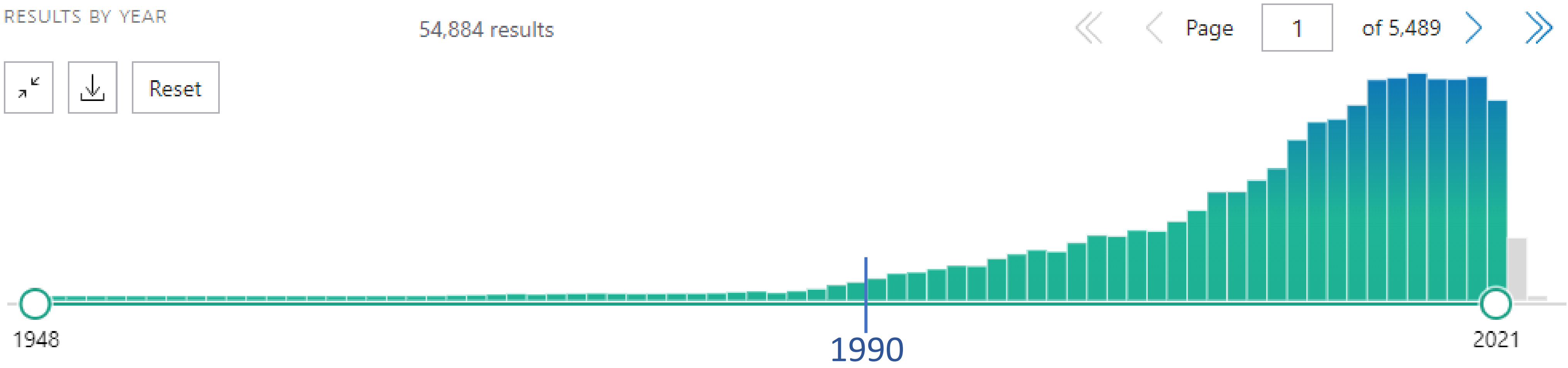
William
Kermack



1915-17

1927-33

Since the 1980/90s the field has been steadily growing



SCIENCE • CORONAVIRUS

What Are Mathematical Models Of Covid-19?

February 4, 2022
9:17 AM EST
Last Updated 6 months ago

United Kingdom

Britain's pandemic modellers say future large waves of COVID possible

Mathematical model suggests a clue as to when COVID-19 pandemic will turn into an endemic

CURRENT EVENTS

The Math of Ending the Pandemic: Exponential Growth and Decay

COVID-19

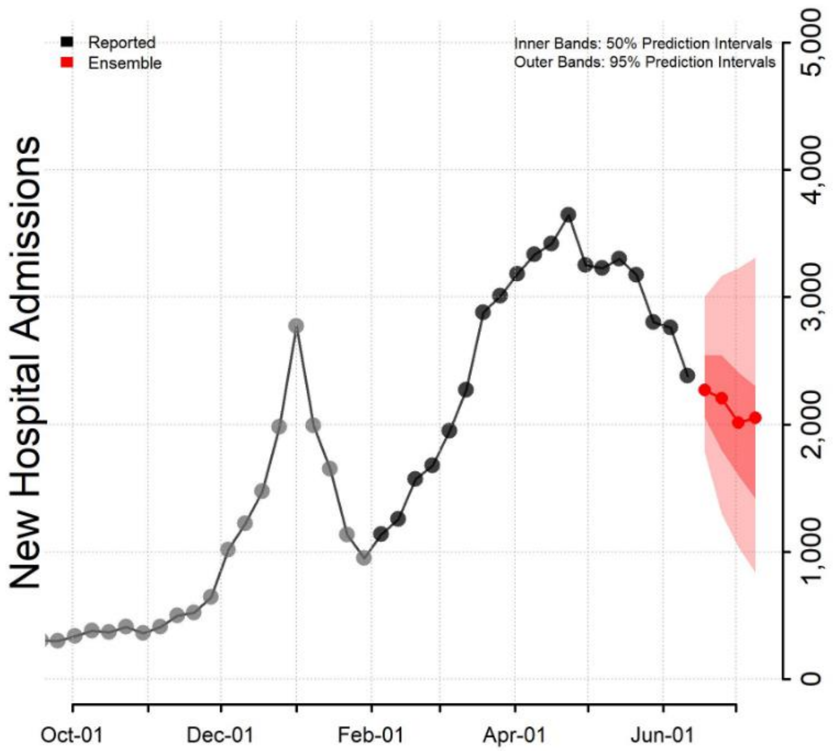
Exponential growth bias: The numerical error behind Covid-19

A model is just a (mathematical) description of how we think a disease spreads

- Forecasting / prediction
- Scenario analysis
- Estimate unknown quantities
- Inference / explaining patterns

Forecasting / prediction

(e.g. how many cases will there be next week?)



Ex: [FluSight Challenge]()

