Modeling COVID-19 Control Measures on a Cruise Ship

OVERVIEW

This case study for the *Modeling Disease Spread* Click & Learn follows the 2020 COVID-19 outbreak on the *Diamond Princess* cruise ship, which captured headlines in the early days of the COVID-19 pandemic. Students model the impact of implementing control measures, specifically lockdown and isolation, on the spread of COVID-19 onboard the ship.

The case study facilitates students' use of the Epidemic Simulator from the *Modeling Disease Spread* Click & Learn. It is recommended for students who have already completed the "SIR Model Basics" section of the Click & Learn, those who are already familiar with the SIR model, and/or college introductory biology classes. By completing this case study, students will deepen their understanding of the SIR model, interpreting SIR graphs, and how control measures impact SIR curves.

This case study is divided into the following parts:

- In **Part 1**, students learn about the COVID-19 outbreak on the *Diamond Princess* cruise ship, which occurred when there was neither much public awareness of COVID-19 nor any COVID-19 vaccines.
- In **Part 2**, students prepare to model the outbreak by determining two key parameters: the recovery and transmission rates in the absence of control measures.
- In **Part 3**, students model the outbreak in the absence of control measures (i.e., no lockdown).
- In **Part 4**, students model the impact of lockdown (i.e., restricting passengers to their cabins).
- In the optional **extension**, students model the combined impact of lockdown and isolation (i.e., removing infected passengers from the ship).

Additional information can be found on this resource's webpage, including suggested audience, estimated time, and curriculum connections.

The educator document contains multiple resources for implementing this case study with students, including the following (select links to go directly to each section in the document):

- background on the SIR model, SARS-CoV-2/COVID-19, and cruise ship outbreaks
- teaching tips for this resource, including discussion considerations, using the extension activity, and a brief description of the Epidemic Simulator
- suggested procedures for this resource, including using the handout and saving/submitting graphs
- assessment guidance for the questions in the "Student Handout"
- additional discussion questions that can be used with students
- appendices with more information on the equations used in the simulator, SARS-CoV-2/COVID-19, and the *Diamond Princess* outbreak

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 (curves) on the graph.
- Parameters that influence transmission and recovery affect the spread of a pathogen in a population and thus the shape of the SIR graph.

- The basic reproduction number (R_0) measures the potential spread of a pathogen in a fully susceptible population.
- Control measures, such as lockdown and isolation, can reduce the spread of a pathogen by reducing the transmission rate and/or increasing the recovery rate.

STUDENT LEARNING TARGETS

- Analyze how a highly infectious disease (large R_0) spreads in a population.
- Describe the relationship between the basic reproduction number (R_0), transmission rate, and recovery rate.
- Modify parameters in the SIR model to integrate control measures.
- Predict how control measures will impact an outbreak when a vaccine is unavailable.
- Compare model results to real outbreak data.

PRIOR KNOWLEDGE

Students should have a basic understanding of:

- pathogens and their relationship to infectious diseases
- the SIR model and SIR graphs
- interpreting line graphs

MATERIALS

- copies of the "Student Handout"
- access to the *Modeling Disease Spread* Click & Learn
- computer or mobile device that can take screenshots, download files, or print images

BACKGROUND

SIR MODEL

More information on the SIR model can be found within the *Modeling Disease Spread* Click & Learn and its downloadable materials. 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 the 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 to infection. This includes both recovered individuals, who were previously infected, and vaccinated individuals. (Note that this case study does not include vaccinated individuals, since COVID-19 vaccines were not yet available at the time.)

SARS-COV-2, COVID-19, AND CRUISE SHIPS

COVID-19 is an infectious respiratory disease caused by the coronavirus SARS-CoV-2, which is transmitted through airborne droplets produced by infected individuals. More information on SARS-CoV-2 and COVID-19 can be found in Appendix 2. You can also use the BioInteractive animation *Biology of SARS-CoV-2* as an introduction for students.

Some of the earliest data on SARS-CoV-2 transmission came from COVID-19 outbreaks on cruise ships, which are also discussed in Appendix 2. Ships used multiple control measures — such as quarantining at sea, passenger lockdowns, and isolating infected individuals — to reduce the spread of disease. This case study focuses on an outbreak onboard the *Diamond Princess* cruise ship in early 2020 and some of the corresponding control measures, detailed in Appendix 3.

TEACHING TIPS

DISCUSSING SARS-COV-2 AND COVID-19 IN A CULTURALLY SENSITIVE MANNER

- At the beginning of the case study, you may wish to have students recall what life was like during the very early days of the pandemic circa January 2020 (e.g., before lockdowns, business shutdowns, or vaccines). This could include uncertainty about how the virus spreads and implementation of early control measures.
  - Keep in mind that memories about the pandemic may be triggering and/or traumatic for some students. Please approach this topic sensitively and alert students ahead of time that they'll be discussing life/events that took place during the pandemic.
- The COVID-19 outbreak in the case study occurred on a cruise ship that traveled to several Asian countries. When facilitating the activity, be prepared to call out anti-Asian racism, discrimination, and misconceptions associated with COVID-19.
  - When discussing COVID-19 outbreaks, clarify that they have occurred throughout the world, not just in Asian countries.
  - Be prepared to challenge students' assumptions when necessary. Be aware that comments that are not fully explained may inadvertently promote stereotypes or suggest inaccurate conclusions. The National Association of Psychiatrists provides tips for educators on countering coronavirus stigma and racism.
  - Zhou et al. 2021 describes the effects of anti-Asian racism on students' mental health.
- When facilitating the activity, also be prepared to address misconceptions and/or conspiracy theories about the origins of SARS-CoV-2 (e.g., the virus was created in a lab). Studies indicate that SARS-CoV-2 has a zoonotic origin (i.e., animal-to-human transmission), possibly from bat hosts, although the precise route remains unknown (Mallapaty et al. 2021, Temmam et al. 2022).
  - When introducing SARS-CoV-2, you may choose to discuss zoonoses and provide other examples of pathogens that entered the human population from infected animal reservoirs (e.g., HIV, Nipah virus, *Ebolavirus*).

USING THE EXTENSION

In the optional extension at the end of the "Student Handout," students model the combined impact of lockdown and isolation on COVID-19 spread on the cruise ship. By completing the extension, students will:

- modify parameters in the SIR model to account for lockdown and isolation
- compare R_0 values in different scenarios (i.e., no control measures, single control measure, multiple control measures)
- consider disease spread in a community based on R_0 values

Since some of the extension questions are similar to those in Part 4 but have students consider a new control measure, you could use the extension to have students reinforce what they previously learned and transfer their knowledge to a new scenario. The end of the extension also has more questions that you can use to explore R_0 with students.

USING THE SIMULATOR

The *Modeling Disease Spread* Click & Learn includes two simulators: the Outbreak Simulator and the Epidemic Simulator. For this case study, students use the **Epidemic Simulator** (under "Simulate an Epidemic" in the "SIR Model Advanced" tab) to model disease spread in a *large* population. This simulator uses difference equations (detailed in Appendix 1) to calculate the number of individuals in each group over time.

Students who are less familiar with the SIR model or who need a refresher can go through the "SIR Model Basics" section of the Click & Learn, which discusses the basic components of the SIR model. It also includes the Outbreak Simulator, which simulates disease spread in a *small* population.

For more information about the differences between the simulators, refer to "Simulating Disease Spread at Different Scales" in the "Simulate an Epidemic" section.

