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COE 322

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Final Project: Infectious Disease Simulation

The following project consists of several exercises that are built upon each other to produce a relatively realistic simulation of the spread of an infectious disease. Using programs coded in C++, I developed a set of models that demonstrate the spread of disease within various population sizes. By taking into account varying rates of transmission, implementing a system of vaccinations, and manipulating the possible networks of person to person contact, I was not only able to observe the progression of infections but measure the variable changes and the effects produced on a population.

To implement this simulation, an explicit status of all the people in the population is defined and tracked as the simulation runs. In this model, a person can have four potential states: susceptible, sick, recovered, or vaccinated. When a person is susceptible, they are at risk of contracting the disease if they come into contact with a sick person. When a person is infected, they become sick for a certain period, during which they can infect others. Eventually, all sick people recover, after which they no longer carry the disease and can no longer be infected again. A vaccinated person is immune to infection; they are healthy and cannot contract or transmit the disease. Since reinfection is not possible in this simulation, the disease will always eventually run its course and end.

The first program is simple and models the disease progression of a single person. The main methods of this exercise serve to infect a person and track their state as they carry the disease. A *Person* class is defined as an object to represent a person, with an attribute state. The *Person* class has the following methods to execute the simulation:

- *status_string()* : returns a description of the person's state as a string;
- *update()* : updates the person's status to the next day;
- *infect(n)* : infects a person, with the disease to run for n days;
- *is_stable()* : returns a bool indicating whether the person has been sick and is recovered.
- *get_state()* : returns the state of the Person
- *vaccinate()* : vaccinates the person

To model the disease status, a member *int state* is given to the *Person* class. To interpret the state of a person using an *int*, a value of -1 represents that the person is susceptible, a value of -2 indicates that the person is vaccinated, a value of 0 indicates that the person has recovered from sickness, and a positive value *n* represents that the person is sick, with *n* days to go before recovery. In this first simulation, we create an instance of a *Person* object, "Joe". In a random period, Joe is infected for 5 days. The simulation ends once he is recovered. In the following sample output, Joe is randomly infected on day 15 and recovers by day 20.

```
On day 1, Joe is succeptable.
On day 2, Joe is succeptable.
On day 3, Joe is succeptable.
On day 4, Joe is succeptable.
On day 5, Joe is succeptable.
On day 6, Joe is succeptable.
On day 7, Joe is succeptable.
On day 8, Joe is succeptable.
On day 9, Joe is succeptable.
On day 10, Joe is succeptable.
On day 11, Joe is succeptable.
On day 12, Joe is succeptable.
On day 13, Joe is succeptable.
On day 14, Joe is succeptable.
On day 15, Joe is sick (5 to go).
On day 16, Joe is sick (4 to go).
On day 17, Joe is sick (3 to go).
On day 18, Joe is sick (2 to go).
On day 19, Joe is sick (1 to go).
On day 20, Joe is recovered.
```

In my method *infect()*, I chose to represent that the person is susceptible by *int state = -1* rather than using the *bool is_susceptible* because I thought the single integer interpretation system was cleaner and more effective. As a point of programming style, I tried to keep this system consistent throughout the exercises.

In the second program, I defined a class *Population* as a vector of *Person* objects. To keep the model simple, only one random person is infected and there is no transmission of the disease. The *Population* class includes the following methods for the second simulation:

- *random_infect()* : randomly infects a person in the population for 5 days.
- *count_infected()* : counts the number of infected people in the population
- *update()* : updates all *Person* objects in the population
- *get_person(n)* : returns the *Person* object at index n of the population vector

The constructor of the *Population* class takes the number of people population *int npeople.* In this simulation, we create a *Population* object called "population". We then randomly infect one person in the population for 5 days, and at each step, we count the number of people that are sick and update every person in the population until no one is sick. To display the state of the popular, a "?" is printed for susceptible, "+" for infected, and "-" for recovered. In the following sample output, I made the size of the population 25. As observed, a random person in the population was infected for 5 days, and the population was fully recovered by day 6.

```
Size of population: 25
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 2,      # of sick: 1    -->  ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 3,      # of sick: 1    -->  ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 4,      # of sick: 1    -->  ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 5,      # of sick: 1    -->  ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 6,      # of sick: 0    -->  ? ? ? ? ? ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
Disease ran its course by step 6
```

In the third program, a contagion will be incorporated begin investigating the spread of disease. To implement a contagion, the following methods are added to the *Population* class:

- *set_probability_of_transfer(p)* : read in a *double* $0 \leq p \leq 1$ representing the probability of disease transmission upon contact
- *random_vaccinate (p)* : read in a *double* $0 \leq p \leq 1$ representing the percentage of people that have been vaccinated, and choose those members of the population randomly.
- *count_recovered()* : counts the number of recovered persons in the population

This program is a very simple model of infection where only the direct neighbors of a sick person can get infected themselves. It will start with one random person being infected for 5 days. This simulation includes the same steps as the last exercise. At the end of each iteration, the method *set_probability_of_transfer(p)* is implemented to allow the disease to spread. Once the simulation ends, the method *count_recovered()* is called to show how many people in the population were infected. In the following sample output, I set the probability of disease transmission to 100% and made the population size 30.

```
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 2,      # of sick: 3    -->  ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 3,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? + + + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 4,      # of sick: 7    -->  ? ? ? ? ? ? ? ? ? + + + + + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 5,      # of sick: 9    -->  ? ? ? ? ? ? ? ? + + + + + + + + + ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 6,      # of sick: 10   -->  ? ? ? ? ? ? ? + + + + + - + + + + + ? ? ? ? ? ? ? ? ? ? ? ?
In step 7,      # of sick: 10   -->  ? ? ? ? ? ? + + + + + - - - + + + + + ? ? ? ? ? ? ? ? ? ? ?
In step 8,      # of sick: 10   -->  ? ? ? ? ? + + + + + - - - - - + + + + + ? ? ? ? ? ? ? ? ? ?
In step 9,      # of sick: 10   -->  ? ? ? ? + + + + + - - - - - - - + + + + + ? ? ? ? ? ? ? ? ?
In step 10,     # of sick: 10   -->  ? ? ? + + + + + - - - - - - - - - + + + + + ? ? ? ? ? ? ? ?
In step 11,     # of sick: 10   -->  ? ? + + + + + - - - - - - - - - - - + + + + + ? ? ? ? ? ? ?
In step 12,     # of sick: 10   -->  ? + + + + + - - - - - - - - - - - - - + + + + + ? ? ? ? ? ?
In step 13,     # of sick: 10   -->  + + + + + - - - - - - - - - - - - - - - + + + + + ? ? ? ? ?
In step 14,     # of sick: 9    -->  + + + + - - - - - - - - - - - - - - - - - + + + + + ? ? ? ?
In step 15,     # of sick: 8    -->  + + + - - - - - - - - - - - - - - - - - - - + + + + + ? ? ?
In step 16,     # of sick: 7    -->  + + - - - - - - - - - - - - - - - - - - - - - + + + + + ? ?
In step 17,     # of sick: 6    -->  + - - - - - - - - - - - - - - - - - - - - - - - + + + + + ?
In step 18,     # of sick: 5    -->  - - - - - - - - - - - - - - - - - - - - - - - - - + + + + +
In step 19,     # of sick: 4    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - + + + +
In step 20,     # of sick: 3    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - + + +
In step 21,     # of sick: 2    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - - + +
In step 22,     # of sick: 1    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
In step 23,     # of sick: 0    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Disease ran its course by step 23
Number of people infected by disease: 30
```

As observed, it took 23 days for the disease to run its course, and with a 100% infection rate, every person in the population was infected. In the following sample output, I set the probability of disease transmission to 50% and made the population size 30.

```
Probability of disease transmission upon contact: .5
Percentage of people that have been vaccinated: 0
Size of population: 30
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ?
In step 2,      # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? ?
In step 3,      # of sick: 3    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ?
In step 4,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + ? ? ? ?
In step 5,      # of sick: 6    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + + ? ? ? ?
In step 6,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - + + ? ? ? ?
In step 7,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - - + + ? ? ? ?
In step 8,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - + + ? ? ?
In step 9,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - + + ? ?
In step 10,     # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - - + + ? ?
In step 11,     # of sick: 6    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + - - - - - - + + ? ?
In step 12,     # of sick: 8    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + - - - - - - + + + ?
In step 13,     # of sick: 7    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + - - - - - - - - + + ?
In step 14,     # of sick: 7    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + - - - - - - - - - - + +
In step 15,     # of sick: 7    -->  ? ? ? ? ? ? ? ? ? ? ? ? + + + + + - - - - - - - - - - - + +
In step 16,     # of sick: 6    -->  ? ? ? ? ? ? ? ? ? ? ? ? + + + + - - - - - - - - - - - - + +
In step 17,     # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - - - - - - - - - - +
In step 18,     # of sick: 3    -->  ? ? ? ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - +
In step 19,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - - -
In step 20,     # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? + - - - - - - - - - - - - - - - - - -
In step 21,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - - - -
In step 22,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - - - -
In step 23,     # of sick: 3    -->  ? ? ? ? ? ? ? ? ? + + + - - - - - - - - - - - - - - - - - -
In step 24,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - - - - -
In step 25,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? + + - - - - - - - - - - - - - - - - - - -
In step 26,     # of sick: 1    -->  ? ? ? ? ? ? ? ? ? + - - - - - - - - - - - - - - - - - - - -
In step 27,     # of sick: 1    -->  ? ? ? ? ? ? ? ? ? + - - - - - - - - - - - - - - - - - - - -
In step 28,     # of sick: 0    -->  ? ? ? ? ? ? ? ? ? - - - - - - - - - - - - - - - - - - - - -
Disease ran its course by step 28
Number of people infected by disease: 21
```