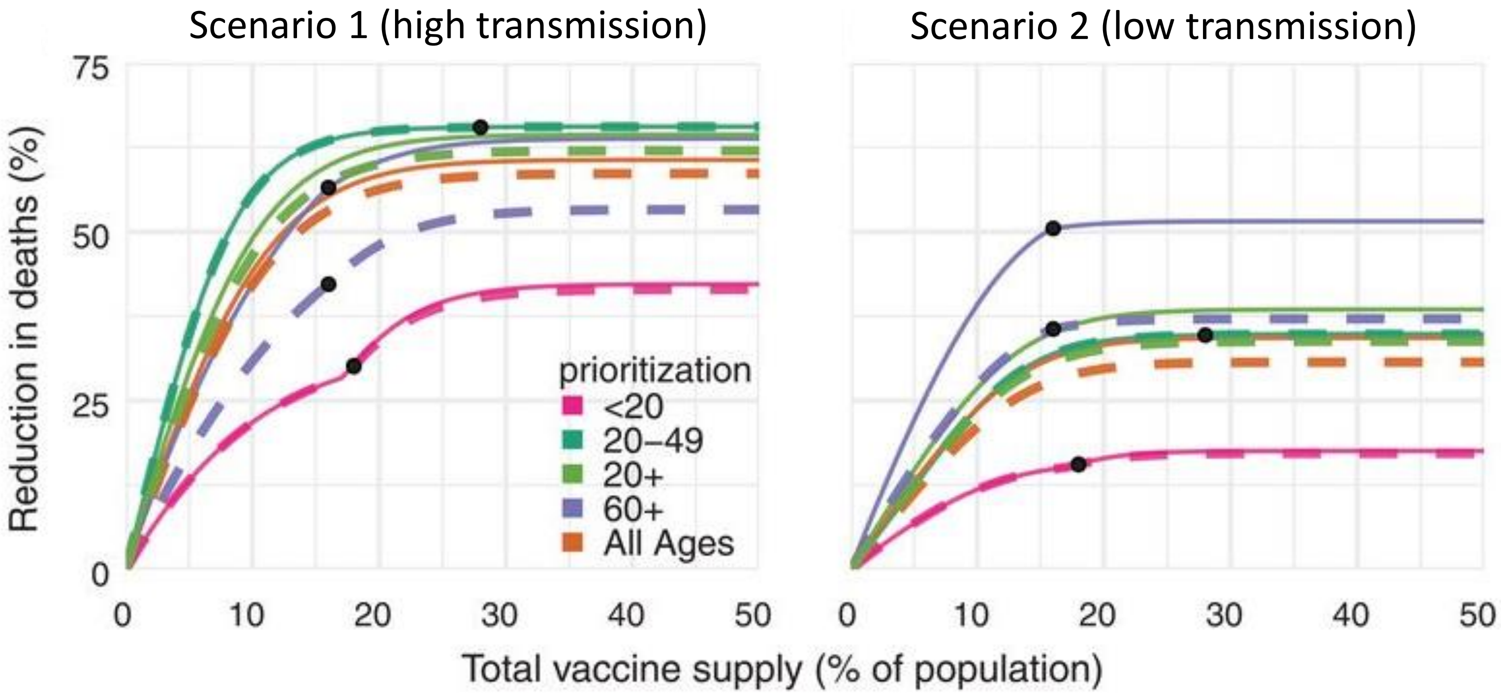
Forecasting flu each season (2013+)

Each week teams predicted hospitalizations 1-4+ wks ahead

Uses include: short-term planning / decision-making

Scenario analysis

(e.g. what ***could happen*** in situation A vs B vs ….?)



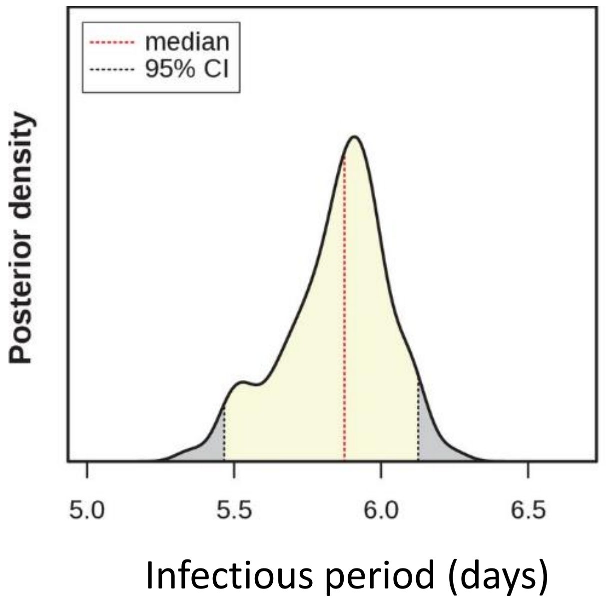
Ex: COVID vax (Bubar et al 2021)

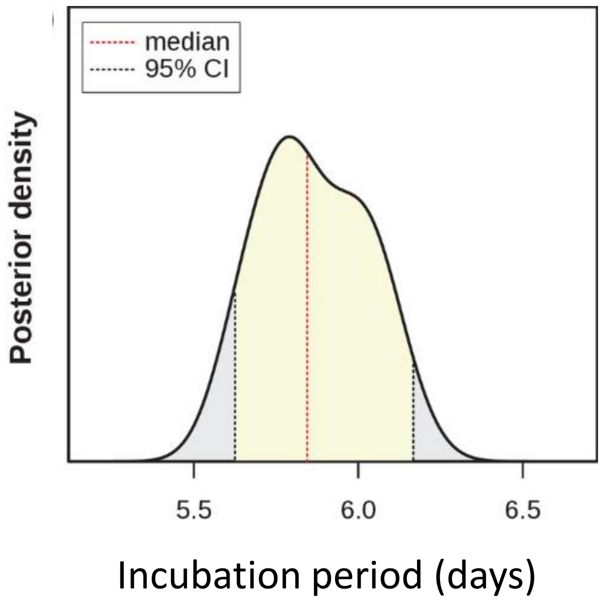
Compare age prioritization
High/low transmission

Uses include:
- explore different hypotheses
- long-term planning / assessment

Estimate unknown quantities

(e.g. what is the infectious period?)





