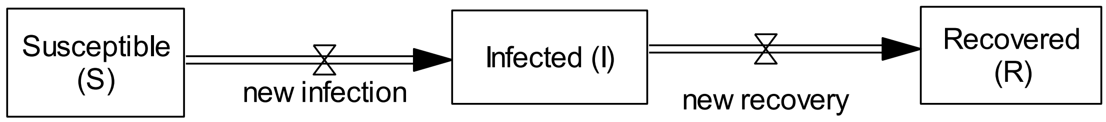
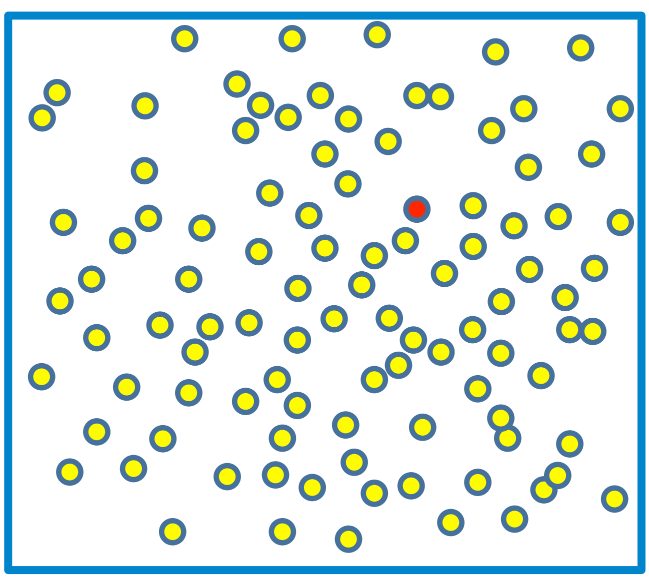
Teacher notes for Lesson Three: Visual simulations and Feedback Loops

Teacher: *Please study this material and then present it to the class in a way that they can interact with you and with each other as the development progresses. Emphasis is on visual understanding and intuition, not formulas!* Many scientists have been studying the spread of infectious diseases, using the basic concepts introduced here. See this figure which includes the back-bone of the famous S-I-R model (Susceptible, Infected, and Recovered).



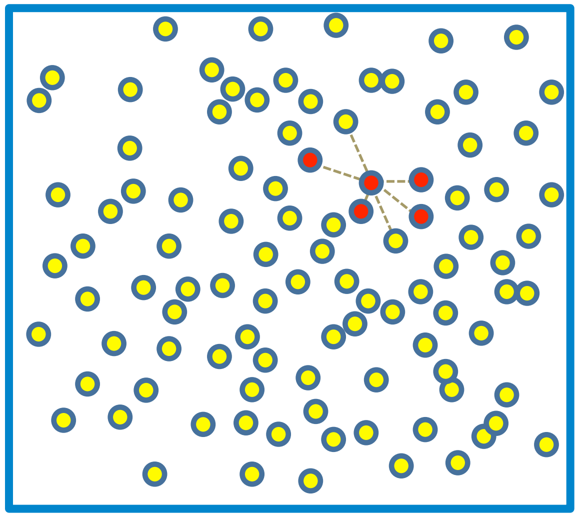
The main point in this figure is that people change their status, from susceptible to infected, and from infected to recovered. We can show this change in status using a simple color-coded figure: **Yellow for susceptible**, **Red for infected**, and **Green for recovered**. This disease status coloring method is similar to the live student simulation game your class played on Day 3 of Week #1. Also, after this lesson, you may want to assign the students to watch and analyze some of the six animated flu simulations on the BLOSSOMS web site https://blossoms.mit.edu/videos/lessons/flu_math_games. (Example: https://blossoms.mit.edu/legacy/FluGames/simulation04.html)

Back to our three colors: Let's think about a community of 100 people. The following figure shows a snap-shot picture of that community, each circle is a person, and total population is 100 people. Yellow dots are susceptible persons, and the red dot is the one individual who is infected. We don't know how he/she got the disease; maybe he/she was traveling and just arrived back in the community. This first person is often referred as **Patient Zero**. See the figure: the infected person (red) is surrounded by susceptible individuals (yellow).



