2023 Harvard/University of Global Health Equity
Mathematical Modeling for Infectious Disease Planning

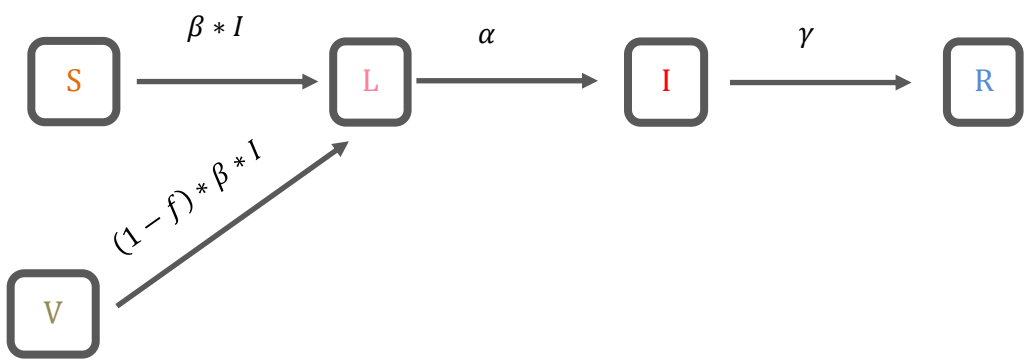
COVID-19 vaccine modeling exercise- Part A

Time: 1 hour 30 minutes

At the end of the activity, you would:

i) extend the COVID-19 model to include vaccination.
ii) understand how vaccination can be modeled to assess its impact on health outcomes.

1) Assume that you are responsible for assessing the effectiveness of the COVID-19 vaccination program in your country. Assume that 30% (parameter *w)* of susceptible individuals are vaccinated at the start of the outbreak (i.e, incorporate *w* in your initial conditions). Also assume a **leaky vaccine with a** 90% effectiveness against infection (vaccine efficacy parameter *f)*. Using a simple SLIR model structure (i.e., no separate compartment for asymptomatic individuals),
   a. Update the compartmental model diagram to account for the **vaccinated state**, "**V**", and the leakiness of the vaccine.



   b. Write down the differential equations for the updated model structure and provide a table of parameter descriptions.

Model equations:

$$\frac{dS}{dt} = \frac{-\beta SI}{N},$$
$$\frac{dL}{dt} = \frac{\beta SI}{N} + \frac{\beta VI}{N}(1-f) - \alpha L,$$

$$\frac{dI}{dt} = \alpha L - \gamma I,$$
$$\frac{dR}{dt} = \gamma I,$$

$$\frac{dV}{dt} = \frac{-\beta V I}{N}(1 - f),$$

$$N = S + L + I + R + V.$$

Parameter descriptions

Parameter	**Description**
β	Transmission rate
α	Rate of progression from latency to infectiousness
γ	Recovery rate
f	Vaccine efficacy

c. Update the initial conditions of the model. (Use the initial conditions from the previous exercise and include a value for the "V" compartment.)

$N = 1000000$
$S = N - 2 - ((N - 2) * w)$
$L = 1$
$I = 1$
$R = 0$
$V = (N - 2) * w$

d. Aside including the vaccination parameter in your initial conditions, how else can vaccination be incorporated into the model?

-daily vaccination rate,
-assume vaccinated individuals moved to the R compartment
-time-varyingg vaccination rate
-waning immunity from vaccination

e. How would the combination of vaccination efficacy and vaccine coverage impact vaccination program outcomes?

-high vaccine efficacy and vaccine coverage most likely lead to a successful vaccination program; more infections averted and achieve herd immunity.

f. Bonus: what proportion of the population should be vaccinated to achieve herd immunity threshold, assuming an effective reproduction number of 3.5?