Ex: Zika virus (Lourenco et al 2017)

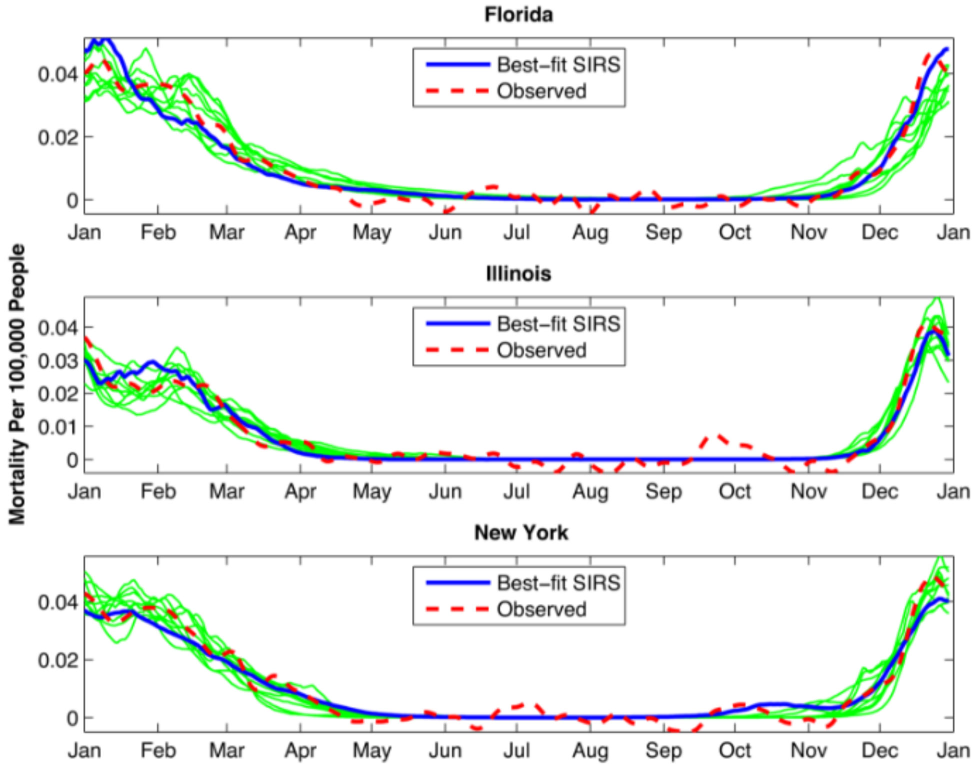
Fit model to case data to estimate parameters

Uses include:

- Understanding disease (e.g. natural history)
- Policy design
- Better inputs for future models

Inference / explaining patterns

(e.g. why are outbreaks seasonal?)



Ex: [Shaman et al (2010)]
Showed that absolute humidity could be one driver of seasonality

Uses include:
- Understanding drivers/mechanisms of spread
- Policy design
- Building more accurate models

Compartmental models

For a particular pathogen / population:

- Define **general health states** that occur during infection progression

  e.g. susceptible, then infected & infectious, then recovered

- Assume **people move through states** at certain rates

- **Transmission equally likely** to occur between anyone ("well-mixed" assumption)

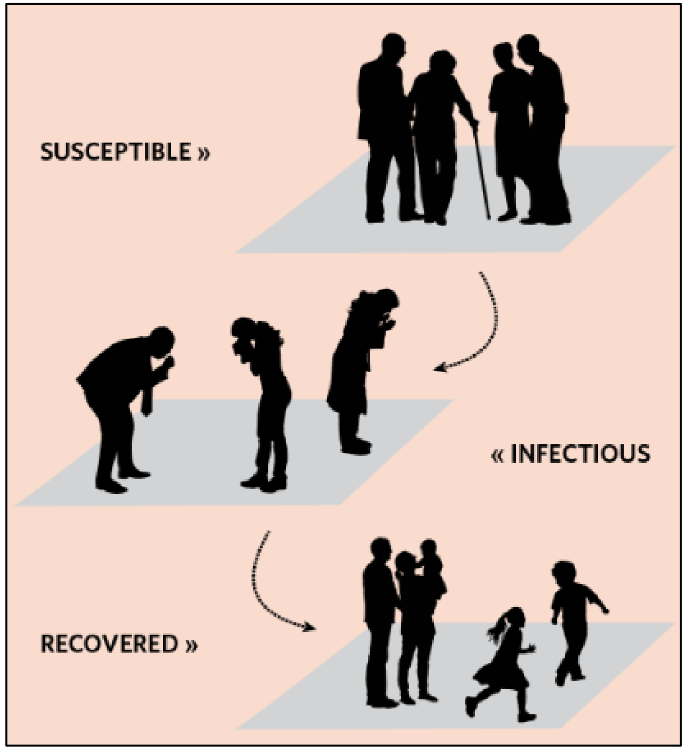


Image source: The Scientist

Basic reproduction number (R_0)