USING DECIMALS OR WHOLE NUMBERS

The Epidemic Simulator calculates the number of individuals in different groups based on mathematical equations. The simulator displays the resulting values with one decimal point for precision.

As a result, students using the simulator may report the numbers of individuals with one decimal place as well. Or they may round these values to whole numbers for the sake of realism (as you cannot have, for example, 0.1 of an individual in real life). If you prefer one approach over the other, instruct your students accordingly.

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).

PROCEDURE

USING THE HANDOUT

Use the "Student Handout" to guide students through the case study. The handout can be completed individually or in small groups. You can customize the handout as needed for your class.

- In Part 2, students should read the "Measuring Early Disease Spread" section of the "Disease Spread Background" tab (found in the "SIR Model Advanced" section of the *Modeling Disease Spread* Click & Learn) *before* answering the questions.
- In Part 3, students model the outbreak in the *absence* of the lockdown control measure. In Part 4, they recalculate the transmission rate when lockdown is in place and model the outbreak in the *presence* of lockdown.
    - If working in pairs, each student can select a different scenario (i.e., absence or presence of lockdown) to model. After completing their simulations, students can engage in peer learning, articulate their thinking, and compare their SIR graphs and the effects of lockdown.
- In the optional extension, students model the combined impact of lockdown and isolation on disease spread. In this case, "isolation" is defined as removing identified infectious individuals from the ship. Increasing the recovery rate in the model serves as a proxy for isolation, since the "removed" infectious individuals are no longer capable of infecting susceptible individuals on the ship. As described in the handout:

- It takes infectious individuals 10 days, on average, to recover from SARS-CoV-2 infection, resulting in an average recovery rate of 10% per day.
- Under the isolation control measure, infected individuals were identified and removed from the ship in four days on average. This can be modeled as an average recovery rate (or "removal rate") of 25% per day.

For **in-person** classes:

- In Part 2, consider guiding the class through example calculations of the recovery rate (Question 4a) and transmission rate (Question 5a) to ensure they know how to calculate the parameters before they begin modeling.
- After students have completed Question 7, consider projecting the resulting SIR graph to the whole class. This will help confirm that students are using the simulator correctly before they continue the activity.

For **online** classes:

- Provide access to a digital version of the handout so that each student or each group has their own copy. Google Docs versions of the handout are provided in the "Resource Google Folder" in the "Materials" box on this resource's webpage.
- If students work on the activity individually:
  - For **synchronous** classes, consider pairing students in Zoom breakout rooms so they can discuss their SIR graphs.
  - For **asynchronous** classes, consider grouping students into teams in a discussion forum where they can compare and discuss their progress through the handout. You may wish to mandate that students share and discuss their responses to specific questions.

SAVING AND SUBMITTING GRAPHS

In several parts of the "Student Handout," students use the Epidemic Simulator in the *Modeling Disease Spread* 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 Epidemic Simulator. This will open a menu (Figure 1) 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 handout.
- **Screenshot** the graph if downloading is unavailable.
  - Screenshot functions and commands will depend on the device. Guide students through the screenshotting process if needed.
  - Students can save the screenshot as an image file to submit or insert it into a digital copy of their handout.

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 1); select the "Print chart" option.
- Students may attach their printed graphs directly to their handout or submit labeled graphs with their handout.

- **Draw** 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.

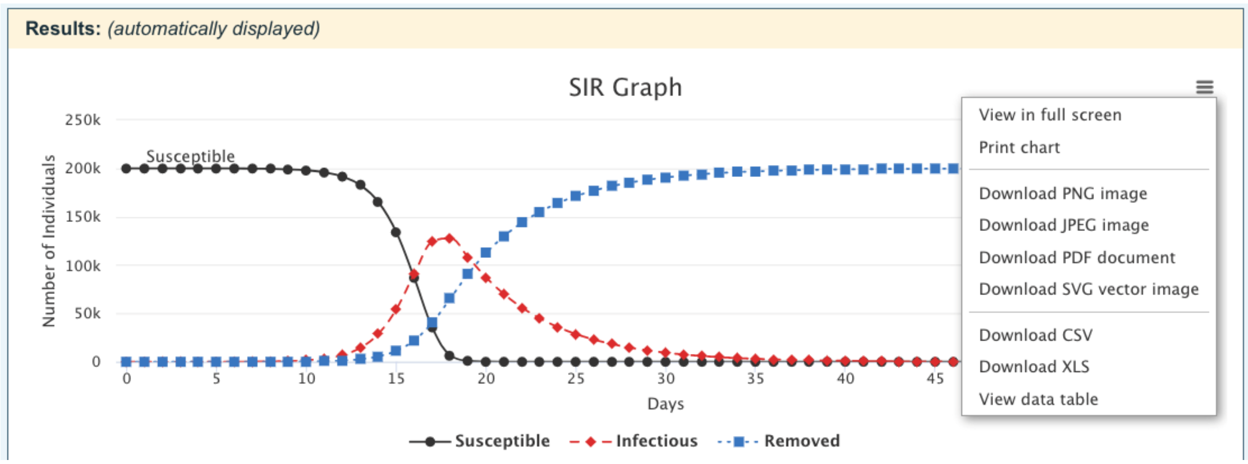


Figure 1. Menu with options for the SIR graph.

ASSESSMENT GUIDANCE

The sample answers below may include more detail than would be provided by most students. They are meant to give you additional information that you may want to discuss with students.

PART 1: THE COVID-19 OUTBREAK ON THE *DIAMOND PRINCESS*

1. Do you predict that an infectious disease would spread faster or slower on a cruise ship than on land? Explain your reasoning.
   Student responses will vary. They may say that the disease would spread faster on a cruise ship, because it contains many people in a confined space. So people on the ship would be more likely to interact with others, and thus spread the pathogen, than people on land.

2. Propose at least **two** control measures that could be used on the ship. Describe how each control measure might reduce the spread of the virus.
   As described in the handout, SARS-CoV-2 is spread through airborne droplets produced by coughing and sneezing. Students may suggest control measures based on this mode of transmission and/or their own experiences. Potential control measures include:
   - ***Lockdown/shelter in place** (e.g., having passengers stay in their individual rooms on the ship) could limit people's interactions with infected individuals.*
   - ***Physical/social distancing** (having people keep a certain distance apart, typically 2 m/6 ft for COVID-19) could reduce their exposure to infected droplets from other people.*
   - ***Handwashing/hand sanitizer** could be used to destroy viruses on people's hands.*
   - ***Disinfecting surfaces** could be used to clean surfaces contaminated with the virus or infected droplets.*
   - ***Air filtration systems** could capture airborne droplets containing the virus.*
   - ***Spending more time outside**, rather than in confined indoor spaces, could reduce the chance of inhaling infected droplets.*

- ***Masks and face shields** could reduce the amount of virus released into the environment by an infectious individual.*
- ***Removing/isolating infected individuals** (e.g., moving them to a hospital) could limit spread of the virus to others.*
- ***Quarantine** (keeping people on the ship) could keep the virus from spreading to people on land. If infected individuals are identified, they can be removed from the ship and treated at a hospital.*
- ***Health monitoring** (e.g., regularly taking people's temperature to detect a fever) can help identify infected individuals more quickly so that they can be isolated and receive treatment.*

Students may also suggest using vaccines or medical treatments. As mentioned in the handout, COVID-19 vaccines were not yet available at the time of this outbreak (early 2020). Not much was yet known or available regarding treatments for COVID-19 either.