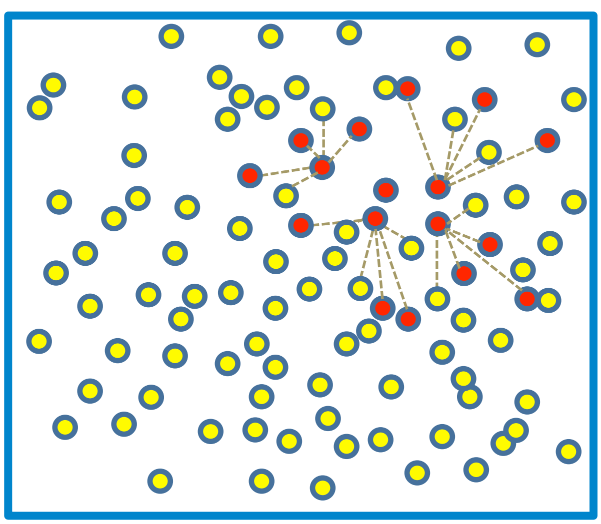
Day 1; 100 people, 99 susceptible, 1 infected.

As you see in the Figure, some people are close to each other, while others maintain their distance. Maybe the close ones are friends, families, classmates, coworkers, etc. Look at the ones close to the one infected individual. It is likely that they get infected if there is a potentially infecting interaction. Let's say the red dot has a close contact with 6 more individuals (shown by dashed-line), two siblings, two parents, and two friends. Some of them, for example 4 out of 6, will get infected in the next time period. Number of infected grows from 1 to 5.



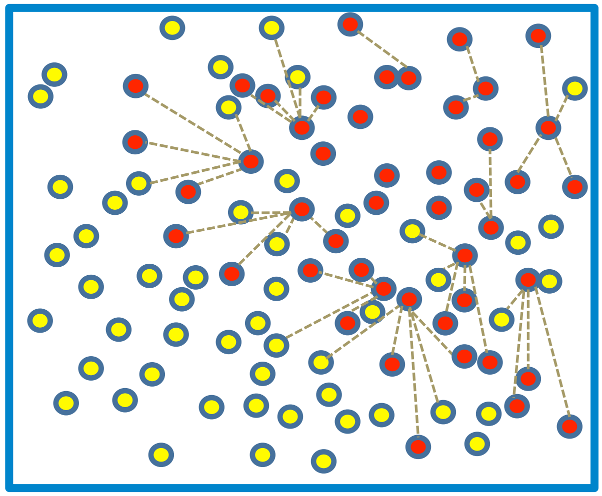
Day 2: 100 people, 95 susceptible, 5 infected.

Our friends, our siblings, even our parents (☺), have friends too! Those infected individuals may have other friends, coworkers, family members, classmates. They may also accidently get close to strangers in a mall, supermarket, or public transportation. Each of those infected may further spread the disease. The following figure is showing the same population the next day. The number of infected is now 12 more (17), which means that the population of susceptibles is declining (100-17=83).



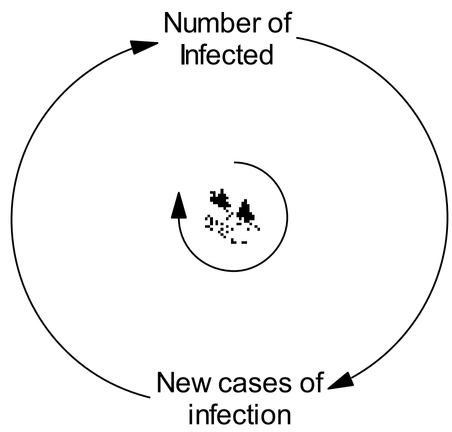
Day 3: 100 people, 83 susceptible, 17 infected.

Obviously, the disease is spreading very fast, and everyday more new people are added to the red dot population. Let's check the next day, and see how many more people get infected. Each of the 12 new infected may have several more friends. We may get to much larger numbers.



