OVERVIEW

The Modeling Disease Spread Click & Learn can be used to model infectious disease spread in a population using the SIR model. The Click & Learn includes background on the components of the SIR model and factors that affect the spread of disease, as well as two simulators for modeling disease spread on different scales: the Outbreak Simulator for small populations and the Epidemic Simulator for large ones. To learn more about the differences between the simulators, go to the “Selecting a Simulator” section.

The “Student Worksheet” for this Click & Learn deepens students’ understanding of the SIR model and helps them connect the curves of an SIR graph to what they represent in a population. The worksheet takes students through the “SIR Model Basics” tab of the Click & Learn and familiarizes them with the Outbreak Simulator. It is divided into the following parts.

- In **Part 1**, students demonstrate their prior knowledge of infectious diseases.
- In **Part 2**, they learn about the components of the SIR model.
- In **Part 3**, they use the Outbreak Simulator to model an outbreak in a small, unvaccinated population using the transmission and recovery probabilities of common pathogens. Students then analyze and interpret graphs of their results.
- In **Part 4**, they model a similar outbreak in a partially vaccinated population.
- In **Part 5**, they compare their results from the unvaccinated and vaccinated populations, to better understand the impacts of vaccination on disease spread.
- In **Part 6**, they consider the assumptions and limitations of the SIR model.
- In the **optional extension**, they begin exploring the Epidemic Simulator by modeling disease spread on a larger scale.

Additional case studies that can be used with the “SIR Model Advanced” tab and Epidemic Simulator are provided in the “Use This Resource With” section on this resource’s webpage. All these case studies are based on actual disease outbreaks and epidemics.

This educator document contains multiple resources for implementing this Click & Learn with students, including the following (select links to go directly to each section in the document):

- **background** on the SIR model and where to find more information
- **teaching tips** for this resource, including selecting a simulator and extension questions
- **suggested procedures** for this resource, including using the Click & Learn, using the worksheet, and saving/submitting graphs
- **assessment guidance** for the questions in the “Student Worksheet”
- **appendices** with more examples of SIR graphs and guidance on how to interpret them, as well as more information on the equations used in this resource

Additional information related to pedagogy and implementation can be found on this resource’s webpage, including suggested audience, estimated time, and curriculum connections.
KEY CONCEPTS

- The SIR model simulates the spread of an infectious disease in a population. The model divides the population into three groups (susceptible, infectious, and removed), among which individuals can move.
- An SIR graph shows how the number of individuals in each group changes over time. There are typical patterns and relationships among the lines on the graph.
- Parameters that influence transmission, recovery, and vaccination affect the spread of a pathogen in a population and thus the shape of an SIR graph.
- All models, including the SIR model, are based on assumptions about their study system.

STUDENT LEARNING TARGETS

- Use the SIR model to simulate the spread of an infectious disease in a population.
- Collect data to build, analyze, and interpret SIR graphs.
- Predict how different parameters (e.g., transmission and recovery probabilities or rates) and interventions (e.g., vaccination) affect disease spread dynamics.
- Describe assumptions and limitations of the SIR model.

PRIOR KNOWLEDGE

Students should have a basic understanding of:
- pathogens and their relationship to infectious diseases
- disease transmission (i.e., that diseases can spread as pathogens are passed from one individual to another)
- vaccines and how they work
- using models and data to predict outcomes
- interpreting a line graph

MATERIALS

- copies of the “Student Worksheet”
- access to the Modeling Disease Spread Click & Learn
- computer or mobile device that can be used to take screenshots, download files, or print images

BACKGROUND

More information on the SIR model can be found within the Click & Learn and in the SIR Model references. A short summary is provided below.

The SIR model is a common epidemiological model that can be used to simulate the spread of an infectious disease in a population. The model divides a population into three distinct groups:

- **Susceptible** individuals who can become infected by the pathogen.
- **Infectious** individuals who can transmit (spread) the pathogen to susceptible individuals.
- **Removed** individuals who are immune from infection. This includes both recovered individuals, who were previously infected, and vaccinated individuals.

The SIR model can be used to predict the number of individuals in each group at specific timepoints during a disease outbreak or epidemic. The model uses mathematical equations to represent processes such as transmission and recovery. More information on the equations can be found in Appendix 3; calculating transmission and recovery rates is discussed in Appendix 4.
TEACHING TIPS

Selecting a Simulator

The Click & Learn includes two simulators that model disease spread at different scales. Both simulators allow students to:

- explore modeling different transmission and recovery parameters
- compare disease spread in the absence and presence of vaccination
- automatically generate SIR graphs to visualize the impact of parameters

The Outbreak Simulator (under “Simulate an Outbreak” in the “SIR Model Basics” tab) can be used to model disease spread in a small population. You can use this simulator to introduce students to the SIR model, as it goes through the basic steps in more detail and provides useful visual representations.

- The Outbreak Simulator generates data based on probabilistic events. So students using the same parameters may still have slightly different graphs and data tables.
- The “Student Worksheet” for this Click & Learn mainly uses the Outbreak Simulator, with an optional extension that uses the Epidemic Simulator.
- This simulator shows all the individuals in the population on a grid with representative icons (Figure 1). As the pathogen spreads through the population, the icons will change to reflect different individual statuses, which are summarized in the “Icon Legend” (Figure 2). Infectious individuals can spread the pathogen only to susceptible individuals who are directly adjacent to them on the grid (called “susceptible close contacts”).
  - The grid provides a visual representation of the population that can help students better understand how individuals transition between the different groups and how the disease spreads among them.
  - Although herd immunity is not explicitly described in the “SIR Model Basics” section, you can use the grid to introduce the idea that removed individuals (recovered and vaccinated individuals) play an important role in slowing disease spread and protecting susceptible individuals in the population (Figure 1). Information on herd immunity can be found in the “Immunity Background” section of the “SIR Model Advanced” tab.
- Students simulate each day in the outbreak by following a list of steps that involve selecting specific individuals on the grid (e.g., choose an individual to vaccinate). For information on these steps, refer to the “Tutorial” section under “SIR Model Basics.”
  - Visualizing individuals on the grid can help students strategically vaccinate susceptible close contacts to reduce disease spread.
**Figure 1.** An example of the population grid displayed by the Outbreak Simulator. Columns A–C demonstrate the concept of herd immunity, as removed individuals (A3, B2, B4, C1–6) protect nearby susceptible individuals from an infectious individual (B3).

