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A Study of Infectious Disease Simulations Using C++

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Abstract

The purpose of the Infectious Disease Simulation Project was to achieve a basic understanding of how an infection propagates through a population by running simulations under a variety of different conditions using object-oriented programming constructs. Pseudo-random number generator functions were employed extensively to generate probability values, select infected members of the population, and to update the health conditions of members in the population. These randomly-generated parameters were treated as a substitute for reading in "real-world probability data" from the literature, and thus constitutes a generalized understanding of how a disease spreads through a fixed population, rather than being tailored towards simulating the progression of a specific disease. The project was broken down into five interrelated exercises. In exercise 1, a simulation was run to infect a single person for a fixed number of days and track their state until recovered from the infection. In this simple case, the person was taken to be healthy and not vaccinated at the beginning of the simulation, and a random-number generator was used to attempt to infect the individual each day. The second exercise built on the first exercise through the use of a population class incorporating a vector of person objects. In a similar fashion to the first exercise, a random-number generator was employed to infect a single member of the population each day, and the simulation was run until every member of the population had recovered from an infection. The conditions of the simulation were run such that there was no transmission of the disease. The third exercise incorporated a contagion

phenomenon where a single member of the population was chosen at random to be infected at the beginning of the simulation, and the individual was allowed to spread the infection to neighboring members of the population each day. The program was developed to read in a number between 0 and 1 from the user constituting the fixed probability of disease transmission upon contact. The simulation was run until every member for whom an infection had been imposed, had recovered. A number of different simulations were run with various probability values and population sizes, and a major conclusion was centered around cases where members of the population escaped becoming infected. The fourth exercise built on the previous through incorporating a fixed, and randomly chosen, number of persons in the population to be vaccinated at the beginning of the simulation. The effect that varying the percentage of vaccinated people in the population had on the spread of the infection from a single member of the population, while keeping the population size, and probability of disease transmission constant was an important study. The project was concluded with exercise 5 where each member of the population was permitted to contact a fixed, and randomly chosen, number of persons on a daily basis. A number of simulations were run while varying the percentage of people vaccinated and the probability the disease was transmitted on contact, and the duration of the simulation as a function of the percentage of the population that was vaccinated, and for a fixed population size, number of (daily) contacts, and probability of transmission, was an important relationship in the study.

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Discussion and Interpretation of Results

The project was initialized through developing a main program that modeled the health condition of a single person per the objectives of exercise 1. When running the executable file, the user is prompted to enter the name of an individual for whom the simulation will be run as

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_1_exe
Please input the name of an individual whose health condition is to be monitored
Justin
On day 1 Justin is healthy but not vaccinated
On day 2 Justin is healthy but not vaccinated
On day 3 Justin is healthy but not vaccinated
On day 4 Justin is healthy but not vaccinated
On day 5 Justin is healthy but not vaccinated
On day 6 Justin is healthy but not vaccinated
On day 7 Justin is healthy but not vaccinated
On day 8 Justin is healthy but not vaccinated
On day 9 Justin is healthy but not vaccinated
On day 10 Justin is healthy but not vaccinated
On day 11 Justin is healthy but not vaccinated
On day 12 Justin is healthy but not vaccinated
On day 13 Justin is healthy but not vaccinated
On day 14 Justin is healthy but not vaccinated
On day 15 Justin is healthy but not vaccinated
On day 16 Justin is healthy but not vaccinated
On day 17 Justin is healthy but not vaccinated
On day 18 Justin is healthy but not vaccinated
On day 19 Justin is healthy but not vaccinated
On day 20 Justin is healthy but not vaccinated
On day 21 Justin is healthy but not vaccinated
On day 22 Justin is healthy but not vaccinated
On day 23 Justin is healthy but not vaccinated
On day 24 Justin is healthy but not vaccinated
On day 25 Justin is healthy but not vaccinated
On day 26 Justin is healthy but not vaccinated
On day 27 Justin is healthy but not vaccinated
On day 28 Justin is healthy but not vaccinated
On day 29 Justin is healthy but not vaccinated
On day 30 Justin is healthy but not vaccinated
On day 31 Justin is healthy but not vaccinated
On day 32 Justin is healthy but not vaccinated
On day 33 Justin is sick with 5 days to go before recovery
On day 34 Justin is sick with 4 days to go before recovery
On day 35 Justin is sick with 3 days to go before recovery
On day 36 Justin is sick with 2 days to go before recovery
On day 37 Justin is sick with 1 days to go before recovery
On day 38 Justin is recovered
```

Figure 1: Sample Output for Exercise 1 (1)

shown in figure 1 below. This name is stored as a string variable in the main program, and when an instance of the "Person" class is created for the individual, the name is passed in through the constructor and stored as a private data member in the status", that constitutes an integer identifier for the health status of the person, is initialized to a value of "0" meaning "healthy and not vaccinated", when the object is created, and is passed in through the constructor as a second argument. The other three integer identifiers for the health status used in this project are "-2" for vaccinated, "-1" for recovered, and "value (n) greater than 0" for infected, where "n" corresponds to the number of days before recovery. After the "Person" object is initialized, a while loop is used to simulate the events that occur on a daily basis. At the beginning of each day, the health status of the individual is first updated, and then output to the terminal. If the person is healthy and not vaccinated, the program invokes a random-number generator to attempt to infect the individual for a fixed number of days (5). This process repeats until the person has become infected, whereby their status will be updated for five consecutive days until they have recovered from their infection. As shown below, the user is then prompted to enter a string "Y" for "yes", and any other key for "no" to run the simulation again for another person, or to terminate the program respectively. The class