As observed, it took 28 days for the disease to run its course, and 21 of the 30 people were infected. In the following sample output, I set the probability of disease transmission to 20% and made the population size 50.

```
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 2,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 3,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 4,      # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 5,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 6,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + - + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 7,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + - + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 8,      # of sick: 6    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - + + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 9,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - - + + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 10,     # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - - - - + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 11,     # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 12,     # of sick: 4    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 13,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - - - - - - - ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 14,     # of sick: 2    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + - - - - - - - ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 15,     # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + - - - - - - - - ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 16,     # of sick: 0    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? - - - - - - - - - ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
Disease ran its course by step 16
Number of people infected by disease: 9
```

As observed, the simulation ran for 16 days, and only 9 people in the population were infected. It is apparent that as the probability of disease transmission decreases, the number of people who get infected also decreases. In cases where the infection rate is small, more people can avoid getting sick. To add to this simulation, I also implemented the method *random_vaccinate(p)* at the beginning of the program. In the following sample output, I set the probability of disease transmission to 50%, set the percentage of people vaccinated to 25%, and made the population size 50.

```
Probability of disease transmission upon contact: .5
Percentage of people that have been vaccinated: .25
Size of population: 50
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V ? ? + ? ? V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 2,      # of sick: 2    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V ? + + ? ? V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 3,      # of sick: 3    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V + + + ? ? V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 4,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V + + + + ? V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 5,      # of sick: 5    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V + + + + + V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 6,      # of sick: 4    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V + + - + + V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 7,      # of sick: 3    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V + - - + + V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 8,      # of sick: 2    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V - - - + + V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 9,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V - - - - + V ? V V ? ? ? V ? V V ? ? ? ? ? V
In step 10,     # of sick: 0    -->  ? ? ? ? ? ? ? ? ? V ? ? V ? ? V ? ? ? ? ? V ? ? ? ? ? V - - - - - V ? V V ? ? ? V ? V V ? ? ? ? ? V
Disease ran its course by step 10
Number of people infected by disease: 5
```

In the following sample output, I set the probability of disease transmission to 70%, set the percentage of people vaccinated to 15%, and made the population size 30.

```
Probability of disease transmission upon contact: .7
Percentage of people that have been vaccinated: .15
Size of population: 30
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? + ? ? ? ? ? ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 2,      # of sick: 3    -->  ? ? ? ? ? + + + ? ? ? ? ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 3,      # of sick: 5    -->  ? ? ? ? + + + + + ? ? ? ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 4,      # of sick: 6    -->  ? ? ? ? + + + + + + ? ? ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 5,      # of sick: 8    -->  ? ? ? + + + + + + + + ? ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 6,      # of sick: 9    -->  ? ? + + + + - + + + + + ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 7,      # of sick: 7    -->  ? ? + + + - - - + + + + ? V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 8,      # of sick: 7    -->  ? + + + - - - - - + + + + V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 9,      # of sick: 7    -->  + + + + - - - - - - + + + V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 10,     # of sick: 5    -->  + + + - - - - - - - - + + V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 11,     # of sick: 3    -->  + + - - - - - - - - - - + V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 12,     # of sick: 3    -->  + + - - - - - - - - - - + V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 13,     # of sick: 1    -->  + - - - - - - - - - - - - V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
In step 14,     # of sick: 0    -->  - - - - - - - - - - - - - V ? ? V ? ? ? ? ? ? ? ? V ? V ? ?
Disease ran its course by step 14
Number of people infected by disease: 13
```

As observed, the vaccinations in these samples are incredibly effective in reducing the number of infected cases. However, this model is unrealistic since interactions in a population are not restricted to just “neighbors”.