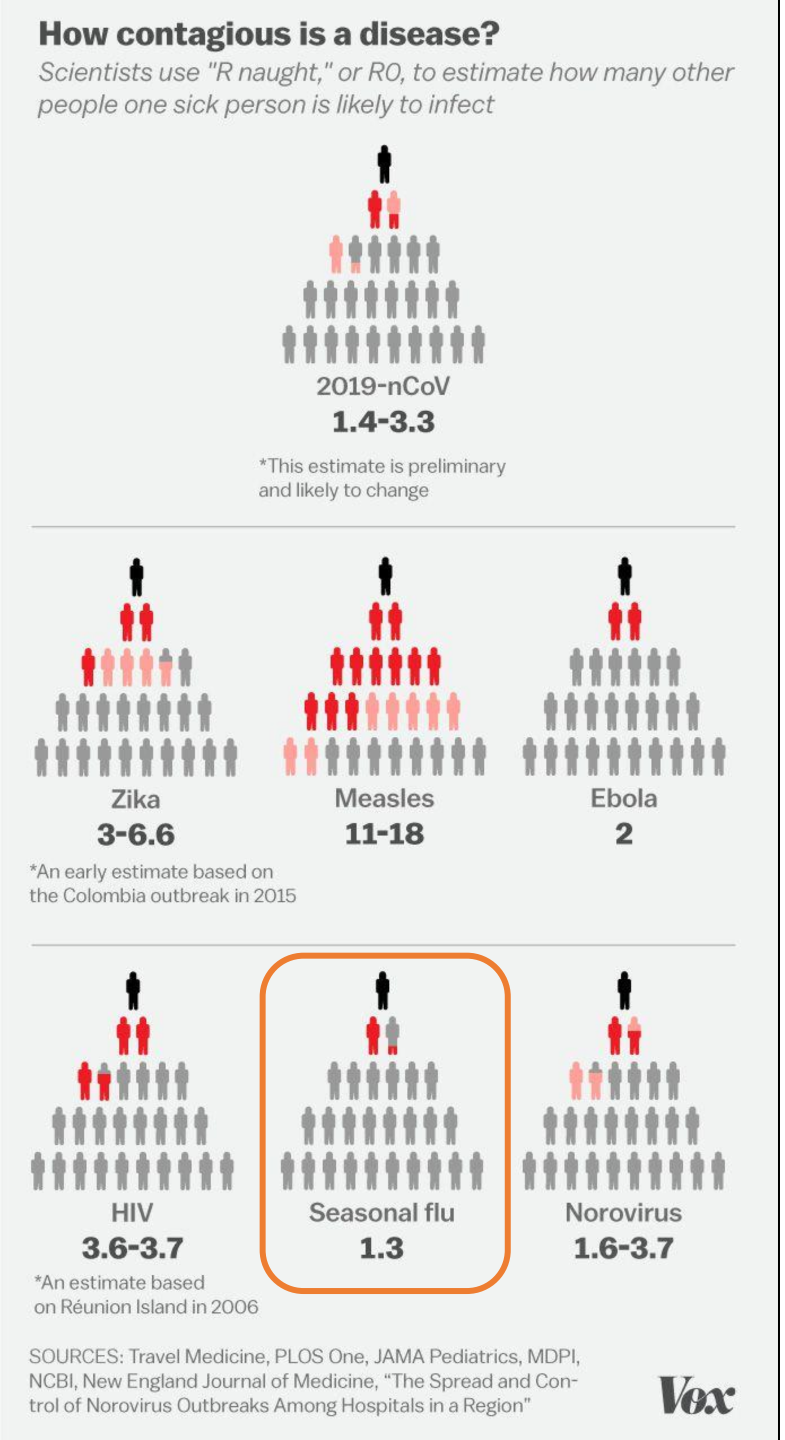
Average # new infections caused by one infected person in a **fully susceptible** population

(# infections / day) per infected person	x	(# days infectious)			
e.g.	1	x	4	=	**4**

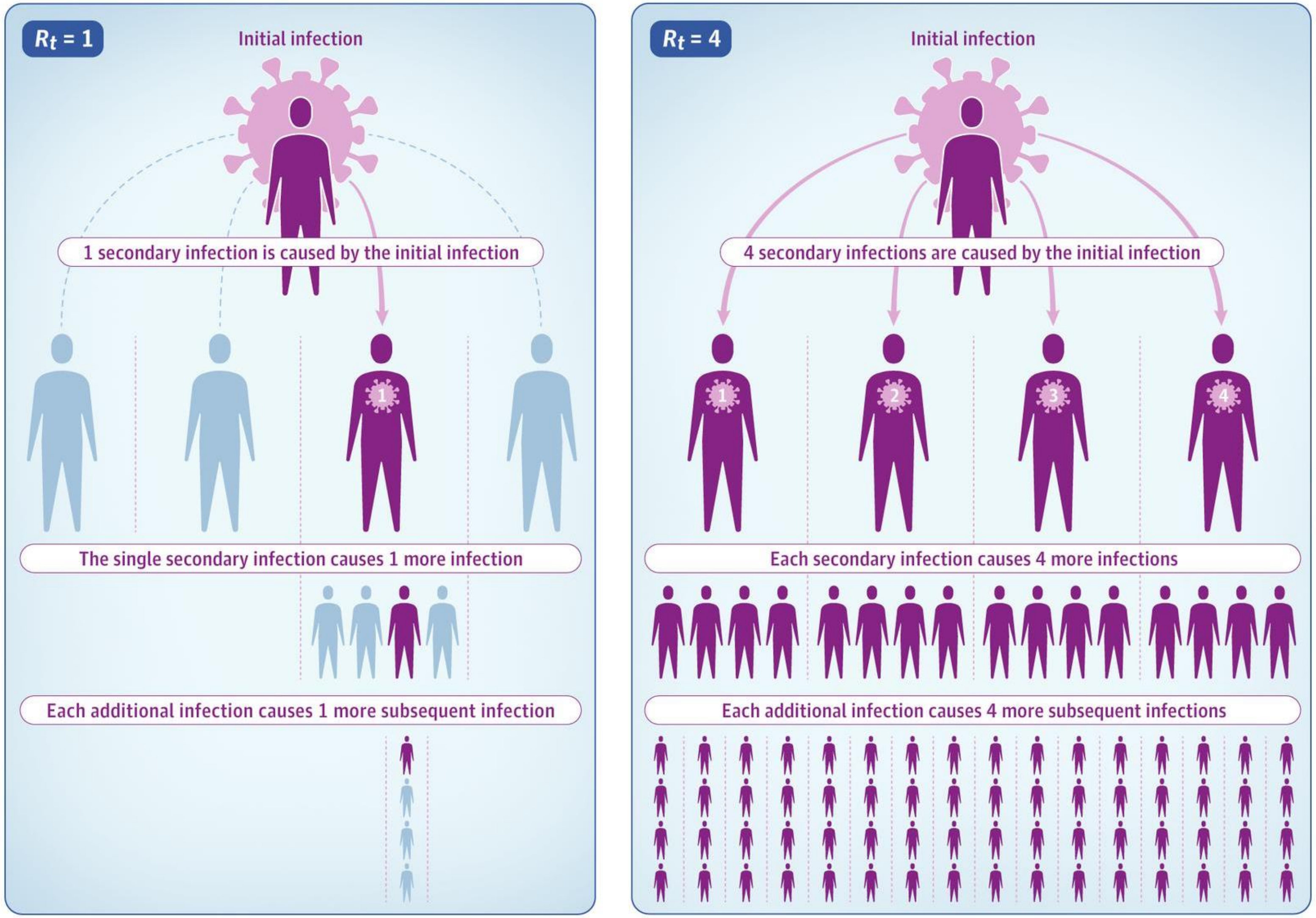
Effective reproduction number (R_t)