PART 2: DETERMINING SARS-COV-2 RECOVERY RATE AND TRANSMISSION RATE

3. Scientists estimated that the R_0 for SARS-CoV-2 on the *Diamond Princess* was 14.8.
   a. In your own words, describe what an R_0 of 14.8 means.
   An R_0 of 14.8 means that each infectious person will, on average, infect 14.8 (about 15) more people throughout the duration of their infection (assuming everyone else in the population is susceptible). (For more information on R_0, refer to the "Disease Spread Background" tab.)

   b. Given this R_0, what might happen to the people onboard the ship if no control measures were put in place? Explain the reasoning for this prediction.
   Given this R_0, each infectious person would infect many more individuals on the ship, resulting in rapid spread of the virus. So if no control measures are put in place, everyone on the ship could rapidly become infected.

4. Scientists estimated that the infectious period for SARS-CoV-2 was 10 days.
   a. Calculate the corresponding recovery rate (r) for SARS-CoV-2 as a percentage per day.
   $$r = \frac{1}{\text{10 days}} \times 100\% = 10\% \text{ per day}$$

   b. Describe how this recovery rate would affect the cruise ship population during the outbreak. (It may be helpful to explain what would happen to an infectious or removed individual in this case.)
   The recovery rate is 10% per day. This means that, on any given day, an average of 10% of infectious individuals on the ship will recover and move to the removed group. Over time, more and more infected individuals on the ship will gradually move to the removed group.

   c. What might happen on the ship if the infectious period for SARS-CoV-2 was 5 days instead of 10 days?
   If the infectious period was 5 days, the recovery rate would be 20% instead of 10%. This means that infectious individuals would be twice as likely to recover on any given day and wouldn't have as much time to spread the virus. The outbreak on the ship could end earlier in this case.

5. Based on an estimated R_0 of 14.8 and the recovery rate you calculated in Question 4a:
   a. Calculate the corresponding transmission rate (t) as a percentage per day.
   $$t = (10\% \text{ per day}) \times (14.8) = 148\% \text{ per day}$$

   b. In your own words, explain what the transmission rate that you calculated means.
   A transmission rate of 148% per day means that, on average, each infectious individual will infect 1.48 susceptible individuals per day throughout the duration of their infection.

c. Given this transmission rate, would you predict that the virus would spread quickly or slowly onboard the ship? Explain your reasoning.
A transmission rate of 148% is relatively high, which suggests that the virus would spread quickly through the susceptible population onboard the ship.

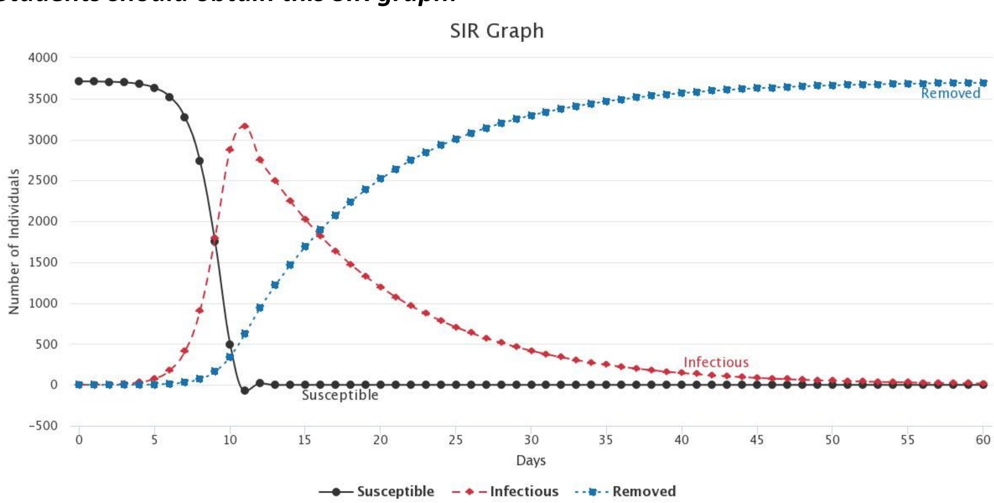
6. In Question 2, you proposed two control measures that could reduce the spread of SARS-CoV-2. Describe whether each control measure affects the transmission rate, the recovery rate, or both. Explain your reasoning.
Student responses will vary depending on the control measures they selected. Control measures that affect the transmission rate would reduce the spread of the virus. Control measures that affect the recovery rate would help people infected with the virus recover more quickly. Students should explain how the control measures they chose do one or the other, or both.

PART 3: MODELING COVID-19 SPREAD WITHOUT CONTROL MEASURES

7. Following the guidance of your instructor, download, print, or sketch an image of your graph. Label it as **"No Control Measures."** Make sure to include your graph when submitting this handout, 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.

Students should use the following settings:
- Total Days: 60
- Transmission Rate (*t*): ***148%*** *(answer to Question 5a)*
- Recovery Rate (*r*): ***10%*** *(answer to Question 4a)*
- Initial Susceptible Population: 3712
- Initial Infected Population: 1
- Initial Removed Population: 0

Students should obtain this SIR graph:



8. Examine the relationship among the three curves (susceptible, infectious, removed) in the graph.
a. The susceptible curve should decrease over time. What happens to individuals who leave the susceptible group? (In other words, which group do they move into?)
They move into the infectious group after being infected with the virus (SARS-CoV-2).

b. The removed curve should increase over time. Where do new individuals in the removed group come from?
They come from the infectious group after recovering from COVID-19.

c. The infectious curve should increase, then decrease. Where do new individuals in the infectious group come from, and what happens to them once they leave the infectious group?
They come from the susceptible group after being infected with the virus (as in Part a). They leave the infectious group by going into the removed group after recovering from COVID-19 (as in Part b).

9. Use these instructions to complete Table 2.
   - For the "Peak" day, record the day with the greatest number of infectious individuals.
   - For the "Peak" column, record the number of individuals in each group for the day that you selected. (You can hover over points on the SIR graph in the simulator to display the number of individuals.)
   - Skip the "Corrected Values" column for now. You will come back to it in Question 10c.

Students may report answers using decimals or whole numbers, as discussed in [this teaching tip](). The last column for corrected values will not be completed until Question 10c; refer to the Question 10c answer below for more information.

Table 2. Data for the model with no control measures at peak infection.

Groups	**Peak** Day ***11***	**Corrected Values (Question 10c)**
Susceptible (S)	***–72.4***	***0***
Infectious (I)	***3,156.6***	***3,084.2***
Removed (R)	***628.8***	***628.8***

10. Use Table 2 to answer the following questions:

a. How many individuals had been infected by peak infection (i.e., those currently infected, plus those who were previously infected and recovered)?
3,785.4 individuals (3,156.6 infectious individuals + 628.8 recovered individuals)

Students may notice that this answer is higher than the total population (3,713 individuals) but is offset by the negative number of susceptible individuals. The following question goes into more detail about why this number of susceptible individuals is negative.

b. According to this model, how many individuals were susceptible at peak infection? How would you interpret this value?
–72.4 individuals. A negative number of individuals wouldn't make sense in real life, and it may be an artifact of how the model was set up. We can interpret it as indicating that there are no more susceptible individuals at this point.