<p>| | | | | | |</p>
<table>
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<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
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<td>1</td>
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<td>5</td>
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<td>6</td>
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</tr>
</tbody>
</table>

**Figure 2.** Icon legend for the Outbreak Simulator.

The **Epidemic Simulator** (under “Simulate an Epidemic” in the “SIR Model Advanced” tab) can be used to model disease spread in a large population. You can use this simulator once students are more familiar with the basics of the SIR model (i.e., how the SIR model works and how to interpret SIR graphs).

- This simulator uses difference equations to calculate the number of individuals in each group over time. More information on these equations is provided in **Appendix 3**.
- Students can modify various parameters in the equations, such as the transmission and recovery parameters, time, population size, and vaccination rate.
- The case studies for this Click & Learn (in the “Use This Resource With” section on this resource’s webpage) use the Epidemic Simulator.

This table summarizes the differences between the simulators (also shown in the “Simulating Disease Spread at Different Scales” section of the “SIR Model Advanced” tab).

<table>
<thead>
<tr>
<th></th>
<th>Outbreak Simulator (SIR Model Basics)</th>
<th>Epidemic Simulator (SIR Model Advanced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>What It Models</td>
<td>Small-scale disease spread</td>
<td>Large-scale disease spread</td>
</tr>
<tr>
<td>Initial Susceptible Individuals ($S$)</td>
<td>35</td>
<td>Up to 200,000</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Notes</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Initial Infectious Individuals ($I$)</td>
<td>1</td>
<td>Up to 300</td>
</tr>
<tr>
<td>Initial Removed Individuals ($R$)</td>
<td>0</td>
<td>Up to 200,000</td>
</tr>
<tr>
<td>Transmission</td>
<td></td>
<td>Described by an individual-level probability</td>
</tr>
<tr>
<td>Recovery</td>
<td></td>
<td>Described by an individual-level probability</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>Up to 25 days</td>
</tr>
<tr>
<td>Vaccination</td>
<td></td>
<td>Up to 1 individual/day</td>
</tr>
<tr>
<td>Basic Reproduction Number ($R_0$)</td>
<td>Not calculated</td>
<td>Calculated</td>
</tr>
<tr>
<td>Effective Reproduction Number ($R_t$)</td>
<td>Not calculated</td>
<td>Displayed as a graph</td>
</tr>
<tr>
<td>Herd Immunity Threshold (HIT)</td>
<td>Not calculated</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

**Discussing Diseases and Death**

While creating this resource, we intentionally chose not to include death in our model in light of the ongoing COVID-19 pandemic. Collectively, as a global society, we have all experienced the devastation of an infectious disease pandemic. We omitted death from our model in an effort to prevent triggering responses from simulating disease-related death, especially since many students and educators may have lost loved ones over the past few years as a result of the pandemic.

If you decide to modify the activity to include questions around disease-related death, please incorporate trauma-informed teaching practices. Resources on these practices include Imad (2022) and the book Intentional Neuroplasticity: Moving Our Nervous Systems and Educational System Toward Post-Traumatic Growth (Desautels 2023).

**Extensions**

The “Student Worksheet” has an optional extension at the end that has students start using the Epidemic Simulator. Additional optional questions are provided below. Consider using these questions in whole-class discussions, either in-person or online, or for graded follow-up assignments.

1. Perform additional simulations in the Outbreak Simulator trying some of the scenarios below.
   a. If you previously simulated a low transmission probability/recovery probability combination, select a high transmission probability/recovery probability combination instead — and vice versa. Compare how the disease moves through the population in both cases.
   b. Simulate an outbreak in which vaccinations are not available right away (e.g., not until Day 7).
   c. Simulate a population in which some individuals did not receive a vaccination (e.g., don’t vaccinate one side of the population grid).
2. The transmission probability for some pathogens, such as human immunodeficiency virus (HIV), is incredibly low. Pathogens like these may infect multiple individuals without causing an outbreak. Sketch or describe what you think the SIR graph would look like for such a pathogen.

3. You may have heard in the news that vaccines can help “flatten the curve.”
   a. Which curve on the SIR graph does this refer to, and what does it mean?
   b. Why might “flattening the curve” help the population?

4. Not all diseases are infectious. Would the SIR model be useful for modeling noninfectious diseases (e.g., heart disease, cancer)? Why or why not?

PROCEDURE

Using the Click & Learn

The goal of this Click & Learn is to explore how one epidemiological model, the SIR model, is used to simulate the spread of a pathogen in a population. Simulators, videos, and images allow this Click & Learn to be explored at varying levels of depth.

The main tabs for the Click & Learn are as follows:

- **Introduction**: Provides background on infectious diseases and how they spread.
- **SIR Model Basics**: Discusses the basic components of the SIR model. Also includes the “Outbreak Simulator” (and an accompanying tutorial), which can be used to simulate disease spread in a small population, collect data, and build a graph.
- **SIR Model Advanced**: Discusses mathematical equations for the SIR model and additional factors that affect the spread of disease, such as the basic reproduction number ($R_0$) and herd immunity. Also includes the “Epidemic Simulator,” which can be used to simulate disease spread in a large population, calculate certain metrics, and generate graphs.