Average # new infections caused by one infected person in a **partially susceptible** population

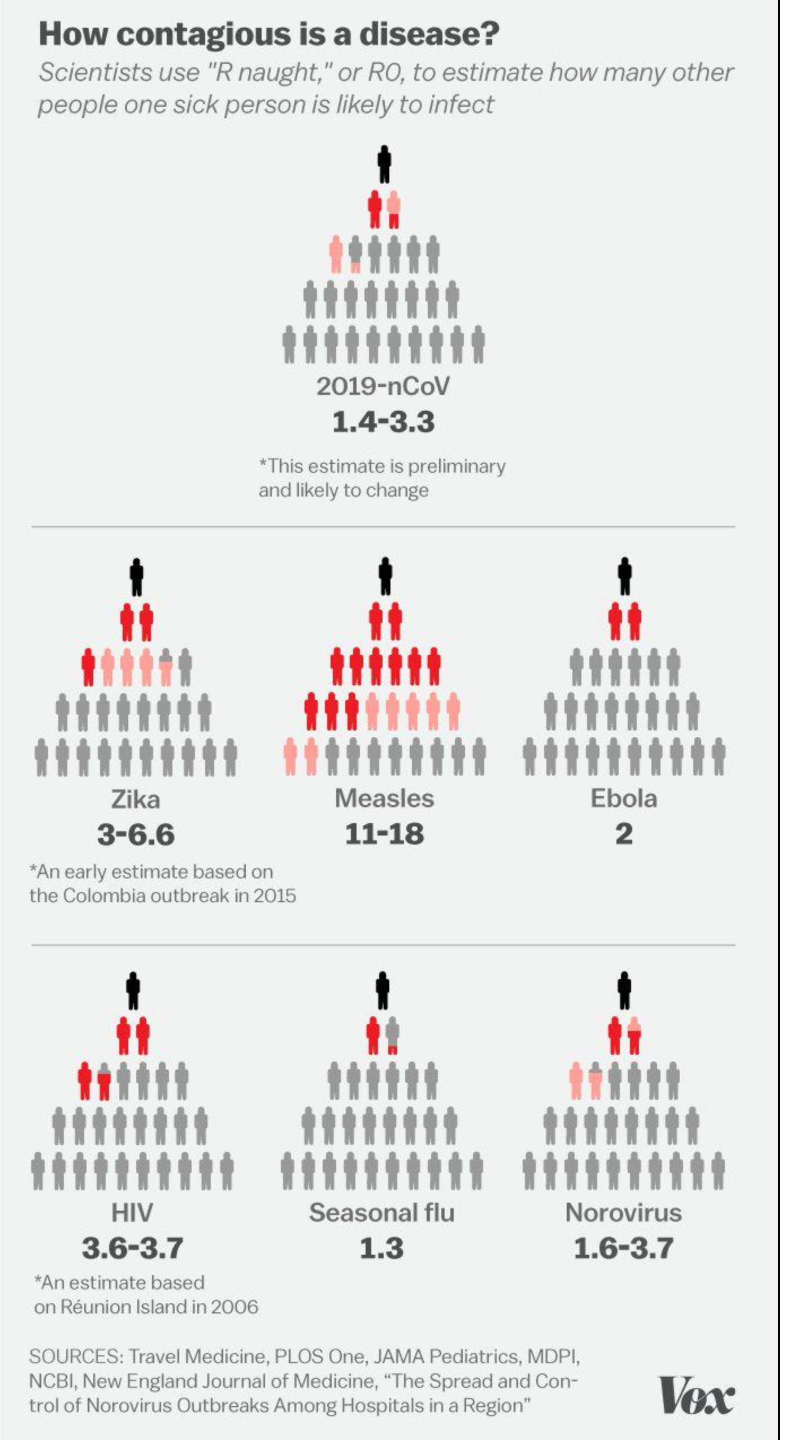
(# infections / day) per infected person	x	(# days infectious)	**x**	**fraction at risk**			
e.g.	1	x	4	**x**	**0.5**	=	**2**



Basic reproduction number (R_0)



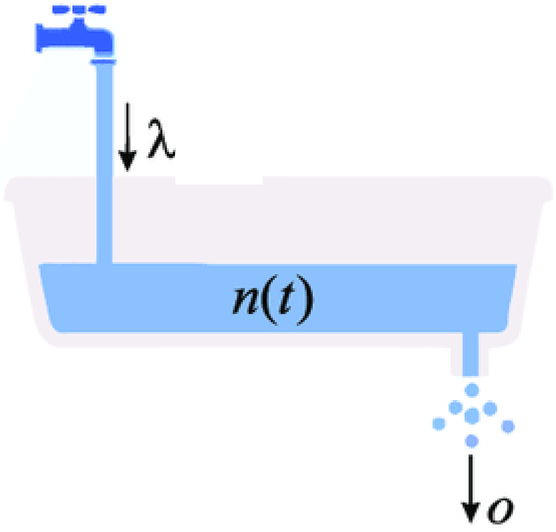
Iceland Monitor



Construct a simple disease model: SIR example

Ordinary differential equations (ODEs)

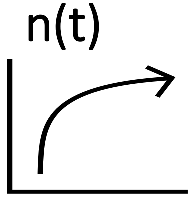
How much water is in the bath?