In the final exercise, I build off the previous exercises once again to create a more realistic simulation by incorporating the spreading of disease by random interaction throughout the population. The simulation once again starts with one random person that is infected for 5 days, The probability of disease transmission upon contact, percentage of vaccinated people, and the size of the population is again read in. In this model, every person can come into contact with 0-6 other random people in the population. If the disease is transmitted, the person can be infected for 1-5 days. To implement these random interactions, I added a method to the *Population* class called *spread_of_disease()* that generates a more realistic random contact network within the population. The first version of this program allows for a small sample population to be observed by printing the profile of each person and monitoring the progress of the disease. Below are several sample outputs using the first version of the final program.

```
Probability of disease transmission upon contact: 1
Percentage of people that have been vaccinated: 0
Size of population: 30
In step 1,     # of sick: 1    -->  ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
In step 2,     # of sick: 9    -->  + ? ? ? ? ? + ? + + ? ? ? ? ? + ? ? ? ? + ? ? ? ? ? + + + ?
In step 3,     # of sick: 25   -->  - ? + + + ? + + + + + ? + + + - + + + + + + + + + + + + + +
In step 4,     # of sick: 20   -->  - + - + + + + + - - + + + - - - + - - + + + + + + - + + + +
In step 5,     # of sick: 16   -->  - + - + - + + + - - + + + - - - + - - + - - + + + - + - + +
In step 6,     # of sick: 11   -->  - - - + - + - + - - + - + - - - + - - + - - + + - - - - + +
In step 7,     # of sick: 5    -->  - - - + - + - + - - - - - - - - - - - - - - + + - - - - - -
In step 8,     # of sick: 0    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Disease ran its course by step 8
Number of people infected by disease: 30
```

```
Probability of disease transmission upon contact: .5
Percentage of people that have been vaccinated: 0
Size of population: 30
In step 1,     # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ?
In step 2,     # of sick: 3    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? + + ?
In step 3,     # of sick: 15   -->  ? ? + ? ? ? ? + + ? + ? + ? + + ? + + + ? ? + + ? ? ? + + +
In step 4,     # of sick: 22   -->  + + + + + ? + + + + - + + + - + + + + - + ? + + ? ? + + - +
In step 5,     # of sick: 16   -->  + - - + + ? + - - - - + + + - + + + + - + + + - ? + - - - +
In step 6,     # of sick: 14   -->  + - - + - + + - - - - + + + - + + - - - + + - - + + - - - +
In step 7,     # of sick: 7    -->  + - - + - - - - - - - + + - - - - - - - - + - - + - - - - +
In step 8,     # of sick: 3    -->  + - - - - - - - - - - - - - - - - - - - - + - - + - - - - -
In step 9,     # of sick: 2    -->  - - - - - - - - - - - - - - - - - - - - - + - - + - - - - -
In step 10,    # of sick: 1    -->  - - - - - - - - - - - - - - - - - - - - - - - - + - - - - -
In step 11,    # of sick: 0    -->  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Disease ran its course by step 11
Number of people infected by disease: 30
```

```
Probability of disease transmission upon contact: .25
Percentage of people that have been vaccinated: 0
Size of population: 30
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ?
In step 2,      # of sick: 2    -->  ? ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ?