Due to the length and breadth of the Click & Learn, it is recommended to tailor which sections you use to your course learning objectives and students’ needs. Some general recommendations are as follows:

- For **general high school biology classes** and students unfamiliar with the SIR model, use the “Introduction” and “SIR Model Basics” section, which can be accompanied by the **“Student Worksheet.”**
- For **college introductory biology classes** and students familiar with the SIR model, focus on the “SIR Model Advanced” section and case studies found on the “Use This Resource With” section on this resource’s [webpage](#).

Using the Worksheet

Use the “Student Worksheet” provided on [this resource’s webpage](#) to guide students through the “SIR Model Basics” section of the Click & Learn. You can customize the worksheet as needed for your class.

The worksheet can be completed individually or in small groups. For small groups, each student can select a different disease to model in Part 3. After completing their simulations, students can engage in peer learning, articulate their thinking, and compare their SIR graphs.

For **in-person** classes, after students have completed their simulations in Part 3, consider projecting an example SIR graph to the whole class. Have students compare their SIR graph to the projected SIR graph.

For **online** classes:

- Provide access to a digital version of the worksheet so that each student or each group has their own copy. Google Docs versions of the worksheet are provided in the “Resource Google Folder” on this resource’s [webpage](#).
● If students work on the activity individually, consider pairing students in Zoom breakout rooms so they can compare and discuss their SIR graphs.

**Saving and Submitting Graphs**

In several parts of the “Student Worksheet,” students use the simulators in the Click & Learn to create SIR graphs. Students will be asked to record and compare SIR graphs from different simulations.

**Let students know how you would like them to save/submit their graphs.** Several options are described below; pick whichever one makes the most sense for your class. It may be helpful to briefly demonstrate or guide students through the process you would like them to use.

To save/submit **digital** copies of their graphs, students can:

- **Download** the graph image.
  - To download the graph from the Click & Learn, select the menu icon with the three horizontal bars in the top-right corner of the “SIR Graph” section of the Outbreak Simulator. This will open a menu (Figure 3) where you can download the graph as a PNG, JPEG, PDF, or SVG image file.
  - Students can submit the image file itself or insert the image into a digital copy of their worksheet.
- **Screenshot** the graph if downloading is unavailable.
  - Screenshot functions and commands will depend on the device. Guide students through the screenshots process if needed.
  - Students can save the screenshot as an image file to submit or insert it into a digital copy of their worksheet.

To save/submit **physical** copies of their graphs, students can:

- **Print** the graph.
  - To print the graph from the Click & Learn, select the menu icon with the three horizontal bars in the top-right corner of the “SIR Graph” section. This will open a menu (Figure 3); select the “Print chart” option.
  - Students may attach their printed graphs directly to their worksheet or submit labeled graphs with their worksheet.
- **Sketch** the graph if printing is unavailable.
  - Encourage students to recreate the graphs as accurately as possible, taking careful note of the units on each axis and where the lines increase, decrease, and intersect.

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**Figure 3.** Menu with options for the SIR graph.
ASSESSMENT GUIDANCE

PART 1: Introduction to Infectious Diseases and Transmission

1. Before watching the video, list three infectious diseases that you have heard of, and which pathogens cause them, in the table below. If you’re unsure, you can do some research online.

   Student responses will vary. The main goal is to help students differentiate between a pathogen and the disease it causes. Though some pathogens have the same name as their disease (e.g., measles virus causes the disease measles), others do not (e.g., the HIV virus causes the disease AIDS, the SARS-CoV-2 virus causes the disease COVID-19).

2. In your own words, describe how pathogens spread in a population.

   Students should indicate that pathogens spread from one individual to another in a population. They may mention that this process is called transmission.

PART 2: What Is an SIR Model?

3. The SIR model divides the population into three distinct groups. In your own words, describe each group in the table below.

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Susceptible</td>
<td>Uninfected and unvaccinated individuals who can become infected</td>
</tr>
<tr>
<td>Infectious</td>
<td>Individuals who are infected with a given pathogen and can pass it to susceptible individuals</td>
</tr>
<tr>
<td>Removed</td>
<td>Immune individuals who have recovered from infection or who were vaccinated against a specific pathogen</td>
</tr>
</tbody>
</table>

4. In the SIR model, both transmission and recovery affect how individuals move from one group to another.
   a. Transmission affects individuals moving between which two groups?
      Susceptible and infectious
   b. Recovery affects individuals moving between which two groups?
      Infectious and removed

5. Proceed to the “Tutorial” tab. A popup will appear to explain how to use the Outbreak Simulator. You will also learn how transmission probabilities (popup screen 6) and recovery probabilities (popup screen 7) are used to calculate the likelihood of new infections and new recoveries each day.
   a. At the beginning of an outbreak, how would a large transmission probability affect the number of individuals moving into the infectious group?
      If the transmission probability is large, the pathogen is more likely to spread among individuals. This means more susceptible individuals will move into the infectious group. This will be particularly apparent at the beginning of an outbreak when there are lots of susceptible individuals to infect.
   b. During the middle of an outbreak, how would a large recovery probability affect the number of individuals moving out of the infectious group?
      If the recovery probability is large, infectious individuals will recover more quickly. So more individuals will move out of the infectious group and into the removed group.

PART 3: Simulate an Outbreak in an Unvaccinated Population

6. Record the name of your selected pathogen and the transmission and recovery probabilities that you will model below.
Students should select their pathogens from the table in the “Student Worksheet” and record the corresponding probabilities. They should use the same pathogen and probabilities at the beginning of Part 4.

