# Connecting Viral Pandemics to Ecological Population Growth Models
## Student Worksheet

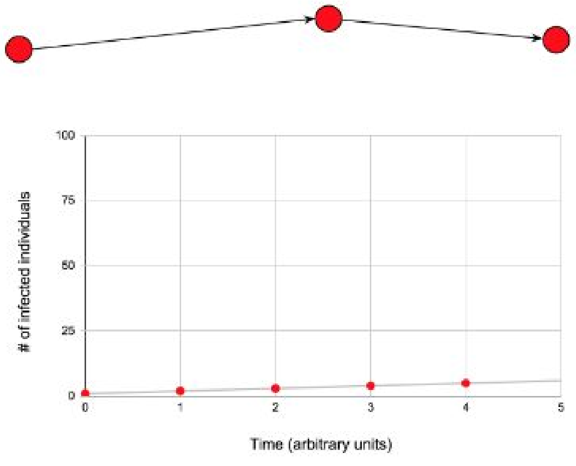
## OVERVIEW

This worksheet complements the HHMI Population Dynamics Click & Learn.

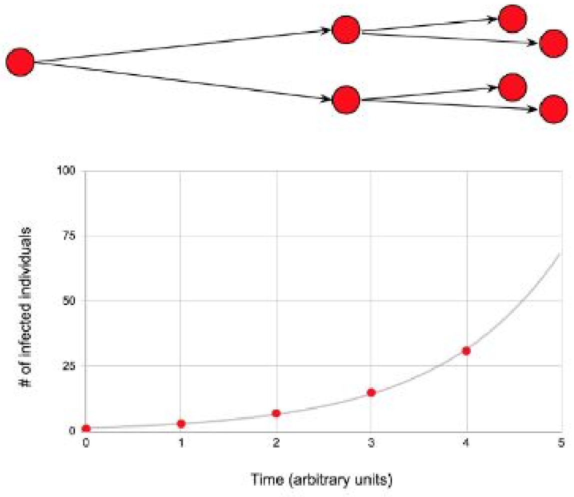
The 2020 zoonotic outbreak of the SARS-CoV-2 virus and the resulting COVID-19 global disease pandemic has been sobering and devastating. The disease spread quietly at first before roaring into nearly every global community. Epidemiologists and medical experts raced to understand the behavior of the disease and the physiological toll it could take on those infected. One critical disease variable that the experts immediately tried to track is $R_0$ (pronounced r-naught). $R_0$ is the basic reproduction rate for a disease and is the potential number of secondary cases one case could produce at the beginning of an outbreak in a completely susceptible (healthy, but not immune) population.

## Modeling $R_0$

The two models below show diseases with an $R_0$ of 1and 2. The red circles in the models are infected and contagious persons. The solid arrows indicate contact and spread of the virus and disease from person to person. The graphs show how the number of people in a population with the disease could increase over time. The time unit is defined as the interval between infections (i.e. the onset of a person's symptoms) in two consecutive generations of the disease and is often symbolized as G/T (generation time). More specifically, the G/T for a disease is the interval between the onset of symptoms in two consecutive generations and depends in part on how soon a person is contagious after becoming infected. The G/T thus determines the speed with which the disease spreads in the population.