```
 Would you like to run another infectious-disease simulation of a single individual?
 Enter 'Y' for yes. Enter any other key for no.
Y
Please input the name of an individual whose health condition is to be monitored
Amanda
On day 1 Amanda is healthy but not vaccinated
On day 2 Amanda is healthy but not vaccinated
On day 3 Amanda is healthy but not vaccinated
On day 4 Amanda is healthy but not vaccinated
On day 5 Amanda is healthy but not vaccinated
On day 6 Amanda is healthy but not vaccinated
On day 7 Amanda is healthy but not vaccinated
On day 8 Amanda is healthy but not vaccinated
On day 9 Amanda is healthy but not vaccinated
On day 10 Amanda is healthy but not vaccinated
On day 11 Amanda is healthy but not vaccinated
On day 12 Amanda is healthy but not vaccinated
On day 13 Amanda is sick with 5 days to go before recovery
On day 14 Amanda is sick with 4 days to go before recovery
On day 15 Amanda is sick with 3 days to go before recovery
On day 16 Amanda is sick with 2 days to go before recovery
On day 17 Amanda is sick with 1 days to go before recovery
On day 18 Amanda is recovered
```

Figure 2: Sample Output for Exercise 1 (1)

definition for the "Person" class is provided in a header entitled "Infectious_Disease_Simulation_Library.h" along with the "Population" class definition to be used in exercises 2-5. Shifting gears to exercise 2, a main program was developed to simulate the random infection of members of a population (vector of "Person" objects), until every

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member of the population had recovered from an infection. The size of the population is read in through the terminal, and, for population sizes less than 28, a table reporting each member

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_2_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the simulation. 20

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
Day Number | Person Number
------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
              |0      |1      |2      |3      |4      |5      |6      |7      |8      |9      |10     |11     |12     |13     |14     |15     |16     |17     |18     |19      |
1             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV     |
2             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |Inf(5) |HNV     |
3             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |Inf(5) |HNV    |HNV    |HNV    |HNV    |Inf(4) |HNV     |
4             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |Inf(5) |HNV    |HNV    |HNV    |Inf(4) |HNV    |HNV    |HNV    |HNV    |Inf(3) |HNV     |
5             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |Inf(4) |HNV    |HNV    |HNV    |Inf(3) |HNV    |Inf(5) |HNV    |HNV    |Inf(2) |HNV     |
6             |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |HNV    |Inf(5) |Inf(3) |HNV    |HNV    |HNV    |Inf(2) |HNV    |Inf(4) |HNV    |HNV    |Inf(1) |HNV     |
7             |HNV    |HNV    |HNV    |HNV    |Inf(5) |HNV    |HNV    |HNV    |Inf(4) |Inf(2) |HNV    |HNV    |HNV    |Inf(1) |HNV    |Inf(3) |HNV    |HNV    |REC    |HNV     |