Day 4: 100 people, 53 susceptible, 47 infected.

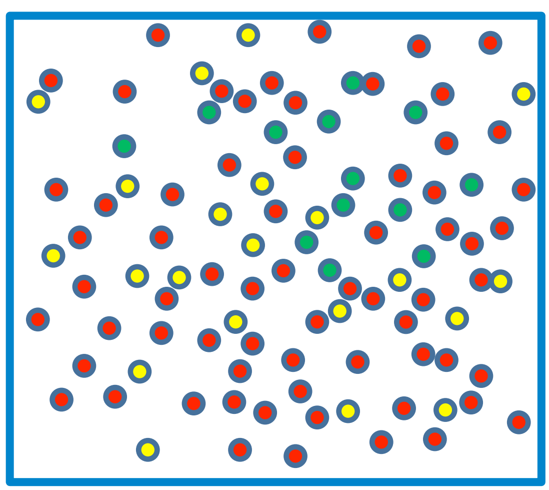
The number in the infected population is growing. With such a fast spread of the disease, soon the great majority will be infected. But why on a daily basis, are the new cases increasing at an accelerating rate? {Teacher note: in a simple terms: a linear increase means "every day, we are adding a constant number, like everyday 2 more new cases, but an exponential increase means every day, we are adding more than what we added yesterday, so the change in "more and more rapidly". Early on, infection dynamics, results in exponential growth.} Remember, patient zero only infected four people, but on day 3 and day 4 we had many more than four new cases. Think about your town: if there is only one infected individual, the chance that you accidently bump in to that person is actually very low. But if half of the population is infected, on average 1 out of 2 people that you see are infected, so there is a larger chance of becoming infected. **That's why infection can increase exponentially**: As more people get infected (red dots), there will be more people who have close contacts with infected individuals (dashed lines), and even if a constant fraction of them getting infected, every day, there will be more and more new cases (yellow dots changing color to red). This is a **reinforcing feedback loop** (also referred as a **positive feedback loop**). It is like a snowball, as it continues, it gathers more momentum and becomes even stronger and stronger – see the figure.



Reinforcing feedback loop: More infected people leads to more new cases

This will continue until the number of yellow dots decreases significantly, or the weather gets warmer, or people start keeping distance. When the infection feedback loop is strong and over time the number of infected increases, the feedback loop works as a **vicious cycle** (do you remember the term from the BLOSSOMS Video?!). In simple words, our outcomes are getting worse and worse every day. But as we close schools, sick people self-isolate themselves, susceptibles take care of themselves (for example by social distancing), we can decrease the power of that vicious cycle, and control the infection.

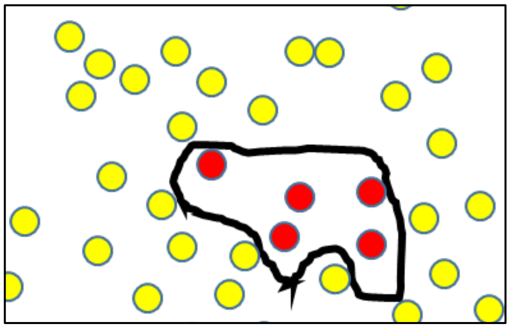
Is there an end to this? Yes, in multiple ways. For example: 1) Depletion of susceptible: As people get infected, the susceptible population (S) depletes over time; in simple words we will have fewer yellow dots. After a period, infected individuals recover (green dots). The following figure is possibly a few days after day 4, when some infected have recovered.



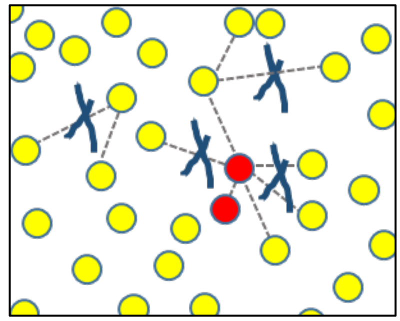
A few days later: 100 people, 21 susceptible, 66 infected, 13 recovered.