7. Select an initial case. Record the position of your initial case in the population grid (e.g., 3C, 4E) below. **Answers will vary depending on what students selected. They should use the same initial case at the beginning of Part 4.**

8. Depending on the transmission probability and recovery probability you selected, the pathogen may spread through the population quickly, slowly, or not at all. **Before starting the simulation, predict whether your pathogen will spread throughout the entire population by the end of the simulation (25 days). Explain your reasoning.**

**Students should justify their answers using a rationale that aligns with the information in the Click & Learn.**

**Predicting the impact of the transmission probability may be more straightforward for students. Higher transmission probabilities (e.g., over 50%) will cause the pathogen to spread through the population more quickly than lower transmission probabilities (e.g., under 20%) will.**

**Predicting the impact of the recovery probability on the spread of the pathogen may take a bit more processing. A relatively high recovery probability (e.g., over 50%) may slow the spread of the pathogen, since infectious individuals will recover quickly. A lower recovery probability (e.g., under 20%) may speed up the spread of the pathogen, as infectious individuals will recover slowly and have more opportunities to infect susceptible individuals.**

9. Once you complete the simulation, answer the following questions:
   a. **Describe how quickly or slowly the pathogen spread in your population. For example, how long did it take for the pathogen to begin spreading? Students should describe when the number of individuals infected by the pathogen increased and peaked based on the infectious curve.**
   b. How does the spread you observed in the simulation compare to what you predicted in Question 8? **Students should compare their results to their predictions. To explain their results, they may describe the spatial spread of infectious individuals in the “Population Grid.” They may also describe changes in the numbers of individuals in each group shown in the “SIR Data Table.”**

10. In the table below:
   a. At the top of the last column, record the last day of your outbreak (the day when everyone has recovered or Day 25, whichever comes first).
   b. In the rest of the table, record the number of individuals in each group on Day 0 (i.e., when the initial case was selected) and the last day of the outbreak. You will come back to this data in Part 4 of this worksheet.

<table>
<thead>
<tr>
<th></th>
<th>Day 0</th>
<th>Day varies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(last day of outbreak)</td>
</tr>
<tr>
<td>Susceptible</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Infectious</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Removed</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

www.BioInteractive.org
Using this table, the “SIR Data Table,” and/or the “SIR Graph” in the Click & Learn, describe how the number of individuals in each group changed throughout the outbreak (i.e., from Day 0 to the last day of the outbreak).

Student responses will vary depending on the results of their simulations. Some responses may include:

- The susceptible group decreases over time.
- The infectious group increases, peaks, and decreases over time.
- The removed group increases over time.
- Many individuals become infected in the first phase of the outbreak.
- Individuals don’t begin recovering until a certain day.
- By a certain day, there aren’t any more susceptible individuals in the population.

If students struggle with this question, have them first compare the number of individuals in each group at the beginning (Day 0) and last day of the outbreak. Once they recognize the overall changes, they can then consider other changes throughout the outbreak.

11. Following the guidance of your instructor, download, print, or sketch an image of your graph. Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.

Instruct your students as to which method you prefer for saving and submitting their SIR graphs. Details on the various methods can be found in the “Saving and Submitting Graphs” section.

12. Examine each curve (line) in the graph individually, then fill in the table below. For each group in the first column:

   a. In the second column, describe how the curve representing the number of individuals in that group changes throughout the outbreak.

   b. In the third column, describe where individuals in that group move to. For example, for the first row, which other groups can susceptible individuals move to? Write “None” if no groups fit.

   c. In the fourth column, describe where individuals in that group come from. For example, for the first row, which other groups can susceptible individuals come from? Write “None” if no groups fit.

Sample answers based on a typical SIR graph are provided below. Additional examples of SIR graphs can be found in Appendix 2.

<table>
<thead>
<tr>
<th>Group</th>
<th>How does this group’s curve change over time?</th>
<th>Where do individuals in this group move to?</th>
<th>Where do individuals in this group come from?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Susceptible</td>
<td>The curve decreases and eventually levels off.</td>
<td>Infectious</td>
<td>None</td>
</tr>
<tr>
<td>Infectious</td>
<td>The curve increases, peaks, and eventually decreases.</td>
<td>Removed</td>
<td>Susceptible</td>
</tr>
<tr>
<td>Removed</td>
<td>The curve starts at zero, increases, and eventually plateaus.</td>
<td>None</td>
<td>Infectious</td>
</tr>
</tbody>
</table>

13. Consider the relationship between the three curves on the SIR graph. Refer to your answers in Question 12 as you consider how individuals move between the three groups.

More information on analyzing and interpreting SIR graphs can be found in Appendix 1.
a. What happens to individuals in the susceptible group over time?
_The number of susceptible individuals decreases over time. As susceptible individuals become infected, they move out of the susceptible group and into the infectious group._

b. What happens to individuals in the infectious group over time?
_The number of infectious individuals increases early in the outbreak, when susceptible individuals are becoming infected and entering the infectious group. The number of infectious individuals then typically peaks and eventually decreases toward the end of the outbreak, when more infectious individuals are recovering and entering the removed group._

c. How many days did it take to reach peak infection (the day with the most infectious individuals)?
_Students should use their infectious curve to identify the day with the highest number of infectious individuals. If this peak spans multiple days, students may select a specific day or provide a range._

d. During peak infection, how would you describe the movement of individuals in the infectious group?
_During peak infection, the number of individuals entering the infectious group (from the susceptible group) and leaving the infectious group (to enter the removed group) are equal. Therefore, there is no net gain or loss of individuals into the infectious group at this point._

e. What happens to individuals in the removed group over time?
_The number of individuals in the removed group increases over time as infectious individuals eventually recover._

f. Do individuals enter the susceptible group or leave the removed group in this model? Why or why not?
_In general, individuals can enter the susceptible group if:_

- New susceptible individuals move into the population. In this model, however, the population cannot increase.
- A removed individual is reinfected. In this model, however, once an infectious individual recovers, they are immune from infection and cannot be reinfected.