This question is meant to help students appreciate that, although a negative number of individuals would not make sense in the real world, this model can still provide useful information about the outbreak if it is properly interpreted. You may wish to discuss the following points with students:

- ***Models like this one use equations to approximate what will happen in the real world, which allows us to make predictions about potential outcomes.***
- ***This particular model uses difference equations (discussed in Appendix 1) to calculate the number of individuals in each group on each day. These difference equations update only once per day, based on the numbers from the previous day. This is useful as an approximation but may not reflect changes throughout the day.***
- ***Since the transmission rate is relatively high (148%), susceptible individuals move to the infectious group very quickly. Since the difference equations update only once per day, the model may overshoot how many individuals are moving out of the susceptible group, resulting in a negative number of susceptible individuals on the day of peak infection.***
- ***Though a negative number doesn't make sense in real life, we can interpret it as indicating that all individuals have moved out of the susceptible group at this point.***

c. Based on your answer to Part b, how might you "correct" the values in Table 2? Fill in the last column of Table 2 with your proposed corrections.
Refer to Table 2 in Question 9 above for sample answers. The number of individuals in the susceptible group should be corrected from –72.4 to 0. To keep the total population constant at 3,713 individuals, the number of individuals in the infectious group could be decreased by 72.4 as well (from 3,156.6 to 3,084.2). Students may also suggest changing the number of removed individuals.

11. Compare the results of your model without control measures (as shown in Table 2 and your graph in Question 7) to the real outbreak (as summarized in Figure 2 and Table 3).
    a. Describe one similarity and one difference between the model and the real outbreak.
    Student responses will vary. Some similarities may include:
    - ***At the start of the outbreak, most of the ship's population was probably susceptible.***
    - ***The number of susceptible individuals decreased over time.***
    - ***As the outbreak progressed, more and more individuals became infectious.***

    Some differences may include:
    - ***In real life, people may have got on or off the ship at different stops before the quarantine. The initial case, for example, got off in Hong Kong on Day 5. In the current model, the ship's population size stays constant (no one enters or leaves) throughout.***
    - ***In real life, passengers onboard the ship may not have mixed homogenously. For example, infectious individuals may have limited their interaction to certain people (such as family and friends), activities, or rooms. This could have reduced the exposure of many susceptible individuals. The current model doesn't account for this.***
    - ***In real life, public health control measures were implemented to reduce the spread of the virus onboard the ship. The current model doesn't include any control measures.***
    - ***The model predicts exactly how many people are in the susceptible, infectious, and removed groups at each time point. In real life, individuals had to be tested to confirm whether they had COVID-19, which could be less precise (e.g., maybe not everyone was tested every day, there could be some false positives/negatives, etc.).***

    b. During the real outbreak, 61 passengers tested positive for COVID-19, 18 days after the initial case boarded the ship. Did the model show a similar number of infected individuals on Day 18?
    No. On Day 18 in the model, everyone onboard the ship had been infected (1,472.3 infectious individuals and 2,240.7 removed individuals). This is many more than the 61 passengers who tested positive in the real outbreak.

12. On February 24, 2020 — 35 days after the initial case boarded the ship — the Japanese government ended the ship's quarantine and allowed everyone onboard to leave. This day corresponds to Day 35 in the model.
    a. Using your SIR graph from Question 7, complete the "End of Quarantine" column in the following table. (Remember that you can hover over points on the SIR graph in the simulator to display the number of individuals.)

Table 4. Data for the model with no control measures at end of quarantine.

Groups	**End of Quarantine** Day 35
Susceptible (S)	***0***
Infectious (I)	***245.5***
Removed (R)	***3,467.5***

    b. How many individuals on the ship had been infected by the end of the quarantine (i.e., those currently infected, plus those who were previously infected and recovered)?
    All 3,713 individuals (245.5 infectious + 3,467.5 removed)
    c. There were 712 confirmed cases of COVID-19 on the ship by the end of the quarantine. How does this outcome compare to your model?
    The 712 cases in real life are far fewer than the 3,713 infected individuals in the model. This may suggest that the outbreak spread much slower in real life than in the model.

13. What may account for the differences you observed between the real outbreak and the model without control measures?
    Student responses will vary. They may mention that during the real outbreak, public health control measures were implemented to reduce the spread of disease onboard the ship. The model doesn't account for any control measures.

PART 4: MODELING THE IMPACT OF LOCKDOWN

14. Scientists estimated that the lockdown reduced the transmission rate of the virus by 70%. Using this information and the transmission rate you calculated in Question 5a, calculate the estimated transmission rate under lockdown.
    The transmission rate with no control measures (from Question 5a) is 148% per day. The transmission rate under lockdown is a 70% reduction, meaning 30% of this transmission rate. This would be 148% per day x 0.30 = 44.4% per day.

15. Predict how the transmission rate you calculated in Question 14 would affect the spread of the virus on the ship. (It may be helpful to explain what might happen to a susceptible, infectious, or removed person with this transmission rate.)
    A transmission rate of 44.4% under lockdown is considerably lower than the transmission rate modeled of 148% with no control measures. This suggests that infectious individuals will transmit the virus to fewer susceptible individuals, resulting in a slower spread of the virus.

16. Consider how lockdown could impact the model — in particular, the three curves (susceptible, infectious, and removed) in the SIR graph.
    a. Briefly describe, or draw directly on your graph from Question 7, how each curve might change if you

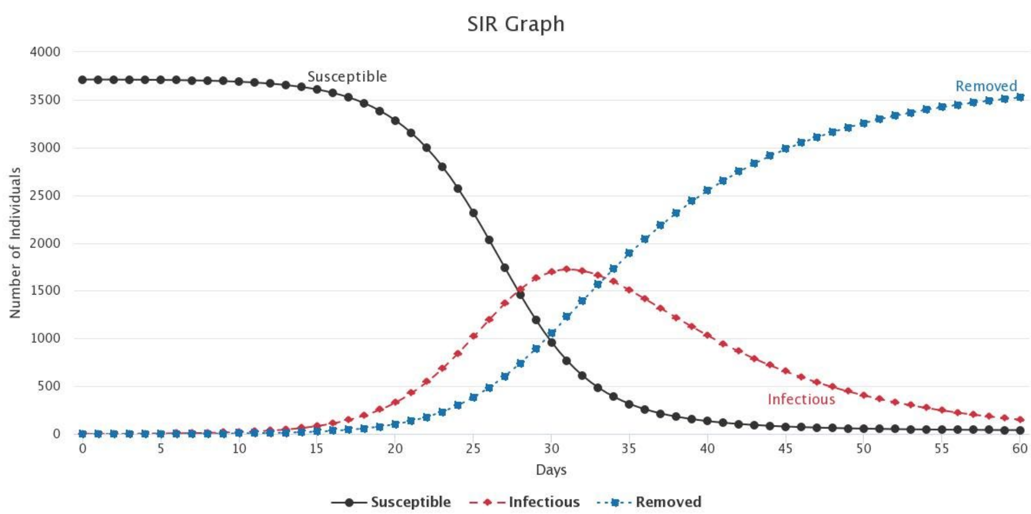
implemented lockdown. For example, would some curves shift to the right/left, up/down, or not at all?
Student predictions will vary. They may suggest shifts that indicate fewer people are being infected or that the outbreak is not spreading as rapidly. They will generate the graph for this scenario in Question 17, then compare it with their predictions in Question 18.

b. Explain your reasoning for the change you predicted.
Student responses will vary but should correspond to the shifts they predicted in Part a. They may mention that fewer individuals will be infected daily and over the duration of the outbreak, because the transmission rate is reduced.