Herd immunity = $1 - \frac{1}{R0}$

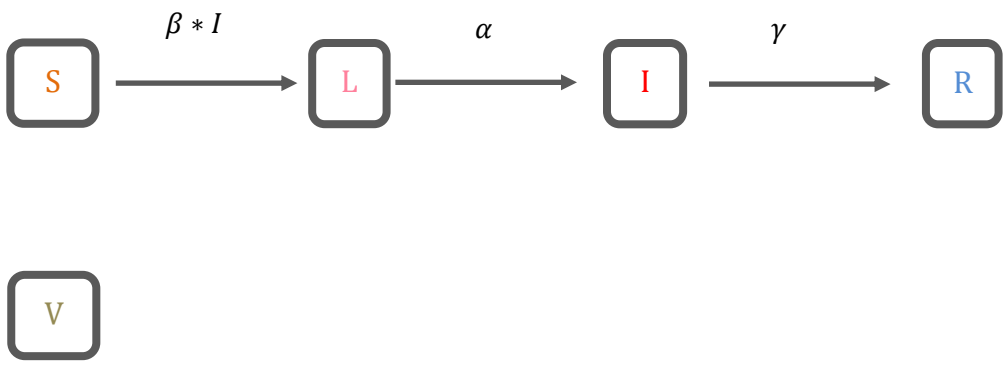
$1 - \frac{1}{3.5}$

= 0.714

~71% of population need to be vaccinated to achieve herd immunity

2) Now, change the model to an **all-or-nothing vaccine**. [Recall what this means from the lecture.] Still assume that 30% of people in our population have received the vaccine before the outbreak starts.

a. Update the compartmental model diagram to account for this **all-or-nothing vaccine.**



b. Write down the differential equations for the updated model structure and provide a table of parameter descriptions.

Model equations:

$$\frac{dS}{dt} = \frac{-\beta SI}{N},$$
$$\frac{dL}{dt} = \frac{\beta SI}{N} - \alpha L,$$
$$\frac{dI}{dt} = \alpha L - \gamma I,$$
$$\frac{dR}{dt} = \gamma I,$$

$$\frac{dV}{dt} = 0$$

$$N = S + L + I + R + V.$$

c. Write down the initial conditions for this model. Are these different from the initial conditions for the previous model?

$N = 1000000$
$S = N - 2 - ((N - 2) * w)$
$L = 1$
$I = 1$
$R = 0$
$V = (N - 2) * w$

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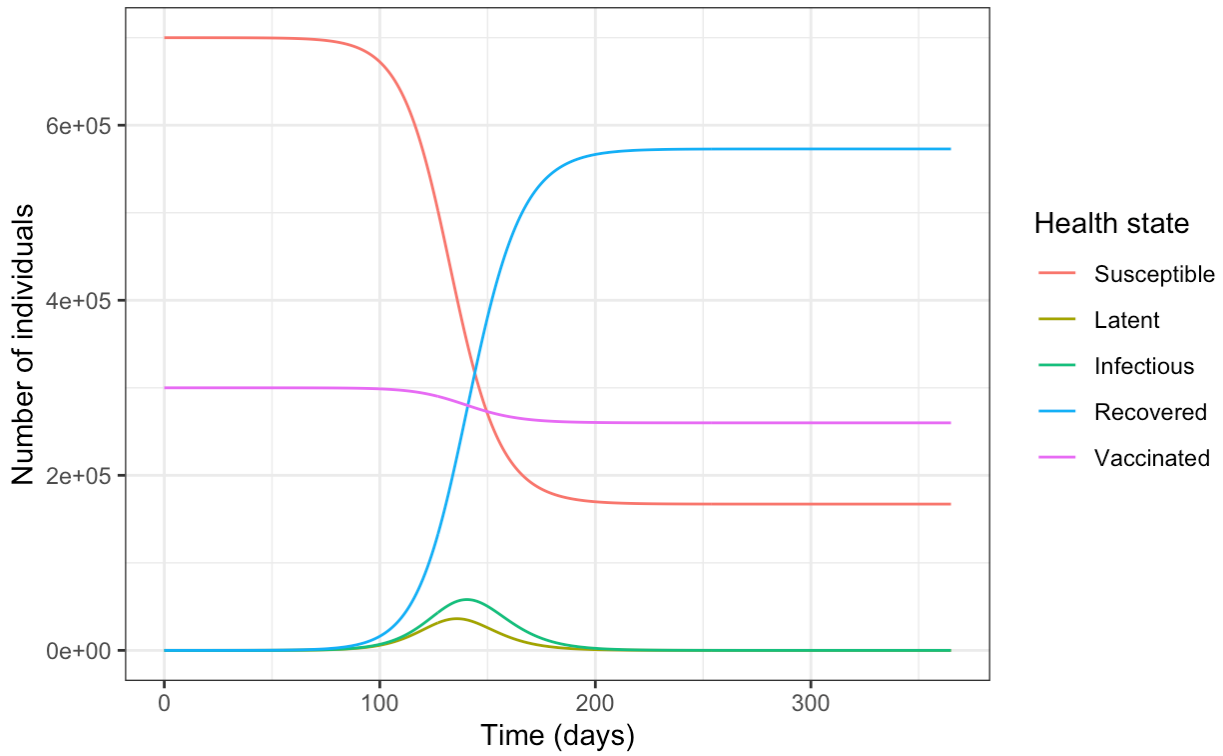
PART B: Berkeley Madonna