Need to know:

1. how much we started with, i.e. **n(0)**

2. how it changes over time,
 i.e. how much is flowing in (λ) vs flowing out (o)



$$\frac{dn}{dt} = \lambda - o$$

Change over time = flow in - flow out

Image sources: Aghamohammadi & Laval 2018

Constructing the SIR model

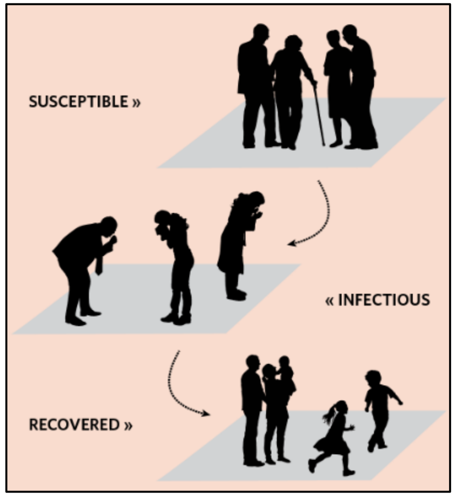


Image source: The Scientist

Model outbreak of influenza during a single season:

- unvaccinated population (of size N)
- assume immediately infectious upon infection
- assume after infection, immune for rest of season

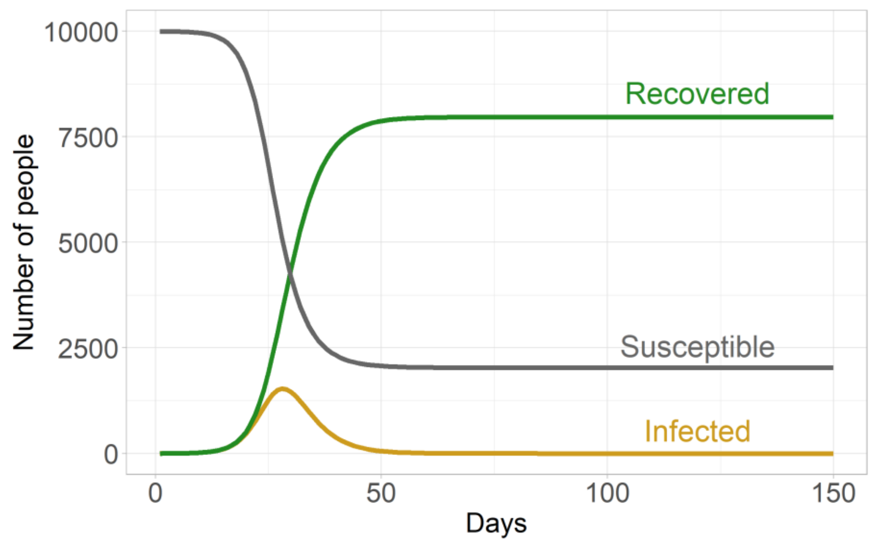
	infection		recovery	
S	→	I	→	R
Susceptible		Infected		Recovered

Describe **flows** between compartments

Constructing the SIR model

Model outbreak of influenza during a single season:

- unvaccinated population (of size N)
- assume immediately infectious upon infection
- assume after infection, immune for rest of season



infection recovery

$$S \xrightarrow{\beta SI} I \xrightarrow{\gamma I} R$$

$$\frac{\mathrm{dS}}{\mathrm{dt}} = -\beta S\, I$$

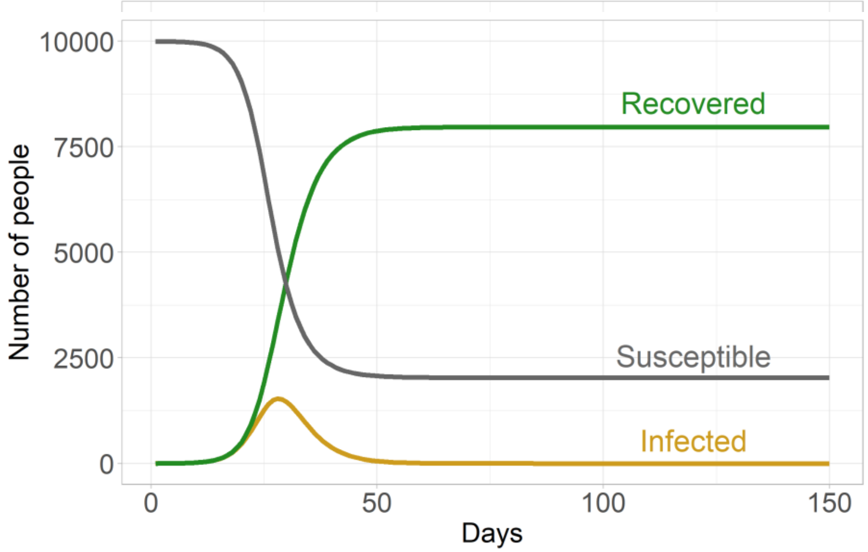
$$\frac{\mathrm{dI}}{\mathrm{dt}} = \beta S\, I \; - \gamma I$$

$$\frac{\mathrm{d}R}{\mathrm{dt}} = \gamma I$$

Constructing the SIR model

Model outbreak of influenza during a single season:

- unvaccinated population (of size N)
- assume immediately infectious upon infection
- assume after infection, immune for rest of season



# infections / day per infected person	x	# days infectious
βS	x	$1/\gamma$

$$R_0 = \beta S \times \frac{1}{\gamma} = \boxed{\beta N \times \frac{1}{\gamma}} = \frac{\beta N}{\gamma}$$

Fully suscept.