In step 3,      # of sick: 5    -->  ? ? ? ? ? ? + ? ? ? ? ? ? ? + ? ? ? + ? + ? ? + ? ? ? ? ? ?
In step 4,      # of sick: 7    -->  + ? ? ? ? ? + ? ? ? ? ? ? ? + ? ? ? + ? + ? ? + ? ? ? ? + ?
In step 5,      # of sick: 12   -->  + ? ? ? ? ? + + ? ? ? ? + ? + ? ? ? + + + ? ? + ? ? ? + + +
In step 6,      # of sick: 12   -->  - ? ? ? ? ? + + ? ? ? ? + ? - + + + + + + ? ? - ? + ? - + +
In step 7,      # of sick: 11   -->  - ? ? ? + ? - + ? + ? ? - ? - + + + - + - + + - ? + ? - + -
In step 8,      # of sick: 9    -->  - ? ? ? + ? - + ? - ? ? - ? - + - + - + - - + - + + ? - + -
In step 9,      # of sick: 3    -->  - ? ? + - ? - - ? - ? ? - ? - + - - - - - - + - - - ? - - -
In step 10,     # of sick: 2    -->  - ? ? - - ? - - ? - ? ? - ? - + - - - - - - + - - - ? - - -
In step 11,     # of sick: 1    -->  - ? ? - - ? - - ? - ? ? - ? - - - - - - - - + - - - ? - - -
In step 12,     # of sick: 0    -->  - ? ? - - ? - - ? - ? ? - ? - - - - - - - - - - - - ? - - -
Disease ran its course by step 12
Number of people infected by disease: 22
```

```
Probability of disease transmission upon contact: 1
Percentage of people that have been vaccinated: .25
Size of population: 30
In step 1,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? V ? ? V V ? ? V ? ? ? ? ? + V ? V ? V ? ?
In step 2,      # of sick: 1    -->  ? ? ? ? ? ? ? ? ? V ? ? V V ? ? V ? ? ? ? ? + V ? V ? V ? ?
In step 3,      # of sick: 3    -->  ? ? ? ? ? ? ? ? ? V + ? V V ? ? V ? ? ? ? ? + V + V ? V ? ?
In step 4,      # of sick: 14   -->  ? + ? + ? + + ? + V + ? V V + ? V + + + ? ? + V + V ? V + +
In step 5,      # of sick: 20   -->  + + + + + + + + + V - + V V + + V - + + + + + V + V + V - +
In step 6,      # of sick: 13   -->  - + + + - + + + + V - - V V - + V - + + + + - V - V + V - -
In step 7,      # of sick: 8    -->  - - + + - + + - + V - - V V - + V - + - - - - V - V + V - -
In step 8,      # of sick: 5    -->  - - + - - - + - + V - - V V - - V - + - - - - V - V + V - -
In step 9,      # of sick: 1    -->  - - - - - - - - - V - - V V - - V - - - - - - V - V + V - -
In step 10,     # of sick: 0    -->  - - - - - - - - - V - - V V - - V - - - - - - V - V - V - -
Disease ran its course by step 10
Number of people infected by disease: 23
```

```
Probability of disease transmission upon contact: .25
Percentage of people that have been vaccinated: .50
Size of population: 30
In step 1,      # of sick: 1    -->  V V V ? ? ? V V ? V ? ? V V ? ? V + ? V V ? V V ? V ? V ? ?
In step 2,      # of sick: 2    -->  V V V + ? ? V V ? V ? ? V V ? ? V + ? V V ? V V ? V ? V ? ?
In step 3,      # of sick: 3    -->  V V V + ? + V V ? V ? ? V V ? ? V + ? V V ? V V ? V ? V ? ?
In step 4,      # of sick: 4    -->  V V V + ? - V V ? V + ? V V ? ? V + ? V V ? V V ? V ? V ? +
In step 5,      # of sick: 3    -->  V V V - ? - V V ? V + ? V V ? ? V + ? V V ? V V ? V ? V ? +
In step 6,      # of sick: 3    -->  V V V - ? - V V + V + ? V V ? ? V - ? V V ? V V ? V ? V ? +
In step 7,      # of sick: 3    -->  V V V - ? - V V + V - ? V V ? + V - ? V V ? V V ? V ? V ? +
In step 8,      # of sick: 3    -->  V V V - ? - V V + V - ? V V ? - V - + V V ? V V ? V ? V ? +
In step 9,      # of sick: 2    -->  V V V - ? - V V + V - ? V V ? - V - + V V ? V V ? V ? V ? -
In step 10,     # of sick: 0    -->  V V V - ? - V V - V - ? V V ? - V - - V V ? V V ? V ? V ? -
Disease ran its course by step 10
Number of people infected by disease: 8
```