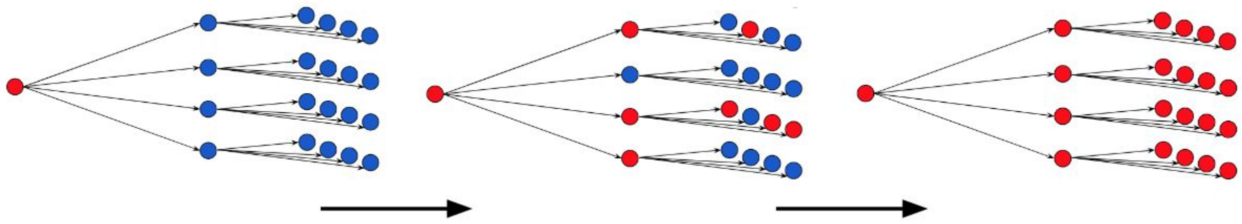


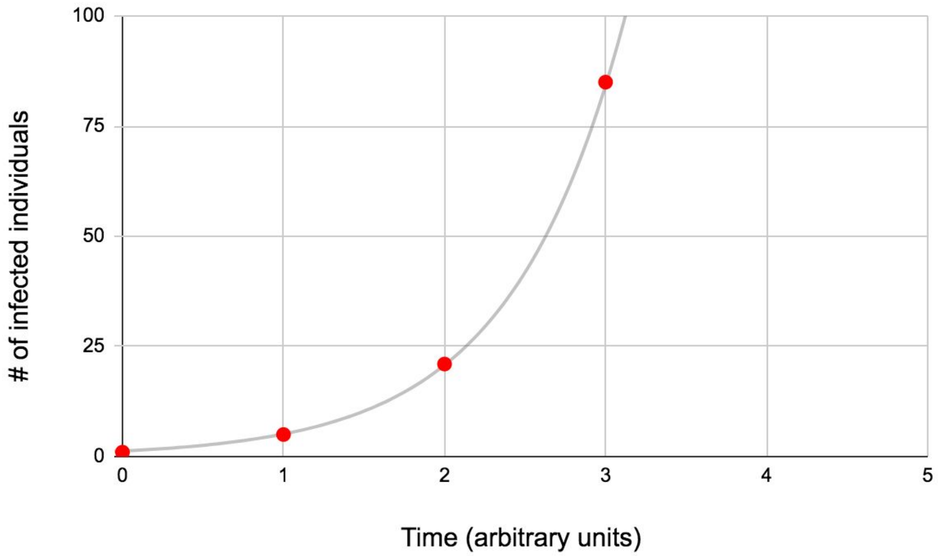
$R_0 = 1$



$R_0 = 2$

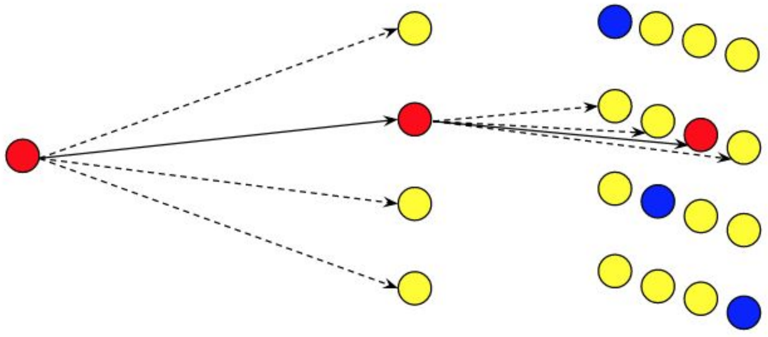
The models below now show how a disease with an $R_0$ of 4 can spread in a population. The first red circle in the leftmost model is called "person zero." Person zero is infected and contagious. The blue circles represent healthy but susceptible individuals in the population. Any additional red circles are people that have also become infected and contagious over the two time periods. Compare the $R_0 = 4$ graph to the $R_0 = 1$ and 2 graphs. What do you notice? What does it mean?





### What is $R_t$?

$R_0$ is not a constant number for a disease as the disease spreads. Later in the life cycle of a disease some people may have had the disease and are immune and some people may have been vaccinated for the disease. The diagram below is for a disease with an initial $R_0$ of 4. An infected and contagious person enters a population (person zero; red circle) but some people in the population have been vaccinated for the disease or have had the disease already and are immune (yellow circles) while others are healthy but not immune (blue circles). At this later time in the spread of the disease each person in the population that is infected now with the disease and is contagious can only infect an average of one additional person. Solid arrows represent direct infections and dashed arrows represent contact with an infected person but no transmission of the disease.



In this simulated population around 70% (15/21) of the people were already protected from the disease and three of the people were protected by others around them (the “herd”) that were already immune.

Thus, the disease could only spread to a few other people. This is what herd immunity looks like.

When a disease has been in a population for a while epidemiologists use a version of $R_0$ called $R_t$. The t stands for time. $R_t$ can be used to indicate how a disease might be currently behaving in a population at a particular time. In the model above, because there is now some herd immunity in the population, the $R_t$ is 1. An outbreak is expected to continue if $R_t > 1$ and is expected to end if $R_t < 1$. $R_t$ is also a function of human behavior. As you remember from the COVID-19 pandemic, people can avoid contracting a disease because they are physically protecting themselves from the disease by using protective equipment (e.g. masks) and keeping their distance from people that might be contagious for the disease. Human behavior can thus drive $R_t$ to less than 1.