2. Public response: We can implement many policies to decrease infections. Discuss in your group how in Day 2 (refer to the figure), you can circle around the first cases and prevent others from infection. That would be isolating the infected cases. How about

school closure? With school closure, you will have many fewer links, thus far fewer new cases of infection.



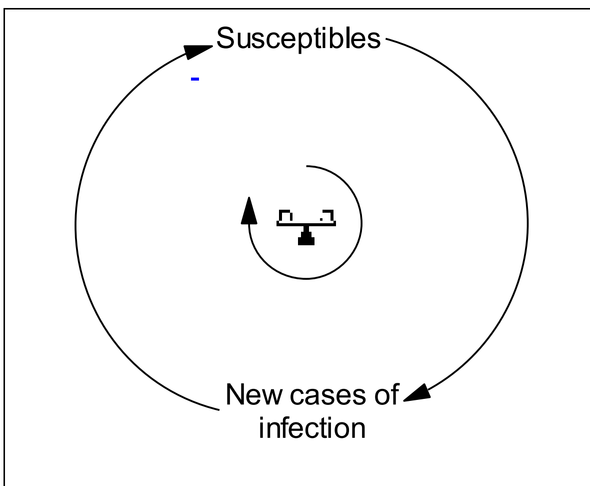
A: Decreasing infection by self-isolating the first infected cases. The closed curve represent separation of infected from the rest of the population.



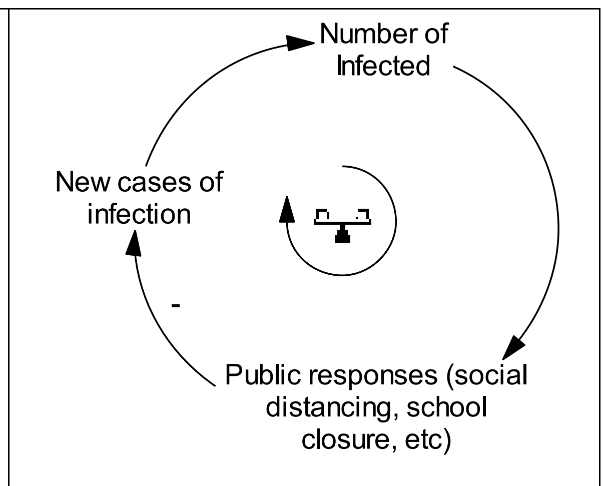
B: Decreasing infection by decreasing contacts by, for example, closing schools. Crosses represent elimination of contacts.

A simple representation of two policies

Both mechanisms of "depletion of susceptible" and "public response" are balancing feedback loops (also known as negative feedback loop; as opposed to reinforcing/positive feedback loops). A balancing feedback loop often represents how the system responds to a problem or to an undesired situation, trying to solve the problem or fill a gap from a desired state. See the Figure below for two examples. On the left, depletion of susceptible: As more people get infected, number of susceptible decline, so overtime there will be fewer and fewer susceptibles (even if there is no vaccine). This leads to herd immunity. A similar story can be told for public response: If more people get infected, others will feel the risks and start reacting (public responses) by, for example, staying at home, which will decrease new cases of infection. These reactions include public or government responses to the risks such as social distancing, school closure, etc.



(a): Depletion of susceptible



(b) Public response

In reality, all these feedback loops, plus several others that we did not discuss, are working together, making the world complex, and hard to predict!

Questions for Teacher to Guide Class Discussion and Discovery. It may be useful to do this conversation with a given value of R_0, an easy one being R_0 = 2.0.