_In general, individuals can leave the removed group if they lose their immunity and become susceptible again. In this model, however, removed individuals are always immune and cannot be reinfected._

_Thus, in this model, individuals do not enter the susceptible group or leave the removed group._

14. Consider how many individuals become infected during the outbreak.
   a. Which curve(s) shows the number of infectious cases (i.e., infectious individuals) on a given day?
      _The infectious curve_

   b. How could you determine how many people have been infected up until a certain point in the outbreak?
      _Some students may incorrectly answer that the infectious curve shows how many people have been infected up until a particular point in the outbreak. However, the infectious curve only provides information about individuals who are currently infectious, not about those who had been infected and recovered._

      _To determine the number of individuals that have been infected up until a certain point, students can add the number of individuals in the infectious and removed groups at that point. Or they can subtract the number of susceptible individuals at that point from the total number of individuals in the population._

   c. How many individuals were infected up until peak infection? (For example, if peak infection occurred on Day 13, how many individuals in the population have been infected up to and including Day 13)?
To calculate this number, students should use the method described in Question 14b with the peak infection point they determined in Question 13c.

d. How many individuals were infected over the entire outbreak?
   To calculate this number, students should use the method described in Question 14b with the last day of the outbreak they determined in Question 10a.

15. Compare your SIR graph to the example graph shown in the “Summary” tab.
   a. Describe one difference between your SIR graph and the example SIR graph. What do you think caused this difference?
      Student responses will vary. Some differences may include:
      ● Curves shifted left or right
      ● Peak for the infectious curve shifted left, right, higher, or lower
      ● Different numbers of susceptible or removed individuals at the end of the outbreak
      Students should offer ideas as to what may have led to the differences they observed.
   b. What might this mean about your population or the settings (i.e., transmission and recovery probabilities) you simulated?
      Students should connect the transmission and recovery probabilities they modeled with the shape of each curve. Appendix 1 discusses how these probabilities can affect the curves in more detail.

   For example, students may observe that their susceptible curve is shifted to the left relative to the example SIR graph’s. This suggests individuals left their susceptible group more quickly, so the transmission probability they modeled may be greater than the one used to generate the example SIR graph.

PART 4: Simulate an Outbreak in a Partially Vaccinated Population

16. Before starting the simulation, answer the following questions.
   a. Predict whether the pathogen will spread throughout the population by the end of the simulation (25 days) if one individual is vaccinated per day. Explain your reasoning.
      Students should justify their answers similar to those in Question 8. They should also consider the impact of vaccination in this case. They may predict that introducing vaccinated individuals will slow the spread of the pathogen by decreasing the number of susceptible individuals.
   b. Do you expect the pathogen to spread similarly to how it did in your previous simulation (for the unvaccinated population)? Why or why not?
      Students should recognize that introducing a vaccinated individual (a member of the removed group) into the population each day will reduce the spread of the pathogen.

17. Following the guidance of your instructor, download, print, or sketch an image of your graph. Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.
   As in Question 11, instruct your students as to which method you prefer for saving and submitting their SIR graphs.

18. Once you complete the simulation, answer the following questions:
   Student responses will depend on their graphs. Additional examples of SIR graphs from unvaccinated and vaccinated populations can be found in Appendix 2.
   a. Describe how quickly or slowly the pathogen spread in your population. For example, how long did it take for the pathogen to begin spreading?
Students should describe when the number of individuals infected by the pathogen increased and peaked in the population based on the infectious curve.

b. How does the spread you observed compare to what you predicted in Question 16?
*Students should compare their results to their predictions like they did in Question 9b. In this case, they may also describe how introducing vaccinated individuals affected the pathogen’s spread. They may note that individuals who remained susceptible throughout the outbreak tended to be close to removed individuals (i.e., recovered or vaccinated individuals) and other susceptible individuals, rather than infectious individuals.*

19. The arrows in the diagram below represent how an individual in the population could move between the three groups. In this case, a susceptible individual becomes infectious and eventually recovers.

a. Consider how a susceptible individual who gets vaccinated would move between these groups. Describe the directions of their movements or add arrows to the diagram below.
*Students should indicate that the vaccinated individual moves directly from the susceptible group to the removed group, as shown in the example below.*

b. In Part a, which group(s) did the individual move between? Which group(s) (if any) did they skip?
*The vaccinated individual moves between the susceptible and removed groups, skipping the infectious group.*

PART 5: Compare Simulated Outbreaks in the Unvaccinated and Vaccinated Populations

20. Compare your SIR graphs for the unvaccinated population (Question 11 in Part 3) and the vaccinated population (Question 17 in Part 4).
*Student graphs will depend on the transmission probability and recovery probability they used. Figures 4 and 5 show examples of graphs using a 60% transmission probability and 25% recovery probability.*
*Additional examples can be found in Appendix 2.*

![SiR Graph](image)

*Figure 4: An example SiR graph of an unvaccinated population (60% transmission probability, 25% recovery probability).*
Figure 5: An example SIR graph of a vaccinated population (60% transmission probability, 25% recovery probability).

a. How are your two graphs similar?
   Some similarities may include:
   ● Overall shape of SIR curves (i.e., susceptible curve trends downward; infectious curve increases, peaks, and decreases; removed curve trends upward).
   ● The number of people in each group at the start of the simulations are the same.

b. How are they different?
   Some differences may include:
   ● The susceptible curve in the vaccinated population may be shifted right compared to the one in the unvaccinated population.
   ● The removed curve in the vaccinated population may be shifted left compared to the one in the unvaccinated population.
   ● The infectious curve in the vaccinated population may be shifted right and have a lower “flattened” peak compared to the one in the unvaccinated population.
   ● The number of people in each group may differ at various points. For example, there may be more susceptible individuals at the end of the vaccinated simulation compared to the unvaccinated one.

c. Based on your comparison of these graphs, how did vaccination affect the spread of the pathogen?
   Students will likely find that vaccination reduced the spread of the pathogen. They may note that infections were less likely to occur in areas with mostly susceptible and immune (removed, including vaccinated) individuals. The outbreak in their vaccinated population may have been shorter than in their unvaccinated population, since more immune individuals were introduced in the former.