**Population dynamics**

$R_0$ represents the maximum epidemic potential of a pathogen, but also the maximum growth potential of a population of organisms. For example, in population dynamics, $R_0$ is the ratio of a population's size (N) at time t (Nt) to the size of the population at time zero ($N_0$). If the quotient of this ratio ($R_0$) is less than 1, the population is shrinking, but if $R_0$ is greater than 1, the population is growing. The $R_0$ for animal species can be used to predict the size of a population in the future. For a threatened or endangered population, $R_0$ can tell us what size a population might decline to over a given time period, or it can tell us how much time we have until a population's size is cut in half.

**ACTIVITY**

In this activity, you will use the HHMI Population Dynamics Click & Learn to explore how different $R_0$ values affect how quickly a disease might spread in a population with no prior immunity. After you launch the interactive it may be helpful to first read through the "Introduction" section of the "Exponential growth model" tab. For some of the questions that give the $R_0$ for a particular region, you will have to convert that value to *r* to plug it into the simulator. The following shows this calculation:

$N(t + 1) = R_0 \times N(t)$

$dN/dt = rN(t)$

$N(t + 1) = N(t) + dN/dt$
$N(t + 1) = N(t) + rN(t)$
$N(t + 1) = (1 + r)\, N(t)$

$\mathbf{R_0 = 1 + r}$ **OR** $\mathbf{r = R_0 - 1}$

The chart below shows what $R_0$ values would look like with varying r values.

| **r** | **+1** | **$R_0$** | **r** | **+1** | **$R_0$** |
|---|---|---|---|---|---|
| 3 | 1 | 4 | -0.05 | 1 | 0.95 |
| 2 | 1 | 3 | -0.1 | 1 | 0.9 |
| 1 | 1 | 2 | -0.3 | 1 | 0.7 |
| 0.5 | 1 | 1.5 | -0.5 | 1 | 0.5 |
| 0.1 | 1 | 1.1 | -0.7 | 1 | 0.3 |
| 0 | 1 | 1 | -0.9 | 1 | 0.1 |

Follow the instructions below and answer the questions in the spaces provided.

## PART I: 1918 Influenza

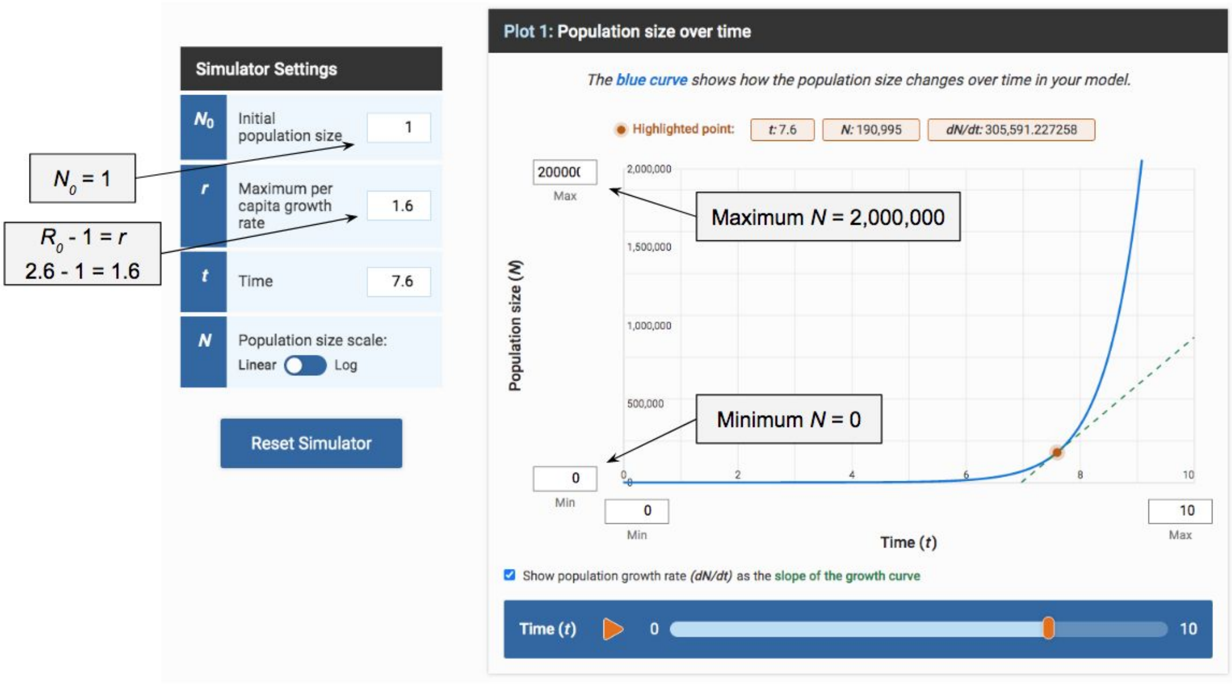
Mae Smith grew up in the Philadelphia suburbs. She was the youngest of five children (four girls and one boy). For two weeks in 1918, constant coughing drowned out the sounds of city life in the Smith house. Mae, her siblings, and both of her parents all became sick at the same time, which caused an extremely stressful period of time. At this point, Mae and her siblings had been out of school for several months (Source: Centers for Disease Control and Prevention).