$$\frac{dS}{dt} = -\beta S\, I$$

$$\frac{dI}{dt} = \beta S\, I - \gamma I$$

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

γ = rate of recovery

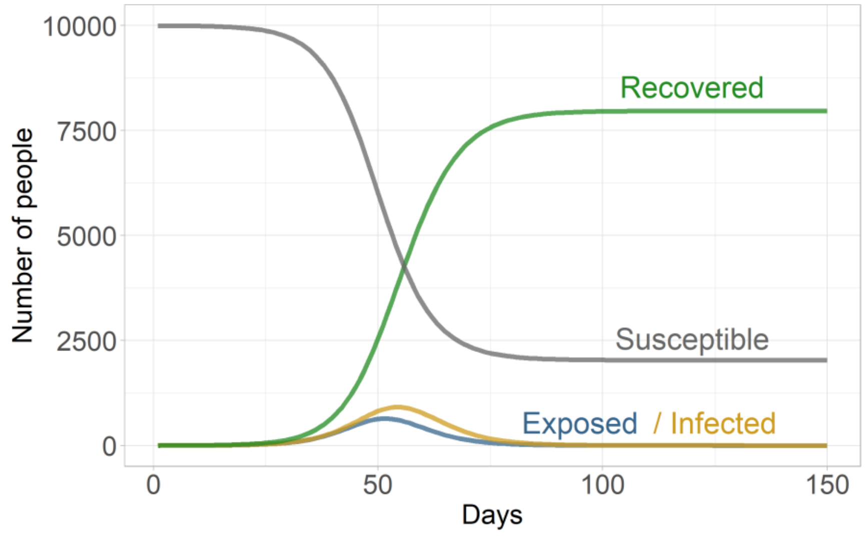
$\frac{1}{\gamma}$ = time to recovery

Case studies: Adapting the model to different needs

#1 *"Have you included latent infection?"*

Model outbreak of influenza during a single season:

- unvaccinated population
- assume after infection, immune for rest of season
- period of latent infection **before** people become infectious



$$S \xrightarrow{\beta SI} E \xrightarrow{\boldsymbol{\sigma E}} I \xrightarrow{\gamma I} R$$

$$\frac{\mathrm{dS}}{\mathrm{dt}} = -\beta S\, I$$

$$\frac{\mathbf{dE}}{\boldsymbol{dt}} = \beta S\, I \; -\boldsymbol{\sigma E}$$

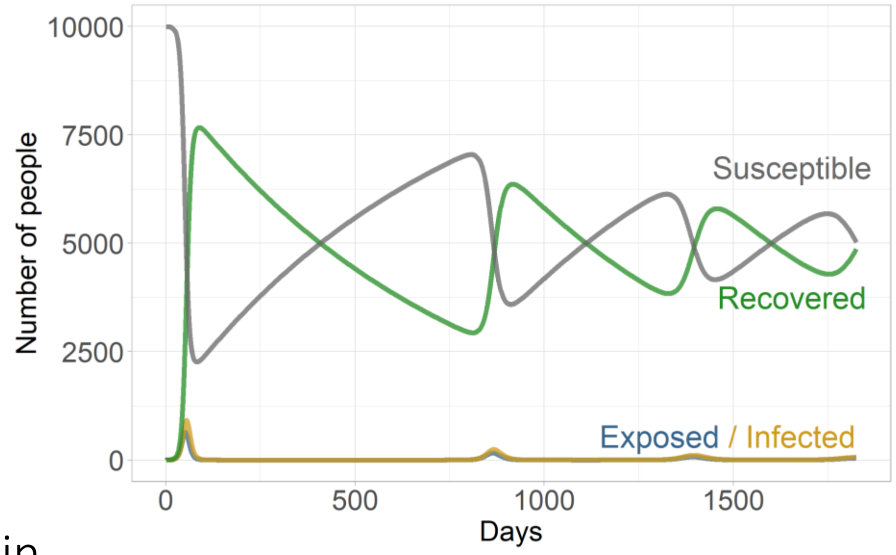
$$\frac{\mathrm{dI}}{\mathrm{dt}} = \boldsymbol{\sigma E} - \gamma I$$

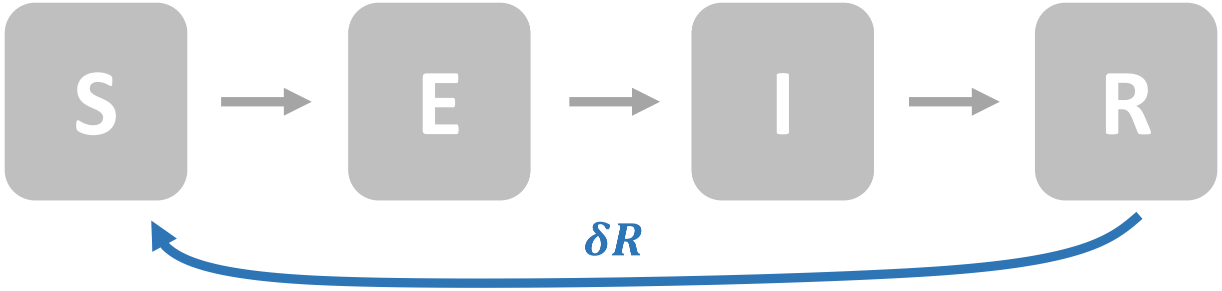
$$\frac{\mathrm{d}R}{\mathrm{dt}} = \gamma I$$

#2 “…and *waning immunity*?”