8             |HNV    |HNV    |HNV    |HNV    |Inf(4) |HNV    |HNV    |HNV    |Inf(3) |Inf(1) |HNV    |Inf(5) |HNV    |REC    |HNV    |Inf(2) |HNV    |HNV    |REC    |HNV     |
9             |HNV    |HNV    |HNV    |HNV    |Inf(3) |HNV    |HNV    |Inf(5) |Inf(2) |REC    |HNV    |Inf(4) |HNV    |REC    |HNV    |Inf(1) |HNV    |HNV    |REC    |HNV     |
10            |HNV    |HNV    |HNV    |HNV    |Inf(2) |HNV    |HNV    |Inf(4) |Inf(1) |REC    |HNV    |Inf(3) |HNV    |REC    |Inf(5) |REC    |HNV    |HNV    |REC    |HNV     |
11            |HNV    |HNV    |HNV    |HNV    |Inf(1) |HNV    |HNV    |Inf(3) |REC    |REC    |HNV    |Inf(2) |HNV    |REC    |Inf(4) |REC    |Inf(5) |HNV    |REC    |HNV     |
12            |HNV    |HNV    |HNV    |Inf(5) |REC    |HNV    |HNV    |Inf(2) |REC    |REC    |HNV    |Inf(1) |HNV    |REC    |Inf(3) |REC    |Inf(4) |HNV    |REC    |HNV     |
13            |Inf(5) |HNV    |HNV    |Inf(4) |REC    |HNV    |HNV    |Inf(1) |REC    |REC    |HNV    |REC    |HNV    |REC    |Inf(2) |REC    |Inf(3) |HNV    |REC    |HNV     |
14            |Inf(4) |Inf(5) |HNV    |Inf(3) |REC    |HNV    |HNV    |REC    |REC    |REC    |HNV    |REC    |HNV    |REC    |Inf(1) |REC    |Inf(2) |HNV    |REC    |HNV     |
15            |Inf(3) |Inf(4) |HNV    |Inf(2) |REC    |HNV    |HNV    |REC    |REC    |REC    |HNV    |REC    |HNV    |REC    |REC    |REC    |Inf(1) |HNV    |REC    |Inf(5)  |
16            |Inf(2) |Inf(3) |HNV    |Inf(1) |REC    |HNV    |HNV    |REC    |REC    |REC    |HNV    |REC    |HNV    |REC    |REC    |REC    |REC    |Inf(5) |REC    |Inf(4)  |
17            |Inf(1) |Inf(2) |HNV    |REC    |REC    |HNV    |HNV    |REC    |REC    |REC    |Inf(5) |REC    |HNV    |REC    |REC    |REC    |REC    |Inf(4) |REC    |Inf(3)  |
18            |REC    |Inf(1) |Inf(5) |REC    |REC    |HNV    |HNV    |REC    |REC    |REC    |Inf(4) |REC    |HNV    |REC    |REC    |REC    |REC    |Inf(3) |REC    |Inf(2)  |
19            |REC    |REC    |Inf(4) |REC    |REC    |HNV    |HNV    |REC    |REC    |REC    |Inf(3) |REC    |Inf(5) |REC    |REC    |REC    |REC    |Inf(2) |REC    |Inf(1)  |
20            |REC    |REC    |Inf(3) |REC    |REC    |HNV    |Inf(5) |REC    |REC    |REC    |Inf(2) |REC    |Inf(4) |REC    |REC    |REC    |REC    |Inf(1) |REC    |REC     |
21            |REC    |REC    |Inf(2) |REC    |REC    |Inf(5) |Inf(4) |REC    |REC    |REC    |Inf(1) |REC    |Inf(3) |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
22            |REC    |REC    |Inf(1) |REC    |REC    |Inf(4) |Inf(3) |REC    |REC    |REC    |REC    |REC    |Inf(2) |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
23            |REC    |REC    |REC    |REC    |REC    |Inf(3) |Inf(2) |REC    |REC    |REC    |REC    |REC    |Inf(1) |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
24            |REC    |REC    |REC    |REC    |REC    |Inf(2) |Inf(1) |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
25            |REC    |REC    |REC    |REC    |REC    |Inf(1) |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
26            |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC    |REC     |
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_2_exe
```