21. Complete the table below to compare how many individuals were in each group at the start and end of each simulation.
   Results for the example graphs in Figures 4 and 5 are shown below. Students should have the same results for Day 0 in both populations. Other results will vary depending on the transmission probability and recovery probability they modeled.
22. For your simulated outbreak in the *vaccinated* population:
   a. How many days did it take to reach peak infection? How does this compare with your answer in Question 13c?
      
      *Students should compare the day(s) in the unvaccinated vs. vaccinated simulations with the greatest number of infectious cases.*

   b. How many individuals were infected up until peak infection? How does this compare with your answer in 14c?
      
      *Students should calculate the number of individuals like they did in Question 14c and compare the results.*

   c. How many individuals were infected over the entire outbreak? How does this compare with your answer in 14d?
      
      *Students should calculate the number of individuals like they did in Question 14d and compare the results.*

   d. How many uninfected individuals remained in the unvaccinated vs. vaccinated population at the end of the outbreak? Use the table in Question 21 to answer this question.
      
      *Student responses will vary. In the unvaccinated population, the number of uninfected individuals is the number of susceptible individuals at the end of the outbreak. In the vaccinated population, the number of uninfected individuals is the number of susceptible individuals plus the number of vaccinated individuals at the end of the outbreak.*

### PART 6: Assumptions and Limitations of the SIR Model

23. Our model, and many others, works by combining assumptions with real data to predict a likely outcome.
   
   a. Describe one assumption of our SIR model.

   b. Explain when this assumption may not be true in real life.
      
      *Student responses for Parts a and b will vary. Some examples of the model’s assumptions and when they wouldn’t be true include:*

      - The population doesn't increase or decrease. This wouldn't be true if there are births, deaths, or individuals moving into/out of the population.
      
      - Recovered individuals are never reinfected. This wouldn’t be true for pathogens (e.g., cold viruses, influenza/flu, SARS-CoV-2) that can reinfect people.
● Once an individual is infected, they are immediately infectious. This wouldn’t be true for pathogens that have an incubation period before an infected individual can infect others.
● All individuals have the same number of daily contacts. This wouldn’t be true if some individuals (e.g., those in densely populated areas) interact with many more individuals than others do (e.g., those in sparsely populated areas).
● Infectious individuals recover at a constant rate based on the average recovery probability. This wouldn’t be true if recovery rates vary based on individual factors.
● The vaccine is 100% effective, so vaccinated individuals are fully immune from becoming infected. This wouldn’t be true if vaccinated people can still be infected in some cases (even if their infections are typically less severe).

c. Why do you think we still made this assumption? For example, why is it helpful to simplify in this way? Students should justify their answers using a rationale that aligns with the information in the Click & Learn. They may indicate that the assumption makes the system easier to study or makes the model easier to develop, analyze, and use.

24. In the Outbreak Simulator, our model assumes that close contacts are located directly next to, but not diagonal to, infectious individuals. In the image shown here, the icons with striped backgrounds indicate the close contacts of the infectious individual (red icon) in the middle.
   a. If our model assumed that close contacts include those on a diagonal, what would be the maximum number of close contacts per infectious individual?
      **8 individuals (4 on the sides and 4 on the diagonals)**
   b. How would increasing the number of close contacts affect transmission in our model?
      **Since infectious individuals can infect only their susceptible close contacts, increasing the number of close contacts would likely increase the number of individuals who can be infected each day. This would increase overall transmission, allowing the pathogen to spread through the population more quickly.**

25. Models allow us to predict a likely outcome based on certain factors and inputs, such as the transmission and recovery probabilities.
   a. What’s one factor that the model in the Outbreak Simulator does not include?
      **Student responses will vary. Some factors include:**
      ● Deaths
      ● Births
      ● Individuals moving into and out of the population
      ● Individuals changing locations between days
      ● Fluctuating transmission or recovery probabilities
      ● Larger population size
   b. When might omitting this factor from the model be appropriate or useful?
      **Student responses will vary. They may identify situations in which the factor can be omitted because it is irrelevant or insignificant for the timeframe, population, pathogen, etc., of interest. For example, deaths/births may be insignificant over a short time period for a disease with a low mortality rate.**

      **Students may also note when omitting the factor makes the model easier to analyze or the results easier to interpret. For example, omitting individuals moving into/out of the population or larger population sizes may make it easier to keep track of individuals. Omitting some details may also be helpful for simplifying the system to gain a broader understanding of general effects and patterns.**
c. When might including this factor in the model be appropriate or useful?
   
   *Student responses will vary. They may describe situations in which the factor is relevant to the main research question (e.g., if we want to investigate the effects of vaccination, we should include vaccination in our model). They may also describe situations in which the factor is likely to have a significant impact on what is being studied. For example, for a pathogen with a high mortality rate, we may want to include deaths in our model because it will greatly affect the number of individuals in each group.*

   d. How might you change the model to include this factor?
   