Model outbreak of influenza during multiple seasons:

- unvaccinated population
- period of latent infection before people become infectious
- assume people lose immunity and become fully susceptible again





$$\frac{\mathrm{dS}}{\mathrm{dt}} = -\beta S\, I + \boldsymbol{\delta R}$$

$$\frac{dE}{dt} = \beta S\, I\ - \sigma E$$

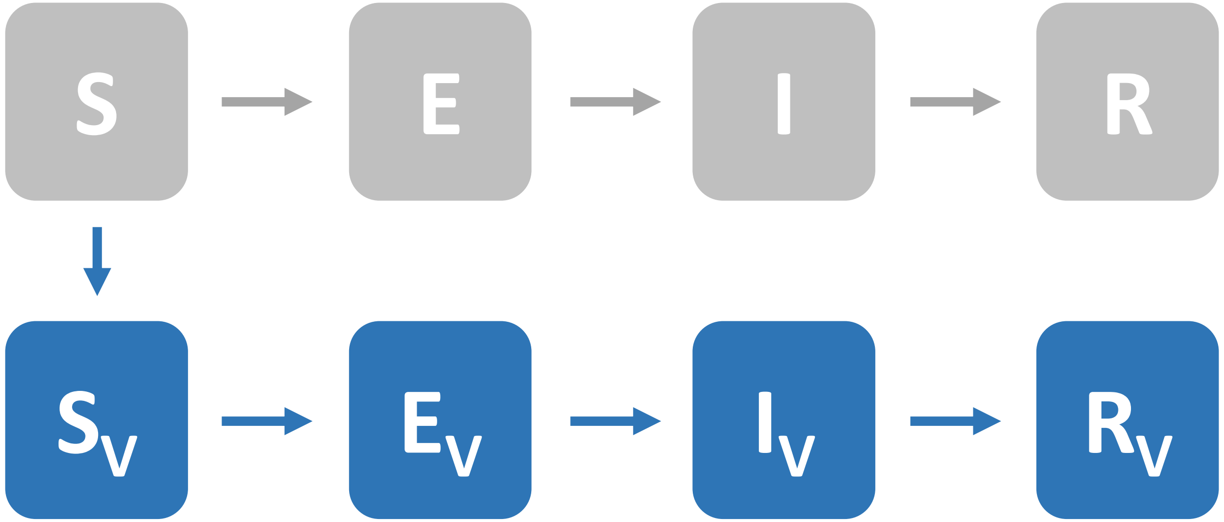
$$\frac{\mathrm{dI}}{\mathrm{dt}} = \sigma E - \gamma I$$

$$\frac{\mathrm{d}R}{\mathrm{dt}} = \gamma I - \boldsymbol{\delta R}$$

#3 *“…or vaccination?”* → SEIRV model

Model outbreak of influenza during a single season:

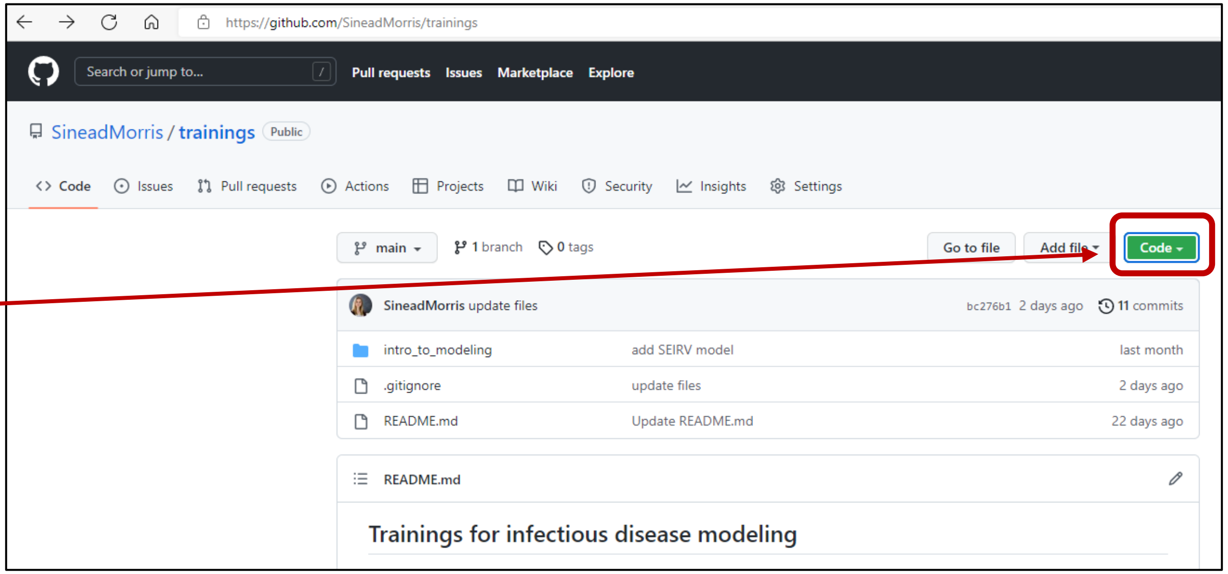
- assume after infection, immune for rest of season
- period of latent infection before people become infectious
- susceptible people can be vaccinated



Code a model in R

Materials at:

github.com/SineadMorris/trainings



Files in 'intro_to_modeling':

SIR_model.Rmd	--	code to simulate the SIR model
SIR_model_extra.Rmd	--	same analysis, with a few extra bells & whistles
SEIR_model.Rmd	--	code to simulate the SEIR model
SEIRS_model.Rmd	--	code to simulate the SEIRS model
SEIRV_model.Rmd	--	code to simulate the SEIRV model

(Optional) Exercise

Try adding **latent infection** to `SIR_model.Rmd`

(without looking at `SEIR_model.Rmd`!)

Additional Qs & resources

Applied Research & Modeling Team (ARM)

SCBS at CDC

CDC R User Group (RUG)

NCIRD Data Science DOJO

R packages: `flumodels, epiestim, tidyverse, patchwork, scico`

R tutorials / help: Harvard online, Applied Epi R Handbook, stackoverflow/google

Modeling tutorials: ICI3D lectures & code, Imperial coursera, Penn State coursera