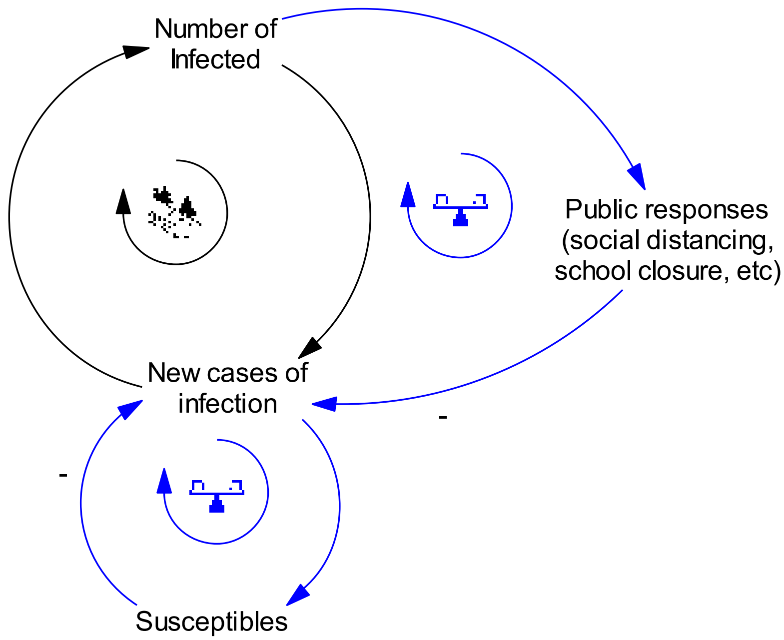
- **Herd Immunity.** As we know from Lesson 2, herd immunity occurs when the number of new infections is equal to the number of new recoveries. Equivalently, any infected individual is infecting only one new person. How can we get there in the diagram? (Teachers: As the number of yellow dots decline, and as green increases, we get closer to herd immunity. Around any infected, there might be only few susceptible left. It R_0 = 2.0, then the students should be able to determine that herd immunity arrives when only half of the population remains susceptible, that is, 50 people; all others are now already infected and/or recovered.)

- **Reinforcing feedback loop.** Ask the students to explain this in the context of influenza or Coronavirus. (You have already done this for them, but you want to see if they can put it into their own words.) Then ask them if they can think of any other phenomena that behave as reinforcing feedback loops. For good examples, see REINFORCING FEEDBACK LOOPS, by Scott Miker, https://www.scottmiker.com/improving-systems-and-habits/2018/3/6/reinforcing-feedback-loops

- **Balancing Feedback Loop.** Ask the students why number of infected individuals cannot grow forever. A simple thought-provoking question: in a community of 1000 people, can we have 10 infected individuals? Yes. Can we have 500 infected individuals? Maybe! Can we have 2000 infected? Of course not, we only had 1000 people to begin with! Then you can review the susceptible depletion feedback loop. If you start with 1000 people, every one of those that get infected, you will be subtracting from 1000, so fewer will be left still susceptible.

  A balancing feedback loop often represents how the system responds to a problem or an undesired situation trying to solve the problem or fill a gap from a desired state (think about public response to an increasing threat of COVID-19). Balancing feedback loops bring stability to a system, and limit the growth. They also represent how public resists against policymakers' policies: harder you push a system, the harder the system pushes back. https://systemsandus.com/foundations/why-you-should-think-like-a-modeler/balancing-loops/

- **Multiple Feedback Loops:** The world is way more complex! In the same time all these feedback loops are working together and influencing the system/society. That's why it is difficult to intuit complexities! Let's put the three feedback loops discussed here together, just to see how this model (which is still very simple) can be hard to digest. And one still needs to add recovery rate, immunization, loss of immunization over time, testing, and many other factors to this model. (note in the figure we included all the three feedback loops that were described before in one graph and since they share variables such as "number of infected" or "new cases of infection", they are connected).



- One attribute of a Complex System is nonlinearity. This is in contrast to "simple system" that behave in a linear way. What do we mean by "linear" performance and "nonlinear" performance? Can you suggest a linear system? Can you show via performance curves the nonlinear behavior of the S-I-R infection system?

- Suppose you put X hours of study into an exam for a math or science course. And G is your grade in the exam. Is this a linear system? Nonlinear? Can you offer a plot that describes YOU of your grade G (y-axis) vs. your study hours, X (x-axis)? Are you a complex system when it comes to studying? Might you have one or more reinforcing loops and one or more balancing loops?

- Open discussion.