Figure 3: Sample Output for Exercise 2 (Small Population Size)

of the population, and their health condition on that particular day is output to the terminal as shown in figure 3 below. As an aside, the number 28 was determined to be the maximum number of members in a population whose status conditions could be output to the terminal

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_2_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the simulation. 10000

Status Report for Population
-------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated           | No. Infected             | No. Recovered            |
-------------------------------------------------------------------------------------------------------------------------
1                  10000                       0                        0                          0
2                  9999                        0                        1                          0
3                  9998                        0                        2                          0
4                  9997                        0                        3                          0
5                  9996                        0                        4                          0
6                  9995                        0                        5                          0
7                  9994                        0                        5                          1
8                  9993                        0                        5                          2
9                  9992                        0                        5                          3
```

Figure 4: Sample Output for Exercise 2 (Large Population Size Beginning of Simulation)

excess of 28, a table reporting the number of members of the population in each of the four health categories for each day is output to the terminal as shown in figure 4. As expected, the number of individuals in the population that are infected during a particular day reaches a maximum value of 5 during day 6 for an increase in the number of infected persons by a value of 1 on a daily basis. After day 6, the number of infected persons remains at a constant value of 5 until the simulation reaches the day number “n+2” where “n” corresponds to the size of the population, and decreases by a value of 1 each day until the simulation concludes at day

10001	0	0	5	9995
10002	0	0	4	9996
10003	0	0	3	9997
10004	0	0	2	9998
10005	0	0	1	9999
10006	0	0	0	10000

Figure 5: Sample Output for Exercise 2 (Large Population Size End of Simulation)

number “n+6”. For example, if we reference figure 5 below, we see that, for a population size of 10000, the number of infected persons decreases from a value of 5 at day number 10001, by a value of 1 each day to a minimum value of 0 at day number 10006.

In exercise 3, a simulation was run to understand the propagation of an infection from a single member of the population to neighboring, healthy, and non-vaccinated members for different probability of infection values. The probability values were fixed for each member of the population, but varied from simulation to simulation. In the main program for the exercise, the user is prompted to input a decimal value in the range of (0,1) where “0” constitutes a 0% probability of neighboring infection, and “1” constitutes a 100% probability of neighboring infection. Similar to exercise 2, a table of values reporting the health condition for each member of the population on a daily basis is output for small population sizes (<=28), and table of values reporting the number of members in each of the four health categories is output on a daily basis for large population sizes (exceeding 28). Two screenshots, depicting, respectively, a sample output for a small population size of 20, and for a probability of neighboring infection of 0, and a sample output for a large population size of 10000, and for a probability of neighboring infection of 100% are provided in figures 6 and 7 below.

```
[43]+  Stopped                 ./Infectious_Disease_Simulation_Exercise_2_exe
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 20

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  0

Status Report for Population
--------------------------------------------------------------------------------------------------------------------------------------------------------------
Day Number | Person Number
--------------------------------------------------------------------------------------------------------------------------------------------------------------
           |0     |1      |2     |3     |4     |5     |6     |7     |8     |9     |10    |11    |12    |13    |14    |15    |16    |17    |18    |19    |
1          |HNV   |Inf(5) |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
2          |HNV   |Inf(4) |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
3          |HNV   |Inf(3) |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
4          |HNV   |Inf(2) |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
5          |HNV   |Inf(1) |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
6          |HNV   |REC    |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |HNV   |
```

Figure 6: Sample Output for Exercise 3: Contagion Simulation (Small Population Size)

```
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 10000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  1.0