   *Students should describe how they would alter the model to account for the factor they are addressing. For example, if they wanted to include reinfections, they could describe how they might add a step or process in the model that allows some individuals in the removed group to reenter the susceptible group.*

**EXTENSION: Modeling an Epidemic**

1. Record the name of your selected pathogen and the transmission and recovery rates that you will model below.
   
   *Students should select their pathogens from the table in the “Student Worksheet” and record the corresponding rates.*

2. For your first simulation, you will model disease spread in a population of 1,000 individuals with a 30% vaccination rate. Determine the number of initial individuals in each group to reflect this scenario. Assume one infectious individual started the outbreak. List the settings below and enter them into the simulator.
   
   a. Initial susceptible individuals: 699
      
      *This is the total number of individuals in the population minus the number of infectious and removed individuals: 1000 – 1 – 300 = 699.*
   
   b. Initial infectious individuals: 1
      
      *As stated in the question, there is only one infectious individual at the start of the outbreak.*
   
   c. Initial removed individuals: 300
      
      *This is 30% of the total population: 1000 × 0.3 = 300.*

3. Following the guidance of your instructor, download, print, or sketch an image of your graph. Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.
   
   *As in Question 11, instruct your students as to which method you prefer for saving and submitting their SIR graphs. Figure 6 shows an example SIR graph for the parameters in Question 2.*

![Figure 6: An example SIR graph for the spread of SARS-CoV-2 (omicron variant) in a vaccinated population (79% transmission probability, 8% recovery probability).](image-url)
4. Next, you will model disease spread in an unvaccinated population of 1,000 individuals using the same pathogen, transmission rate, and recovery rate as in Question 1. You will need to adjust the number of individuals in each group to model an unvaccinated population. List your new settings below:

   a. Initial susceptible individuals: **999**
   
   *This is the total number of individuals in the population minus the number of infectious and removed individuals: 1000 – 1 – 0 = 999.*

   b. Initial infectious individuals: **1**
   
   *As in Question 2, there is only one infectious individual at the start of the outbreak.*

   c. Initial removed individuals: **0**
   
   *Since the population is unvaccinated, there are no individuals initially in the removed group.*

5. Again, following the guidance of your instructor, download, print, or sketch an image of your graph. Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for. *Figure 7 shows an example SIR graph for the parameters in Question 4.*

![Figure 7: An example SIR graph for the spread of SARS-CoV-2 (omicron variant) in an unvaccinated population (79% transmission probability, 8% recovery probability).]

6. Compare the graphs for the vaccinated population (Question 3) and the unvaccinated population (Question 5).

   a. Describe one similarity between these graphs.
   
   *Student responses will vary. Some responses for the graphs in Figures 6 and 7 include:*
   
   ● The overall shape of the infectious curve is the same in both SIR graphs. Each infectious curve increases near the beginning of the outbreak, peaks, and then decreases toward the end of the outbreak.
   
   ● By the end of each outbreak, everyone in the population is in the removed group.
   
   ● The number of individuals in the susceptible group decreases over time.
   
   ● The number of individuals in the removed group increases throughout the outbreak.

   b. Describe one difference between these graphs.

   *Student responses will vary. Some responses for the graphs in Figures 6 and 7 include:*

   ● At the start of each outbreak, the numbers of individuals in the susceptible and removed groups are different.

   ● The peak of the infectious curve for the vaccinated population is shifted right compared to the one for the unvaccinated population.

   ● The peak of the infectious curve for the vaccinated population is lower than the one for the unvaccinated population.
● At peak infection, there are approximately 700 individuals infected on Day 15 in the unvaccinated population and approximately 420 individuals infected on Day 20 in the vaccinated population.
● The number of individuals in the susceptible group approaches 0 earlier in the outbreak for the unvaccinated population (around Day 17) compared to the vaccinated population (around Day 23).

c. How does the “removed” curve differ between graphs?

In the unvaccinated population, the removed curve starts at 0, since the population is fully susceptible at the start of the outbreak, and gradually increases over time. For the example in Figure 4, it takes until Day 10 for the removed group to begin gaining individuals.

In the vaccinated population, the removed curve starts at 300 individuals and gradually increases over time, starting around Day 15 for the example in Figure 3.

7. When might it be more beneficial to model vaccination like you did in the Outbreak Simulator (Part 4), instead of modeling it like you did in the Epidemic Simulator here?

Student responses will vary. They may suggest that the Outbreak Simulator is more useful for visualizing the individuals in a population and selecting individuals in a specific position or area to vaccinate.

REFERENCES

SIR Model


Data for Pathogens in Part 3


Data for Pathogens in the Extension


**Trauma-Informed Teaching Practices**


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APPENDIX 1: ANALYZING AND INTERPRETING SIR GRAPHS

The “Summary” tab under “SIR Model Basics” in the Click & Learn summarizes some key takeaways about SIR graphs. This appendix provides additional information on analyzing and interpreting each curve of an SIR graph. It may be helpful to refer to an example SIR graph, such as the ones below and in Appendix 2.

![Figure A1: An example “idealized” SIR graph.](image1)

![Figure A2: An example SIR graph generated by the Outbreak Simulator for 15% transmission probability and 50% recovery probability.](image2)

Susceptible Curve

During an outbreak, the number of susceptible individuals typically decreases over time, either to zero (as shown in Figures A1 and A3–4) or to a stable plateau (as shown in Figures A2 and A5–6).

The processes of transmission and recovery impact how many individuals move out of the susceptible group.

- **Transmission** directly impacts how quickly susceptible individuals become infected and move to the infectious group.
- **Recovery** indirectly impacts the number of susceptible individuals that move to the infectious group. For example, if the recovery probability is small, infectious individuals will remain infectious for a relatively long period of time and have more opportunities to infect other susceptible individuals.
As a result, transmission and recovery probabilities/rates will affect how quickly the susceptible curve decreases.