17. The following settings are for when lockdown is put in place.
    - Total Days: 60
    - Transmission Rate (*t*): ***44.4%*** *(answer to Question 14)*
    - Recovery Rate (*r*): ***10%*** *(answer to Question 4a)*
    - Initial Susceptible Population: 3712
    - Initial Infected Population: 1
    - Initial Removed Population: 0

    Enter these settings into the Epidemic Simulator, then start the simulation to generate a new graph. Following the guidance of your instructor, download, print, or sketch an image of your graph. Label it as **"Lockdown."** Make sure to include your graph when submitting this handout, in whichever format your instructor asks for.

    Students should obtain this SIR graph:



18. How does this graph compare to what you predicted in Questions 15 and 16?
Student answers will vary depending on their predictions.

19. Compare your SIR graph for *lockdown* (Question 17) with your previous SIR graph for *no control measures* (Question 7).
    a. How do the curves in these two graphs differ? (Compare the timelines and number of people in each group.)
    Student responses will vary but should indicate that the outbreak spreads more slowly when lockdown is implemented. For example:

- ***The curves are shifted to the right in the lockdown graph.***
- ***Peak infection occurs on Day 11 in the graph for no control measures, but it occurs on Day 31 for the graph with lockdown (because the infectious curve shifted to the right).***
- ***The peak of the infectious curve is lower and more spread out in the lockdown graph, indicating that fewer people are infectious on any given day. (As discussed in Part b, the curve is "flattened.")***

b. You may have heard that implementing control measures like lockdowns can help "flatten the curve." Which curve is being "flattened," and why might this be desirable?
The infectious curve is "flattened" in the lockdown graph compared to the graph with no control measures, suggesting that fewer individuals would become infected under lockdown. In general, this is desirable because it can slow the spread of the disease and reduce stress on the healthcare system, especially during peak infection.

20. Complete Table 5 using similar instructions as in Question 9.
As discussed in the answer for Question 9, students can also round these values to whole numbers.

Table 5. Data for the model with lockdown at peak infection.

Groups	**Peak** Day ***31***
Susceptible (S)	***765.1***
Infectious (I)	***1,721.8***
Removed (R)	***1,226***

21. Use Table 2 (data for the model with *no control measures*) and Table 5 (data for the model with *lockdown*) to answer the following questions:
    a. How does the day of peak infection differ between the model with *no control measures* versus the model with *lockdown*?
    Peak infection occurs sooner in the model with no control measures (Day 11) than in the model with lockdown (Day 31).
    b. At peak infection, how does the number of infected individuals (i.e., those currently infected, plus those who were previously infected and recovered) compare between the model with *no control measures* versus the model with *lockdown*?
    At peak infection, there are more infected individuals in the model with no control measures (basically everyone on the ship on Day 11) than in the model with lockdown (only 2,947.8 of 3,713 on Day 31).
    c. At peak infection, how does the number of susceptible individuals compare between the model with *no control measures* versus the model with *lockdown*?
    At peak infection, there are fewer susceptible individuals in the model with no control measures (basically 0, since everyone has already been infected, on Day 11) than in the model with lockdown (765.1 on Day 31).

22. Let's compare the results of both models on the same day — specifically, the day of peak infection in the model with *no control measures*.
    a. Use these instructions to complete Table 6:

- In the first row, record the day of peak infection in the model with *no control measures* (same as in Table 2).
- In the "No control measures" column, record the number of individuals in each group on that day (same as in the "Corrected Values" column for Table 2).
- In the "Lockdown" column, record the number of individuals in each group for the model with *lockdown* on that same day.

Table 6. Comparison of the models *with no control measures* and with *lockdown*.

Day *11* (peak infection for model with *no control measures*)		
Groups	**No control measures**	**Lockdown**
Susceptible (S)	***0***	***3,680.2***
Infectious (I)	***3,084.2***	***25.6***
Removed (R)	***628.8***	***7.2***

b. Compare the number of infected and susceptible individuals on that day for these two models. How do they differ?
On this day (Day 11):
- ***There are substantially fewer infected individuals in the model with lockdown (32.8) than in the model with no control measures (basically everyone on the ship).***
- ***There are more susceptible individuals in the model with lockdown (3,680.2) than in the model with no control measures (basically 0).***

c. Based on these models, was lockdown an effective control measure? Use evidence to support your reasoning.
Yes, lockdown was effective in slowing the spread of disease. Student responses should be supported with evidence, which may include the following:
- ***Peak infection occurred later in the model with lockdown (Day 31) than in the model with no control measures (Day 11).***
- ***At peak infection, fewer individuals had been infected in the model with lockdown (2,947.8 of 3,713 on Day 31) than in the model with no control measures (basically everyone on the ship by Day 11).***
- ***On Day 11, fewer individuals had been infected in the model with lockdown (32.8) than in the model with no control measures (basically everyone on the ship).***

23. Compare the results of the model with lockdown (as shown in Table 5 and your graph in Question 17) to data from the real outbreak (as summarized in Figure 2 and Table 3).
   a. Describe one similarity and one difference between the model and the real outbreak.
   Student responses will vary and may be similar to their responses for Question 11a.
   b. During the real outbreak, 61 passengers tested positive for COVID-19, 18 days after the index case boarded the ship. Did the model show a similar number of infected individuals on Day 18?
   No. On Day 18 in the model, 249.2 individuals had been infected (191.6 infectious individuals and 57.6 removed individuals). This is about four times as many individuals as the 61 passengers who tested positive in the real outbreak.

24. Remember that the ship's quarantine ended on Day 35.
    a. Using your SIR graph from Question 17, complete the "End of Quarantine" column in the following table.

Table 7. Data for the model with lockdown at end of quarantine.

Groups	**End of Quarantine** Day 35
Susceptible (S)	***313.8***
Infectious (I)	***1,505.1***
Removed (R)	***1,894***

    b. How many individuals on the ship had been infected by the end of the quarantine (i.e., those currently infected, plus those who were previously infected and recovered)?
    3,399.1 individuals (1,505.1 infectious + 1,894 removed)

    c. There were 712 confirmed cases of COVID-19 on the ship by the end of the quarantine. How does this outcome compare to your model?
    The 712 cases in real life are still fewer than the 3,399.1 infected individuals in the model. This may suggest that the outbreak spread more slowly in real life than in the model.

25. What may account for the differences you observed between the real outbreak and the model with lockdown?
Student responses will vary. They may mention that this model includes only one control measure, whereas multiple control measures may have been implemented during the real outbreak.

26. During the real outbreak, control measures were implemented approximately two weeks after the initial case boarded the ship.
    a. How could the timing of control measure implementation affect the spread of the virus on the ship?
    Implementing control measures earlier may reduce the spread of the virus.

    b. In the model with lockdown, when are control measures implemented?
    Immediately. The effects of lockdown (reduced transmission rate) are present throughout the entire simulation, starting on Day 0 (when the initial case boards the ship).

    c. Based only on timing of control measure implementation, would you have expected more disease spread in the lockdown model or the real outbreak? What might explain the differences between your expectations and reality?
    We might expect more disease spread in the real outbreak, since control measures were implemented later. But in reality, there was less disease spread in the real outbreak. This suggests that the timing of control measure implementation is not the only factor that affects disease spread, and other factors (such as implementing multiple control measures) may have played a bigger role during the real outbreak.