Status Report for Population
--------------------------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered              |
--------------------------------------------------------------------------------------------------------------------------------------------------------------
1                    9999                     0                         1                          0
2                    9997                     0                         3                          0
3                    9995                     0                         5                          0
4                    9993                     0                         7                          0
5                    9991                     0                         9                          0
6                    9989                     0                         10                          1
7                    9987                     0                         10                          3
8                    9985                     0                         10                          5
9                    9983                     0                         10                          7
```

Figure 7: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection(100%) Beginning of Simulation)

Looking at the table in figure 7, we note that, for a probability of neighboring infection value of 100%, the number of infected persons increases by two each day from a minimum value of 1 at the beginning of the simulation, to a maximum value of 10 after six total days. This output adheres to the desired results since, the infection will spread to two neighboring, and healthy, members of the population each day, thus increasing the number of infected persons by two up to a maximum value of 10. Then, depending on the location of the first infected person in the simulation, the number of infected persons will decrease from this maximum value by a value of one on a daily basis over the course of 5 days to a total number of 5. This will happen when one or more of the infected persons has spread their infection to a neighbor at the boundaries of the population. For this particular simulation, this process occurred just under 4000 days into the model as shown in figure 8 below. It can be concluded that either the infection spread to the rightmost, or leftmost member in the population at the day number 3892.

3892	2217	0	10	7773
3893	2216	0	9	7775
3894	2215	0	8	7777
3895	2214	0	7	7779
3896	2213	0	6	7781
3897	2212	0	5	7783
3898	2211	0	5	7784
3899	2210	0	5	7785
3900	2209	0	5	7786
3901	2208	0	5	7787
3902	2207	0	5	7788
3903	2206	0	5	7789
3904	2205	0	5	7790
3905	2204	0	5	7791
3906	2203	0	5	7792
3907	2202	0	5	7793
3908	2201	0	5	7794
3909	2200	0	5	7795
3910	2199	0	5	7796
3911	2198	0	5	7797
3912	2197	0	5	7798
3913	2196	0	5	7799
3914	2195	0	5	7800
3915	2194	0	5	7801

Figure 8: Sample Output for Exercise 3: Contagion Simulation (Large Population Size(10000), Probability of Neighboring Infection: 100%, Middle of Simulation)

A few thousand of days after this constraint in the infection occurred, the second and final constraint to the spread of the infection (resembling the infection spreading to the other population boundary) occurred as shown in figure 9.

6109	0	0	5	9995
6110	0	0	4	9996
6111	0	0	3	9997
6112	0	0	2	9998
6113	0	0	1	9999
6114	0	0	0	10000

Figure 9: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 100%, End of Simulation)

As expected, once the infection spreads to the second population boundary, the number of infected persons decreases from a value of 5, by one each day to a value of 0. If the simulation is run under the conditions where the probability of neighboring infection is very low, 20% for example, the duration of the simulation decreases exponentially. As shown in figure 10 below, for a probability of 20%, the disease infects a maximum of two members of a relatively large population of 10000 people on a daily basis, and concludes after just 15 days.

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 10000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  0.2

Status Report for Population
----------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered              |
----------------------------------------------------------------------------------------------------------------------------------------
1               9999                    0                         1                         0
2               9998                    0                         2                         0
3               9998                    0                         2                         0
4               9998                    0                         2                         0
5               9997                    0                         3                         0
6               9997                    0                         2                         1
7               9997                    0                         1                         2
8               9997                    0                         1                         2
9               9997                    0                         1                         2
10               9996                    0                         1                         3
11               9996                    0                         1                         3
12               9996                    0                         1                         3
13               9996                    0                         1                         3
14               9996                    0                         1                         3
15               9996                    0                         0                         4
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
```

Figure 10: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 20%, Total Simulation)

Holding the population size constant at 10000, and increasing the probability of neighboring infection from 20% to 50% increases the length of the simulation considerably. The maximum number of infected persons nearly quadruples from a value of 2 in the 20% case to a value of 7 in the 50% case. Referencing figure 11 below, it can be determined that the number of infected persons increases linearly by one each day from the beginning of the simulation to a value of 5 after the fifth day, before slowly increasing to a maximum of 7, and oscillating at random in a range of (4,7). After about the 60th day or so, (roughly half the duration of the simulation (total duration being 123 days)), the number of infected persons drops to oscillating in a range of

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(1,3) before decreasing linearly from a value of 3 to a value of 0 over the last four days of the simulation as expected.