Amos Brownell lived 880 miles to the west in St. Louis, Missouri. He was born just before the beginning of the Civil War. Amos married, had six children, and spent most of his adult life working as a railroad switchman. He was a healthy, hard-working man. Until he wasn't. His seemingly sudden death in 1919 was hard on the entire community. What made matters worse is that his burial and memorial service were delayed because gravediggers could not keep up with the demand for new graves (Source: Centers for Disease Control and Prevention).

Unfortunately, the stories of Mae and Amos are not unique. An influenza virus was wreaking havoc in 1918. People in Philadelphia and St. Louis as well as all over the world were struggling. Some communities closed public schools so that the recently deceased could be displayed for memorial services. This virus, though, did not impact all communities the same. St. Louis and Philadelphia had two totally different responses to the pandemic. One response saved lives.

1. The $R_0$ in Philadelphia in 1918 was estimated to be 2.6 (Bootsma and Ferguson 2007). At the time, Philadelphia had a population of 1.7 million. Check your parameters. Set $N_0 = 1$ to indicate patient zero. Set the minimum N to zero and the maximum N to at least 1.7 million. You will also need to use $R_0$ to solve for *r*, and then insert the correct value. See the figure below for how to set up the simulator for this first scenario.

   a. Assume no one was immune and everyone had the same chance of contracting this virus. How many time periods (*t*) would it take to infect the entire population of Philadelphia? Drag the orange slider below the graph or the orange circle in the graph to manipulate the time variable.
   b. Remember that for a pandemic such as this, the time unit (*t*) actually represents G/T (generation time), the interval between the onset of symptoms in two consecutive generations. The G/T of the 1918 pandemic was estimated at 3.1 days. In other words, each *t* unit = 3.1 days. How many days would it take to infect the entire population of Philadelphia? Hint: Multiply your answer from question 1a above by the G/T.



Simulator Settings

$N_0$ Initial population size: 1

$r$ Maximum per capita growth rate: 1.6

$t$ Time: 7.6

$N$ Population size scale: Linear Log

Plot 1: Population size over time

*The blue curve shows how the population size changes over time in your model.*

Highlighted point: *t:* 7.6 *N:* 190,995 *dN/dt:* 305,591.227258

☑ Show population growth rate *(dN/dt)* as the slope of the growth curve

$N_0 = 1$

$R_0 - 1 = r$

$2.6 - 1 = 1.6$

Maximum $N$ = 2,000,000

Minimum $N$ = 0

2. $R_0$ in St. Louis in 1918 was estimated to be 2.18 (Bootsma and Ferguson 2007). At the time, St. Louis had a population of 687,000. Set the simulator to the proper parameters as you did for the question above and solve for r.

   a. Assume no one was immune and everyone had the same chance of contracting this virus. How long (t) would it take to infect the entire population of St. Louis? Use the same procedure you did in the previous question.
   b. Using the G/T for the 1918 pandemic, how many days would it take to infect the entire population of St. Louis?

3. Are there any differences between how long it would take for the entire population of Philadelphia to get infected compared to St. Louis? Please explain these differences.

4. What type of safety precautions could the two cities put in place to help with the spread of this disease? Please explain why each precaution would work.