27. Return to the Epidemic Simulator with the same settings as in Question 17, the model with lockdown. In the simulator, R_0 is automatically calculated and displayed below the SIR graph.
    a. What is the R_0 value when lockdown is implemented?
    4.4

b. In your own words, describe what this R_0 value means.
An R_0 of 4.4 means that each infectious person will infect 4.4 (about 4) susceptible individuals on average.

c. How does this R_0 value compare to the estimated R_0 value when no control measures are in place (Question 3)?
This value is lower than the R_0 when no control measures are in place (14.8). Thus, each infectious individual infects fewer susceptible individuals, on average, under lockdown.

28. What's the overall impact of implementing lockdown on the ship? In other words, does the implementation of lockdown protect the susceptible population? Consider the number of susceptible individuals left in the population in Tables 2 and 5.
Student responses will vary. They should mention that lockdown led to fewer infected individuals on the ship, as well as slower disease spread. For example, comparing Tables 2 and 5 shows fewer infected individuals at peak infection in the lockdown model compared to the model with no control measures.

29. What other control measures could we use today to reduce the spread of the virus in a confined location, such as a cruise ship?
Student responses will vary. Refer to the answer for Question 2 for a list of potential control measures. Another option that is available today is COVID-19 vaccines. Since vaccines need some time to work, students may suggest that cruise lines require passengers and crew members to be vaccinated prior to a cruise.

30. Think about using lockdown as a control measure in society in general, not just on a ship. In your opinion, would the costs of implementing lockdown (for example, restricting people's movement) outweigh the benefits? Use evidence to justify your response.
Student responses will vary. Some may argue that the costs (e.g., social or economic) of implementing lockdown outweigh the benefit of reducing disease spread. Others may argue that the benefits of protecting as many susceptible individuals as possible outweigh the costs. Students should use evidence to support their argument.

EXTENSION: MODELING THE IMPACT OF LOCKDOWN AND ISOLATION

31. Is there a benefit to removing infectious passengers from the ship? Explain your reasoning.
Yes, removing infectious individuals would reduce the likelihood of susceptible individuals interacting with infectious individuals and potentially getting infected.

32. Explain how increasing the recovery rate can simulate the effects of the isolation control measure (removing infectious individuals from the ship).
The effects of isolation and recovery are similar, in that they both result in infectious individuals being "removed" so that they are no longer able to infect susceptible individuals. (In the case of isolation, infectious individuals are physically removed from the ship. In the case of recovery, infectious individuals enter the "removed" group.) Thus, increasing the recovery rate can be used to simulate removal due to isolation.

33. Consider how both lockdown and isolation together could impact the model — in particular, the three curves (susceptible, infectious, and removed) in the SIR graph — compared to lockdown alone.

a. Briefly describe, or draw directly on your graph from Question 17, how each curve might change if you implemented both lockdown and isolation. For example, would some curves shift to the right/left, up/down, or not at all?

Student predictions will vary. They may suggest shifts that indicate fewer people are being infected or that the outbreak is not spreading as rapidly. They will generate the graph for this scenario in Question 34, then compare it with their predictions in Question 35.

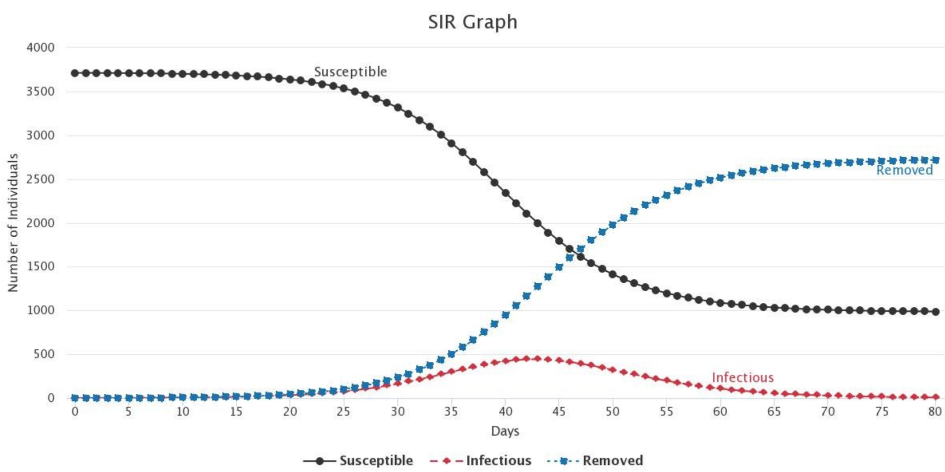
b. Explain your reasoning for the change you predicted.
Student responses will vary but should correspond to the shifts they predicted in Part a. They may suggest that fewer individuals will be infected daily and over the duration of the outbreak, because the recovery rate is increased.

34. The following settings are for when both lockdown and isolation are put in place. The transmission rate represents the effects of lockdown, and the recovery rate represents the effects of isolation (infectious individuals removed from the ship in four days on average). As before, the "Removed Population" represents individuals who recovered from SARS-CoV-2 infection, *not* individuals who were removed from the ship.

- Total Days: **90**
- Transmission Rate (*t*): ***44.4%*** (*answer to Question 14)*
- Recovery Rate (*r*): 25%
- Initial Susceptible Population: 3712
- Initial Infected Population: 1
- Initial Removed Population: 0

Enter these settings into the Epidemic Simulator, then start the simulation to generate a new graph. Following the guidance of your instructor, download, print, or sketch an image of your graph. **Label it as "Lockdown and Isolation."** Make sure to include your graph when submitting this handout, in whichever format your instructor asks for.

Students should obtain this SIR graph:



35. How does this graph compare to what you predicted in Question 33a?
Student responses will vary depending on their predictions.

36. Compare your SIR graph for *both lockdown and isolation* (Question 34) with your previous SIR graph for *lockdown* only (Question 17). How do the curves in these two graphs differ? (Compare the timelines and number of people in each group.)
Student responses will vary but should indicate that fewer individuals are infected when both lockdown and isolation are implemented. For example:

- ***The curves are shifted to the right in the graph with both lockdown and isolation.***
- ***Peak infection occurs on Day 31 in the graph for lockdown only, but it occurs on Day 43 for the graph with both lockdown and isolation (i.e., infectious curve shifted to the right).***
- ***The peak of the infectious curve is flatter in the graph with both lockdown and isolation, indicating that fewer people are infectious on any given day.***
- ***In the model with both lockdown and isolation, the susceptible curve plateaus with around 1,000 susceptible individuals remaining in the population.***

37. Answer the following questions regarding the population makeup at peak infection. For the model with *both lockdown and isolatio*n, refer to your results in the Epidemic Simulator. For the model with *lockdown* only, refer to your previous results in Table 5.
    a. How many days did it take to reach peak infection in the model with *both lockdown and isolation*?
    43 days
    b. How does the day of peak infection differ between the model with *lockdown* versus the model with *both lockdown and isolation*?
    Peak infection occurs sooner in the model with lockdown only (Day 31) than in the model with both lockdown and isolation (Day 43).
    c. At peak infection, how does the number of infected individuals (i.e., those currently infected, plus those who were previously infected and recovered) compare between the model with *lockdown* versus the model with *both lockdown and isolation*?
    At peak infection, there are more infected individuals in the model with lockdown only (2,947.8 on Day 31) than in the model with both lockdown and isolation (1,717 on Day 43).
    d. At peak infection, how does the number of susceptible individuals compare between the model with *lockdown* versus the model with *both lockdown and isolation*?
    At peak infection, there are fewer susceptible individuals in the model with lockdown only (765.1 on Day 31) than in the model with both lockdown and isolation (1,996.1 on Day 43).