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 10000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  0.5

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered             |
------------------------------------------------------------------------------------------------------------------------------------------
1                 9999                         0                          1                          0
2                 9997                         0                          3                          0
3                 9996                         0                          4                          0
4                 9995                         0                          5                          0
5                 9994                         0                          6                          0
6                 9993                         0                          6                          1
7                 9991                         0                          6                          3
8                 9990                         0                          6                          4
9                 9989                         0                          6                          5
10                 9987                         0                          7                          6
11                 9986                         0                          7                          7
12                 9984                         0                          7                          9
13                 9984                         0                          6                          10
14                 9983                         0                          6                          11
15                 9982                         0                          5                          13
16                 9981                         0                          5                          14
17                 9980                         0                          4                          16
18                 9980                         0                          4                          16
19                 9978                         0                          5                          17
20                 9978                         0                          4                          18
21                 9976                         0                          5                          19
22                 9974                         0                          6                          20
23                 9973                         0                          7                          20
24                 9972                         0                          6                          22
25                 9972                         0                          6                          22
26                 9970                         0                          6                          24
27                 9970                         0                          4                          26
```

Figure 11: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 50%, Beginning of Simulation)

```
91                9921                         0                          1                          78
92                9920                         0                          2                          78
93                9920                         0                          2                          78
94                9919                         0                          3                          78
95                9919                         0                          3                          78
96                9919                         0                          2                          79
97                9919                         0                          1                          80
98                9918                         0                          2                          80
99                9918                         0                          1                          81
100                9918                         0                          1                          81
101                9917                         0                          2                          81
102                9916                         0                          3                          81
103                9915                         0                          3                          82
104                9915                         0                          3                          82
105                9914                         0                          4                          82
106                9913                         0                          4                          83
107                9913                         0                          3                          84
108                9913                         0                          2                          85
109                9913                         0                          2                          85
110                9912                         0                          2                          86
111                9912                         0                          1                          87
112                9911                         0                          2                          87
113                9910                         0                          3                          87
114                9910                         0                          3                          87
115                9909                         0                          3                          88
116                9908                         0                          4                          88
117                9908                         0                          3                          89
118                9907                         0                          3                          90
119                9907                         0                          3                          90
120                9907                         0                          2                          91
121                9907                         0                          1                          92
122                9907                         0                          1                          92
123                9907                         0                          0                          93
```

Figure 12: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 50%, End of Simulation)

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Shifting gears to a simulation of 10000 persons under a probability of neighboring infection of 75%, the number of infected persons increases steadily from 1 to 8 over the course of the first few days, before oscillating in the range of (5,10) over the course of the next 140 days or so (approximately 15% of the duration of the simulation). After this time, the range of oscillation decreases to (3,5) for the next several hundred of days until the number of infected persons decreases linearly from 5 to 1 at the tail end of the simulation.

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 10000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  0.75

Status Report for Population
--------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered             |
--------------------------------------------------------------------------------------------------------------------------------------------
1                 9999                  0                            1                            0
2                 9997                  0                            3                            0
3                 9995                  0                            5                            0
4                 9993                  0                            7                            0
5                 9992                  0                            8                            0
6                 9991                  0                            8                            1
7                 9989                  0                            8                            3
8                 9987                  0                            8                            5
9                 9986                  0                            7                            7
10                9985                  0                            7                            8
11                9984                  0                            7                            9
12                9984                  0                            5                            11
13                9983                  0                            4                            13
14                9982                  0                            4                            14
15                9981                  0                            4                            15
16                9980                  0                            4                            16
17                9979                  0                            5                            16
18                9978                  0                            5                            17
19                9978                  0                            4                            18
20                9978                  0                            3                            19
21                9977                  0                            3                            20
22                9976                  0                            3                            21
23                9975                  0                            3                            22
24                9974                  0                            4                            22
25                9973                  0                            5                            22
26                9972                  0                            5                            23
27                9972                  0                            4                            24
28                9971                  0                            4                            25
29                9970                  0                            4                            26
30                9970                  0                            3                            27
31                9970                  0                            2                            28
32                9970                  0                            2                            28
33                9969                  0                            2                            29
34                9968                  0                            2                            30
35                9968                  0                            2                            30
36                9968                  0                            2                            30
37                9967                  0                            3                            30
38                9966                  0                            3                            31
39                9965                  0                            3                            32
40                9964                  0                            4                            32
41                9963                  0                            5                            32
42                9962                  0                            5                            33
43                9962                  0                            4                            34
44                9961                  0                            4                            35
```