Time: 1 hour

1. Given the leaky vaccine model in part A, do the following.

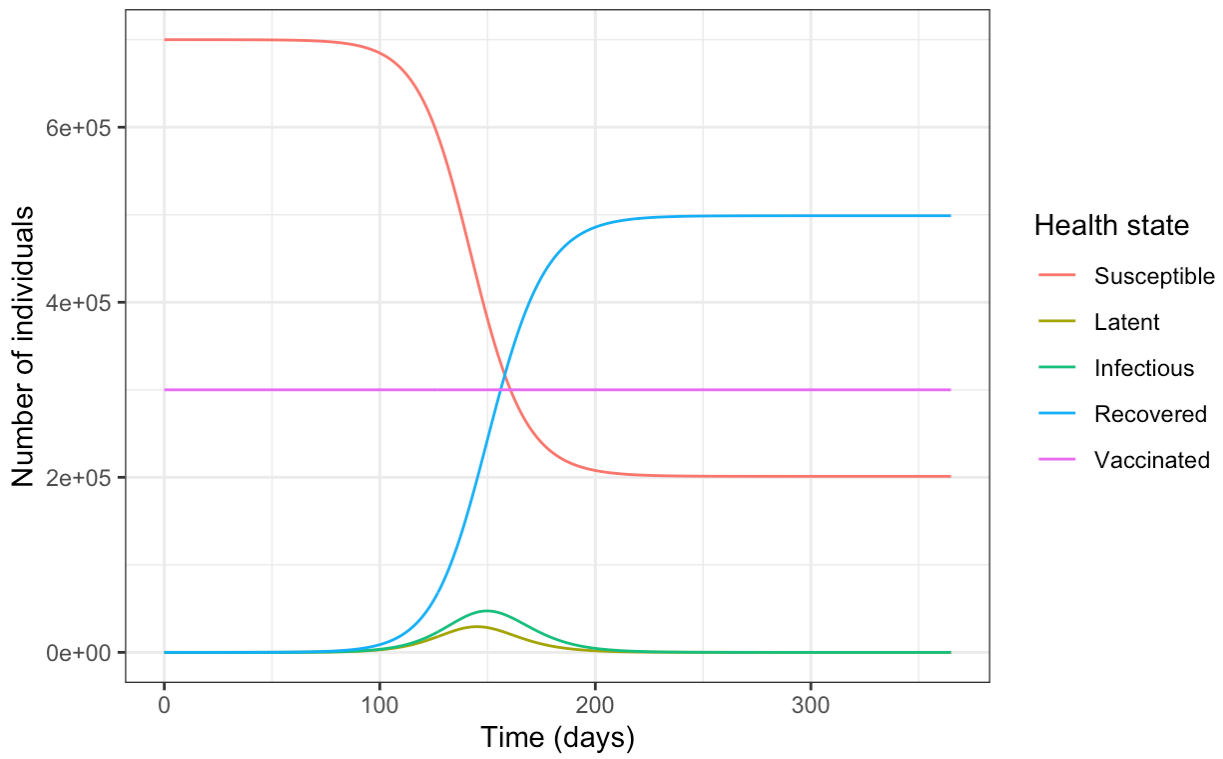
   a. Run the model for 365 days and provide the figure of disease dynamics. [*Use parameter values as in previous activity.*]



b. What is the cumulative incidence proportion after 365 days?

The cumulative incidence proportion after 365 days given a leaky vaccine with 90% efficacy is about 0.57.

2. Given the **all-or-nothing vaccine** model in part A, do the following.
   a. Run the model for 365 days and provide the figure of disease dynamics. [*Use parameter values as in previous activity.*]



b. What is the cumulative incidence proportion after 365 days?

The cumulative incidence proportion after 365 days given an all-or-nothing vaccine is about 0.50.

3. Explain the difference between the model outputs in Q1 and Q2.

The cumulative incidence proportion (that is, the fraction of individuals in the population who get infected) by day 365 is lower with an all-or-nothing vaccine (0.50) than with a leaky vaccine (0.57).