38. Let's compare the results of both models on the same day — specifically, the day of peak infection in the model with *lockdown* only.
    a. Use these instructions to complete Table 8:
        - In the first row, record the day of peak infection in the model with *lockdown* only (same as in Table 5).
        - In the "Lockdown" column, record the number of individuals in each group on that day (same as in the "Peak" column for Table 5).
        - In the "Lockdown and Isolation" column, record the number of individuals in each group for the model with *both lockdown and isolation* on that same day.

Table 8. Comparison of the models *with lockdown* and with *both lockdown and isolation*.

Day *31* (peak infection for *lockdown* model)		
Groups	**Lockdown**	**Lockdown and Isolation**
Susceptible (S)	***765.1***	***3,247.9***
Infectious (I)	***1,721.8***	***187.4***
Removed (R)	***1,226***	***277.7***

b. Compare the number of infected and susceptible individuals on that day for these two models. How do they differ?
On this day (Day 31):
- ***There are substantially fewer infected individuals in the model with both lockdown and isolation (465.1) than in the model with lockdown only (2,947.8).***
- ***There are more susceptible individuals in the model with both lockdown and isolation (3,247.9) than in the model with lockdown only (765.1).***

c. Based on your models, were both lockdown and isolation together more effective than lockdown alone? Use evidence to support your reasoning.
Yes, both control measures were more effective than lockdown alone. Student responses should be supported with evidence, which may include the following:
- ***Peak infection occurred later in the model with both lockdown and isolation (Day 43) than in the model with lockdown only (Day 31).***
- ***At peak infection, fewer individuals had been infected in the model with both lockdown and isolation (1,717 on Day 43) than in the model with lockdown only (2,947.8 on Day 31).***
- ***On Day 31, fewer individuals had been infected in the model with both lockdown and isolation (465.1) than in the model with lockdown only (2,947.8).***

39. Compare the results of your model (as shown in Table 8 and your graph in Question 34) to the data from the real outbreak (as summarized in Figure 2 and Table 3). During the real outbreak, 61 passengers tested positive for SARS-CoV-2, 18 days after the initial case boarded the ship.
   a. Did the model show a similar number of infected individuals on Day 18?
   Yes. On Day 18 in the model, 53.4 individuals had been infected (23.7 infectious individuals and 29.7 removed individuals). This is relatively close to the 61 passengers who tested positive in the real outbreak.

   b. There were 712 confirmed cases of COVID-19 on the ship by the end of the quarantine. How does this outcome compare to your model?
   The 712 cases in real life is relatively similar to the model's predictions of 805 infected individuals (299.4 infectious individuals and 505.6 removed individuals) on Day 35.

40. In Table 9, record the results at the end of the quarantine (Day 35) for each of the three models. You can use the number of susceptible and infected individuals that you previously recorded in Table 4 for the model with *no control measures* and in Table 7 for the model with *lockdown*. For the model with *both lockdown and isolation*, refer to your graph from Question 34.

Table 9. Comparisons of the three models at the end of quarantine (Day 35).

Model	Transmission rate	Recovery rate	# Susceptible on Day 35	# Infected (Infectious + Removed) on Day 35
No control measures (Table 3)	148	10	***0***	***3,713***
Lockdown (Table 7)	44.4	10	***313.8***	***3,399.1***
Lockdown and isolation (Extension)	44.4	25	***2,907.9***	***805***

41. Answer the following questions based on Table 9.
    a. What's the overall impact of implementing both lockdown and isolation on the ship? In other words, do these control measures protect the susceptible population?
    When both lockdown and isolation were implemented, far fewer individuals were infected. So these control measures protected most of the susceptible population from infection.
    b. Is there a benefit to implementing more than one control measure? Use evidence from your simulation results to support your response.
    Yes, implementing both lockdown and isolation together resulted in the fewest infected individuals. For example, the model with both lockdown and isolation had far fewer individuals infected on Day 35 (805) than the model with lockdown only (3,399.1) and the model with no control measures (3,713).
42. Examine potential disease spread based on R_0 in the three models (no control measures, lockdown only, both lockdown and isolation). The R_0 value for the model without control measures has been provided in the first row of Table 8.
    a. Complete Table 10 with the R_0 values (on Day 0) for the model *with lockdown* (Question 27a) and the model with *both lockdown and isolation*.

Table 10. R_0 values on Day 0 for the three models.

Model	R_0 on Day 0
No control measures	***14.8***
Lockdown	***4.4***
Lockdown and isolation	***1.8***

    b. How do the R_0 values in these three models differ?
    The R_0 value is highest for no control measures, in the middle with lockdown only, and lowest with both lockdown and isolation.
    c. What do these differences indicate about the effects of the control measures?
    The differences indicate that implementing more control measures can decrease R_0 (since this results in infectious individuals transmitting the virus to fewer susceptible individuals).
43. All the people on the *Diamond Princess* were allowed to leave on Day 36. Some of these people may still have been infectious. Propose at least **two** control measures that infectious individuals leaving the ship could personally implement to reduce the spread of the virus to their communities.
    Student responses will vary and may include:
    - ***self-quarantining for up to 10 days, the duration of the infectious period (As of December 2023, the CDC recommends that individuals who test positive isolate at home for at least 5 days, as studies suggest that infected individuals are most infectious during the first 5 days.)***
    - ***masking around others***
    - ***social distancing around others***

    Although this case study focuses on population-level control measures, this question helps students realize that people can also take individual actions to reduce the spread of disease.

ADDITIONAL DISCUSSION QUESTIONS

Optional questions are provided below. Consider using these questions in whole-class discussions, either in-person or online, or for graded follow-up assignments.

PART 1: THE COVID-19 OUTBREAK ON THE *DIAMOND PRINCESS*

- In the city of Wuhan, China, where COVID-19 was first reported a few months before the *Diamond Princess* outbreak, the R_0 for SARS-CoV-2 was estimated to be 3.7 (Rocklöv et al. 2020). Propose a hypothesis to explain the difference between this R_0 and the R_0 of 14.8 during the *Diamond Princess* outbreak.

PART 2: DETERMINING SARS-COV-2 RECOVERY RATE AND TRANSMISSION RATE

- Of the 3,713 people onboard the *Diamond Princess*, 2,645 were passengers and 1,068 were crew members. Passengers (average age 66 years) were more likely to test positive for COVID-19 than crew members (average age 36.6 years), despite the crew members interacting with more people. Why do you think this was the case?

PART 3: MODELING COVID-19 SPREAD WITHOUT CONTROL MEASURES

- By the end of quarantine, there had been seven COVID-19-related deaths on the ship. The SIR model in the Click & Learn assumes no deaths in the population. If you wanted to include deaths in the model, which group (susceptible, infectious, or removed), if any, would you put them into? Explain your reasoning.
- In the simulation, we assumed that there was only one infectious individual (the “initial case”) at the start of the outbreak.
  - How would you modify the settings to include more than one infectious individual at the start of the outbreak?
  - Would having more than one infectious individual at the start affect the course of the outbreak? Explain your reasoning.
  - Using the Epidemic Simulator, model an outbreak with five infectious individuals at the start. Compare your SIR graph to the one you generated in Question 7.