Figure 13: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 75%, Beginning of Simulation)

```
141         9782          0          6          212
142         9782          0          4          214
143         9781          0          4          215
144         9780          0          4          216
145         9779          0          4          217
146         9779          0          3          218
147         9778          0          4          218
148         9777          0          4          219
149         9776          0          4          220
150         9775          0          4          221
151         9774          0          5          221
152         9773          0          5          222
153         9772          0          5          223
154         9771          0          5          224
155         9771          0          4          225
156         9770          0          4          226
```

Figure 14:Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 75%, 15% Mark of Length of Simulation)

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_3_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 100000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  1.0

Status Report for Population
--------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated           | No. Infected             | No. Recovered             |
--------------------------------------------------------------------------------------------------------------------------------------
1                 99999               0                  1                 0
2                 99997               0                  3                 0
3                 99995               0                  5                 0
4                 99993               0                  7                 0
5                 99991               0                  9                 0
6                 99989               0                  10                1
7                 99987               0                  10                3
8                 99985               0                  10                5
9                 99983               0                  10                7
10                 99981               0                  10                9
```

Figure 15:Sample Output for Exercise 3: Contagion Simulation (Large Population Size (100000), Probability of Neighboring Infection: 100%, Beginning of the Simulation)

Upon increasing the population size from 10000 to 100000 persons, and running the simulation under a probability of neighboring infection of 100%, the number of infected persons increased from 1 to 10 over the course of the first six days of the model which takes on the same characteristics as that of the model when run under a population size of 10000 as expected. This is shown above in figure 15. Thus, it can be concluded that for a neighboring infection probability of 100%, the characteristics of the propagation of the disease from a single infected person through to each member of the population are independent of the population size.

```
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 100000

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  0.20

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated           | No. Infected             | No. Recovered            |
------------------------------------------------------------------------------------------------------------------------------------------
1                99999                    0                        1                        0
2                99999                    0                        1                        0
3                99998                    0                        2                        0
4                99997                    0                        3                        0
5                99996                    0                        4                        0
6                99996                    0                        3                        1
7                99996                    0                        3                        1
8                99996                    0                        2                        2
9                99996                    0                        1                        3
10                99996                    0                        0                        4
[jcam98@isp02 Infectious_Disease_Simulation]$
```

Figure 16: Sample Output for Exercise 3: Contagion Simulation (Large Population Size (10000), Probability of Neighboring Infection: 20%, Total Simulation)

Now, if we change the probability of neighboring infection from 100% to 20% for a population size of 100000, we arrive at the table depicted in figure 16 above. We notice that, like the population size of 10000 simulated under a probability of 20%, the number of infected persons increases to a maximum of 4, and the simulation is very short (10 days which bears a lot of similarity to the 15 day length of the 10000 day, 20% prob simulation). Thus, it can be concluded that for small values of neighboring infection probability (~20%), the infection will propagate from an original source to affect a handful of other members in the population, before all infected persons recover in a very short time frame. Additionally, these characteristics again appear to be independent of the population size. After running simulations for 50% and 75% probability of neighboring infection, and for a population size of 100000, it

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was again determined that a function depicting the relationship between the number of infected persons, and the day number, as well as the range of the number of daily infected persons, and the length of the simulation itself, were all essentially independent of the population size since each simulation was subjected to the same infection constraints (two population boundaries). To examine cases where members of the population escaped getting infected, simulations were run for large population sizes in the range of 10000 to 100000000 persons, and it was determined that members of the population (independent of the population size) avoid contracting the disease for infection probability values less than approximately 5% (p = 0.05). In exercise 4, the simulation was run while incorporating a percentage of the population to be vaccinated at the beginning of the simulation. This value was read in from the terminal. Running the simulation for a fixed population size of 100000, and a fixed probability of infection upon contact of 100%, while varying the vaccination percentage between 25%, 50%, and 75% produced the three respective tables below.

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_4_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 100000

Please enter a decimal number in the range (0,1) for the percentage of the population that is to be chosen randomly for vaccination at the beginning of the simulation: 0.20

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  1.0

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated           | No. Infected              | No. Recovered              |
------------------------------------------------------------------------------------------------------------------------------------------------
1                   79999                     20000                       1                          0
2                   79997                     20000                       3                          0
3                   79995                     20000                       5                          0
4                   79993                     20000                       7                          0
5                   79992                     20000                       8                          0
6                   79991                     20000                       8                          1
7                   79990                     20000                       7                          3
8                   79990                     20000                       5                          5
9                   79990                     20000                       3                          7
10                   79990                     20000                       2                          8
11                   79990                     20000                       1                          9
12                   79990                     20000                       0                          10
[jcam98@isp02 Infectious_Disease_Simulation]$
```