It is apparent in these samples that increasing vaccination percentages dramatically reduces the spread of the disease, especially as transmission probability decreases. The second version of the final program is better suited for realistically sized, large populations. With this program, I can simulate a “city” of people, and monitor the number of cases as the disease runs its course. I can also use this to investigate the matter of ‘herd immunity’: if enough people are vaccinated, then some people who are not vaccinated will still never get sick. The following sample outputs document the findings of this simulation on a large scale, as well as herd immunity by setting percentage of people that are vaccinated to 95%.

```
Probability of disease transmission upon contact: 1
Percentage of people that have been vaccinated: .5
Size of population: 1000000
In step 1,      # of sick: 1
In step 2,      # of sick: 3
In step 3,      # of sick: 13
In step 4,      # of sick: 43
In step 5,      # of sick: 101
In step 6,      # of sick: 308
In step 7,      # of sick: 989
In step 8,      # of sick: 3005
In step 9,      # of sick: 9212
In step 10,     # of sick: 28071
In step 11,     # of sick: 79448
In step 12,     # of sick: 189010
In step 13,     # of sick: 310370
In step 14,     # of sick: 324106
In step 15,     # of sick: 255286
In step 16,     # of sick: 167582
In step 17,     # of sick: 87260
In step 18,     # of sick: 31296
In step 19,     # of sick: 7403
In step 20,     # of sick: 1669
In step 21,     # of sick: 393
In step 22,     # of sick: 88
In step 23,     # of sick: 16
In step 24,     # of sick: 4
In step 25,     # of sick: 0
Disease ran its course by step 25
Number of people infected by disease: 498580
```

```
Probability of disease transmission upon contact: .25
Percentage of people that have been vaccinated: .75
Size of population: 1000000
In step 1,      # of sick: 1
In step 2,      # of sick: 3
In step 3,      # of sick: 3
In step 4,      # of sick: 6
In step 5,      # of sick: 7
In step 6,      # of sick: 8
In step 7,      # of sick: 6
In step 8,      # of sick: 5
In step 9,      # of sick: 5
In step 10,     # of sick: 7
In step 11,     # of sick: 5
In step 12,     # of sick: 3
In step 13,     # of sick: 2
In step 14,     # of sick: 2
In step 15,     # of sick: 1
In step 16,     # of sick: 1
In step 17,     # of sick: 0
Disease ran its course by step 17
Number of people infected by disease: 19
```

```
Probability of disease transmission upon contact: .5
Percentage of people that have been vaccinated: .95
Size of population: 1000000
In step 1,      # of sick: 1
In step 2,      # of sick: 1
In step 3,      # of sick: 1
In step 4,      # of sick: 1
In step 5,      # of sick: 3
In step 6,      # of sick: 2
In step 7,      # of sick: 3
In step 8,      # of sick: 3
In step 9,      # of sick: 2
In step 10,     # of sick: 0
Disease ran its course by step 10
Number of people infected by disease: 5
```

```
Probability of disease transmission upon contact: .75
Percentage of people that have been vaccinated: .95
Size of population: 1000000
In step 1,      # of sick: 1
In step 2,      # of sick: 1
In step 3,      # of sick: 2
In step 4,      # of sick: 3
In step 5,      # of sick: 5
In step 6,      # of sick: 7
In step 7,      # of sick: 6
In step 8,      # of sick: 8
In step 9,      # of sick: 9
In step 10,     # of sick: 6
In step 11,     # of sick: 5
In step 12,     # of sick: 4
In step 13,     # of sick: 2
In step 14,     # of sick: 1
In step 15,     # of sick: 2
In step 16,     # of sick: 1
In step 17,     # of sick: 2
In step 18,     # of sick: 2
In step 19,     # of sick: 1
In step 20,     # of sick: 0
Disease ran its course by step 20
Number of people infected by disease: 20
```

```
Probability of disease transmission upon contact: 1
Percentage of people that have been vaccinated: .95
Size of population: 1000000
In step 1,      # of sick: 1
In step 2,      # of sick: 2
In step 3,      # of sick: 3
In step 4,      # of sick: 2
In step 5,      # of sick: 3
In step 6,      # of sick: 1
In step 7,      # of sick: 0
Disease ran its course by step 7
Number of people infected by disease: 4
```

In conclusion, the sample outputs revealed that in order to prevent large outbreaks, we must nip it at the source and act upon its earliest stages. When the probability of transmission upon contact was low, there were instances where only a few people became infected, even in populations of one million. In order for an outbreak to occur, the initial spike must spread exponentially in the early stages. Decreasing the probability of transmission at these stages is vital to containing the spread of infectious diseases. With COVID-19 currently, this observation highlights the importance of wearing masks and social distancing, two actions that decrease infection chances.

The biggest takeaway from these simulations was the effectiveness of vaccines. Even with 100% infection rates upon contact, having large numbers of vaccinated people greatly decreased the number of infections. With herd immunity of 95% vaccinated populations, the disease had brief controlled outbreaks and very few people were infected. This follows realistic situations, where small outbreaks of now rare diseases occur and are easily controlled since they have vaccines that are well distributed. These simulations of infectious diseases were really informational and highlighted the effectiveness of decreasing infection chances and the importance of vaccinations.