PART 4: MODELING THE IMPACT OF LOCKDOWN

- Were lockdowns an effective way of controlling COVID-19 outbreaks globally when vaccines were not yet available? (Students may need to consult other resources to address this question.)
- In general, how does the effective reproduction number, R_e, differ from R_0? (To learn more about R_e and how it relates to R_0, students can read the “Measuring Later Disease Spread” section of the “Disease Spread Background” tab in the Modeling Disease Spread Click & Learn.)
- When modeling lockdown in this model, why do we use R_0 on Day 0 to examine disease spread instead of R_e?

EXTENSION: MODELING THE IMPACT OF LOCKDOWN AND ISOLATION

- In what ways were control measures implemented on the ship similar to those implemented on land (e.g., in cities) during the COVID-19 pandemic? In what ways were they different? (Students may need to consult other resources to address this question.)
- How might a similar outbreak on a cruise ship progress today, now that many people are vaccinated against COVID-19?
- How could you model vaccination in the SIR model?

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Figure 1 in the "Student Handout" adapted from Figure 1 in Nakazawa et al. 2020, used under CC BY 4.0

APPENDIX 1: SIR MODEL MATHEMATICAL EQUATIONS FOR EPIDEMIC SIMULATOR

This appendix shows the difference 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 focused on day-to-day changes, which may be more intuitive for students.

The simulator uses a system of three difference equations:

$$S_{D+1} = S_D - t\left(\frac{S_D}{N}\right)I_D$$
$$I_{D+1} = I_D + t\left(\frac{S_D}{N}\right)I_D - rI_D$$
$$R_{D+1} = R_D + rI_D$$

The variables 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 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 2: ADDITIONAL BACKGROUND ON SARS-COV-2, COVID-19, AND CRUISE SHIPS

SARS-COV-2 (THE VIRUS)

The virus that causes COVID-19 is a member of the coronavirus family. It is called SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) and is related to SARS-CoV-1, the virus that caused the worldwide SARS epidemic in 2002–2004. Both viruses are closely related to coronaviruses found in bats, so it is hypothesized that SARS-CoV-2 arose from a spillover event (zoonotic transmission) from bats to humans (Mallapaty 2021; Temmam et al. 2022). The exact origin of the virus is an active area of investigation.

SARS-CoV-2 is transmitted through aerosolized droplets that linger in the air when an infected person breathes, talks, laughs, sings, or coughs. The virus-containing droplets can be inhaled by a susceptible person, in whom the virus can infect cells of the nasal passage and lungs.

SARS-CoV-2 is an RNA virus. RNA viruses (which also include influenza) are known to mutate quickly, and SARS-CoV-2 has given rise to many variants through mutation. Some of these variants vary in the severity of the disease they cause and their rate of transmission to susceptible hosts (Tao et al. 2021). For this reason, and also because some newer variants evade the immune system's protection against previous variants, individuals are susceptible to reinfection (Cromer et al. 2021; Harvey et al. 2021).

COVID-19 (THE DISEASE)

COVID-19 (coronavirus disease 2019) is an infectious respiratory disease first reported in Wuhan, China, in December 2019. COVID-19 symptoms vary from asymptomatic to severe. Symptoms experienced by some infected individuals vary but typically include cough, fever, shortness of breath, sore throat, loss of taste or smell, diarrhea, headache, and/or fatigue.

Symptoms generally appear two days to two weeks after exposure. Infected individuals who experience mild or no symptoms may still spread the virus to susceptible individuals through aerosolized droplets (Cevik et al. 2020). A small proportion of infected individuals (typically people over the age of 60 and those who have other medical conditions) experience severe symptoms such as respiratory failure, heart damage, renal failure, or lasting neurological impairments (Cevik et al. 2020).

In December 2020, the first vaccines against COVID-19 were approved by the health authorities of several countries, including the United States.

ROLE OF CRUISE SHIPS

In the early days of the COVID-19 pandemic, a myriad of news stories reported on COVID-19 outbreaks on cruise ships (e.g., Moriarty et al. 2020, Ito et al. 2020, Wikipedia 2023). Several passengers boarded ships while unknowingly infected with SARS-CoV-2. Little was known about the virus or ways to control its spread (and vaccines were not yet available), so governments struggled to deal with ships that arrived at their borders with onboard outbreaks.

These outbreaks were also unique in that they allowed epidemiologists to study transmission of this novel virus in a closed population (i.e., individuals generally could not enter or leave the ship) and provided some of the earliest data on SARS-CoV-2 transmission.

To avoid spreading the virus to mainland populations, many cruise ships with active COVID-19 outbreaks quarantined at sea for at least 14 days. During quarantine, ships used control measures such as lockdowns (i.e., restricting passengers to their cabins) and isolation (i.e., removing infected passengers from ships and sending

APPENDIX 3: DETAILED ACCOUNT OF THE 2020 COVID-19 OUTBREAK ON THE *DIAMOND PRINCESS* CRUISE SHIP

(Summary based on Nakazawa et al. 2020, Jimi and Hashimoto 2020, and Yamagishi et al. 2020. A simplified version of these events is provided in the "Student Handout," which also shows the route of the ship in Figure 1/Table 1 and a timeline of events in Figure 2/Table 3.)

THE INITIAL CASE

On January 20, 2020, an 80-year-old passenger boarded the *Diamond Princess* in Yokohama, Japan. This person had been experiencing COVID-19 symptoms (i.e., coughing) for one day, but was unaware that they were infected with SARS-CoV-2. The infected individual, whom we will call the "initial case," boarded the ship 10 days *before* the World Health Organization (WHO) declared that COVID-19 was a Public Health Emergency of International Concern, and it would still be more than a month before the WHO declared COVID-19 a pandemic. The initial case was on the ship for 6 days between January 20–25, 2020. After disembarking in Hong Kong, the initial case developed a fever and was diagnosed with COVID-19 on February 1, 2020.

EARLY RESPONSES

Through international health regulation channels, officials in Japan, the final arrival point for the *Diamond Princess*, were notified that a passenger infected with SARS-CoV-2 had been onboard the cruise ship. When the ship arrived in Yokohama, Japan, in the evening on February 3, 2020, the Japanese government denied the ship's request to dock and to disembark passengers.

On February 5, a medical team boarded the ship to assess the situation. They administered polymerase chain reaction (PCR) tests to the 273 individuals who displayed COVID-19 symptoms or had had close contact with the initial case. Of those who were tested, 22% tested positive for COVID-19. This strongly suggested that an onboard outbreak was underway.

QUARANTINE PERIOD

The Japanese government put public health measures in place to contain the outbreak on the ship, and the ship was required to anchor at sea for a 14-day health observation period. Passengers were required to stay in their cabin during the quarantine period (i.e., lockdown) and were allowed to go outdoors one hour per day in small groups. While outdoors, passengers practiced physical distancing, wore masks, and were encouraged to engage in frequent hand sanitization.

Passengers used thermometers to monitor their body temperature. Anyone with a fever was tested for SARS-CoV-2 using a PCR test. Those who tested positive were removed from the ship and placed in isolation in designated hospitals. Cabinmates of infected individuals were required to reset their 14-day lockdown period.

LEAVING THE SHIP

Passengers who tested negative gradually began disembarking on February 13, and all passengers and crew members were allowed to leave the ship by February 24. At the end of the quarantine period, there were a total of 712 confirmed cases of COVID-19 and 7 COVID-related deaths.