5. The following chart shows a timeline of measures put in place by each city:

| **Date** | **Philadelphia** | **St. Louis** |
|---|---|---|
| 4 October 1918 | Schools, churches, other public places closed (Lynch 1998) | |
| 7 October 1918 | | Schools, churches, and other public places closed. Individuals diagnosed with flu were quarantined in their homes for 14 days (Kalnins 2006) |
| 11 October 1918 | Businesses voluntarily closed (Lynch 1998) | |
| 26 October 1918 | Public places allowed to open (Barry 2004) | |
| 27 October 1918 | Churches reopened (Crosby 1976) | |
| 28 October 1918 | Schools reopened (Crosby 1976) | |
| 30 October 1918 | Theaters and bars reopened (Crosby 1976) | |
| 13 November 1918 | | Businesses reopened (Kalnins 2006) |
| 14 November 1918 | | Schools reopened (Kalnins 2006) |
| 28 November 1918 | | Ban on public gatherings was reinstated and elementary schools were closed again (Kalnins 2006) |
| 22 December 1918 | | Some businesses reopened (Kalnins 2006) |
| 2 January 1919 | | Elementary schools reopened (Kalnins 2006) |

6. What do you think happened in each city over the course of the fall and winter of 1918?

7. The graph below shows the death rate by pneumonia and influenza in Philadelphia compared to St. Louis during 1918. Knowing the safety measures put into place by each city, is this what you would expect? Why or why not?

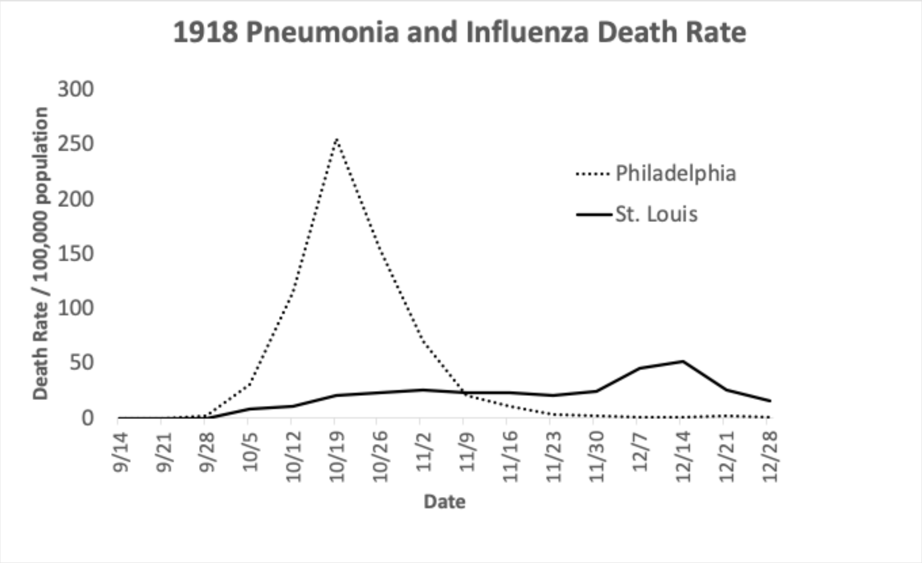


Figure 1. Death rate / 100,000 population by pneumonia and influenza in both Philadelphia and St. Louis. Figure was modified from Hatchett et al. (2007).

## PART II: 2020 COVID-19

At the beginning of the 2020 pandemic, the World Health Organization estimated the $R_0$ of COVID-19 to be between 1.4 and 2.5 (Viceconte and Petrosillo 2020). Later studies showed the median $R_0$ to be anywhere from 2.79 (Liu et al. 2020) to 5.7 (Sanche et al. 2020). Remember that $R_0$ is not a constant number for a disease. The $R_0$ changes regionally as mitigation strategies are put in place and as local citizens begin to follow (or not) the recommended and/or mandated strategies.

1. Assume the initial $R_0$ of COVID-19 to be 2.5. Measles can have an $R_0$ as high as 15 while seasonal influenza tends to have an $R_0$ of 1.3.
   a. Create a graph showing the spread of COVID-19. How many people would be infected when t = 10?
   b. Create a graph showing the spread of measles. How many people would be infected when t = 10?
   c. Create a graph showing the spread of seasonal influenza. How many people would be infected when t = 10?
   d. Which disease would you consider more contagious? Least contagious?

2. New York City, with a population of around 8.4 million, was hit extremely hard by COVID-19. $R_0$ in this area may have been as high as 6.4 (Ives and Buzzuto 2020). If we assume patient zero entered the city and that the generation time was 5.2 days, how many people would potentially be infected in 15 days?

3. Using what you have learned about $R_0$ and $R_t$, explain how it would be possible for places like New York City to get the $R_t$ close to 1.

4. After using this simulator to look at the impacts of varying $R_0$ (or $R_t$) values, explain why strategies like distancing, wearing masks, washing hands, and sanitizing areas are so important.

## Sources

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