- When *transmission is high and recovery is low*, the pathogen can spread more rapidly. So, the susceptible curve declines more rapidly (shifts left).
- When *transmission is low and recovery is high*, the pathogen is less likely to spread. So, the susceptible curve declines more slowly (shifts right).

### Infectious Curve

During an outbreak, the infectious curve typically increases, peaks, and then decreases over time.

- The curve initially increases as the pathogen spreads and infects susceptible individuals.
- The curve reaches a peak when the number of newly infectious individuals (which enter the infectious group from the susceptible group) equals the number of infectious individuals recovering (which leave the infectious group and enter the removed group).
- The curve eventually decreases when there are fewer susceptible individuals to infect and more infectious individuals recover and move to the removed group.

The shape of the infectious curve depends on the transmission and recovery probabilities/rates.

- When *transmission is high and recovery is low*, the infectious curve shifts to the left. As an example, compare Figure A3 (high transmission) and Figure A5 (low transmission).
- When *transmission is low and recovery is high*, the infectious curve shifts to the right.
- When *transmission is very low and recovery is very high*, an outbreak may not occur. Since the number of infectious individuals remains low, the infectious curve is relatively flat (Figure A2).

The infectious curve in a vaccinated population is typically “flatter” than the infectious curve in an unvaccinated population. As an example, compare Figure A3 (measles, unvaccinated) with Figure A4 (measles, vaccinated) or Figure A5 (mumps, unvaccinated) with Figure A6 (mumps, vaccinated).

### Removed Curve

The removed curve starts at zero in a fully susceptible population. It typically increases over time (as susceptible individuals become infected and recover) and eventually plateaus. If an outbreak does not occur, the number of removed individuals may remain low over time (e.g., Figure A2).

The removed curve is affected by the recovery probability/rate.

- When *recovery is low*, infectious individuals are recovering more slowly. So, the curve may shift to the right.
- When *recovery is high*, infectious individuals are recovering relatively quickly. So, the removed curve may shift to the left.
APPENDIX 2: ADDITIONAL EXAMPLE SIR GRAPHS FOR PART 3

In Part 3 of the “Student Worksheet,” students use the Outbreak Simulator to generate SIR graphs. This appendix shows several example graphs generated by the Outbreak Simulator for different transmission and recovery probabilities.

Note that the Outbreak Simulator generates graphs based on probabilistic events. So students modeling the same transmission and recovery probabilities may still obtain slightly different SIR graphs.

Examples of high transmission probability: Measles

**Figure A3:** An example SIR graph for the spread of measles in an *unvaccinated* population (75.6% transmission probability, 12.5% recovery probability).

**Figure A4:** An example SIR graph for the spread of measles in a *vaccinated* population (75.6% transmission probability, 12.5% recovery probability, one individual vaccinated per day).
Examples of low transmission probability: Mumps

**Figure A5:** An example SIR graph for the spread of mumps in an *unvaccinated* population (25% transmission probability, 16.1% recovery probability).

**Figure A6:** An example SIR graph for the spread of mumps in a *vaccinated* population (25% transmission probability, 16.1% recovery probability, one individual vaccinated per day).
APPENDIX 3: SIR MODEL MATHEMATICAL EQUATIONS FOR EPIDEMIC SIMULATOR

This appendix shows the equations used in the Epidemic Simulator to calculate changes in the number of individuals in each group (S, I, and R) from one day to the next. Although many other SIR models use differential equations (continuous time) instead of difference equations (discrete time), we used difference equations for this simulator because it focuses on day-to-day changes, which may be more intuitive for students.

The simulator uses a system of three difference equations:

\[
\begin{align*}
S_{D+1} &= S_D - t \left( \frac{S_D}{N} \right) I_D \\
I_{D+1} &= I_D + t \left( \frac{S_D}{N} \right) I_D - r I_D \\
R_{D+1} &= R_D + r I_D
\end{align*}
\]

The variables in these equations are as follows:

- \( D \): day number
- \( S_D \): the number of **susceptible** individuals on day \( D \)
- \( I_D \): the number of **infectious** individuals on day \( D \)
- \( R_D \): the number of **removed** individuals on day \( D \)

The constant parameters are as follows:

- \( t \): the **transmission rate**, which represents the average likelihood, per day, that a susceptible individual becomes infected
- \( r \): the **recovery rate**, which represents the average likelihood, per day, that an infectious individual recovers
- \( N \): the **total** number of individuals in the population, which always equals \( S_D + I_D + R_D \)

Additional information about these equations can be found in the “Model Calculations Background” section in the “SIR Model Advanced” tab. Note that the Click & Learn shows simplified versions of the equations without subscripts.
APPENDIX 4: TRANSMISSION AND RECOVERY RATE CALCULATIONS
This appendix describes how transmission and recovery rates can be calculated for a given pathogen. The rates in the “Extension” section of the “Student Worksheet” were calculated in this way.

The recovery rate \( r \) is approximately:
\[
r = \frac{1}{\text{infectious period length (days)}}
\]

The transmission rate \( t \) is:
\[
t = R_0 r
\]

where \( R_0 \) is the basic reproductive number. Additional information on \( R_0 \) can be found in the “Disease Spread Background” section in the “SIR Model Advanced” tab.

An example calculation for common cold (rhinovirus), based on data from Spencer et al. (2022), is shown below.

The average infectious period length for rhinovirus is 9.4 days. So:
\[
r = \frac{1}{9.4} = 0.106 \approx 11\%
\]

The average \( R_0 \) for rhinovirus is 1.88. So:
\[
t = (1.88)(0.106) = 0.199 \approx 20\%
\]