Figure 17: Sample Output for Exercise 4: Contagion Simulation (Large Population Size (100000), Probability of Neighboring Infection: 100%, Percentage Vaccinated: 20%, Total Simulation)

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Comparing the output from exercise 3 where the simulation was run for a population size of 100000, and probability of neighboring infection of 100%, when a small percentage of persons (20%) in the same-sized population are vaccinated at the beginning of the simulation, the length of the simulation decreases exponentially. When the percentage of vaccinated persons is increased to larger values of 50% and 75%, the duration of the simulation drops even further to, for instance, 6 days in total as depicted in the figures below.

```
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 100000

Please enter a decimal number in the range (0,1) for the percentage of the population that is to be chosen randomly for vaccination at the beginning of the simulation: 0.50

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  1.0

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered              |
------------------------------------------------------------------------------------------------------------------------------------------------------------------------
1                 49999                      50000                      1                          0
2                 49999                      50000                      1                          0
3                 49999                      50000                      1                          0
4                 49999                      50000                      1                          0
5                 49999                      50000                      1                          0
6                 49999                      50000                      0                          1
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_4_exe
```

Figure 18: Sample Output for Exercise 4: Contagion Simulation (Large Population Size (100000), Probability of Neighboring Infection: 100%, Percentage Vaccinated: 50%, Total Simulation)

```
[jcam98@isp02 Infectious_Disease_Simulation]$ ./Infectious_Disease_Simulation_Exercise_4_exe
Please enter an integer corresponding to the number of individuals in the population you would like to monitor for the contagion simulation. 100000

Please enter a decimal number in the range (0,1) for the percentage of the population that is to be chosen randomly for vaccination at the beginning of the simulation: 0.75

Please input a decimal number in the range (0,1) to represent the  probability (p) of disease transmission upon contact for the entire simulation  1.0

Status Report for Population
------------------------------------------------------------------------------------------------------------------------------------------------------------------------
Day Number|No. Healthy but not Vaccinated| No. Vaccinated            | No. Infected              | No. Recovered              |
------------------------------------------------------------------------------------------------------------------------------------------------------------------------
1                 24999                      75000                      1                          0
2                 24999                      75000                      1                          0
3                 24999                      75000                      1                          0
4                 24999                      75000                      1                          0
5                 24999                      75000                      1                          0
6                 24999                      75000                      0                          1
[jcam98@isp02 Infectious_Disease_Simulation]$
```

Figure 19: Sample Output for Exercise 4: Contagion Simulation (Large Population Size (100000), Probability of Neighboring Infection: 100%, Vaccination Percentage: 75%, Total Simulation)

Thus, for disease propagation conditions whereby an infection spreads from a single source, and only through neighboring members of a population, introducing increasing percentages of vaccinated persons in the population exponentially decreases the duration of the disease propagation. It should be noted that this model is unrealistic because these simulations were built under the assumption that a member of the population who contracts the infection has it for a fixed number of days, and is always able to recover. However, in the real world, people in different age groups, and with different health backgrounds will be more susceptible to infections than others; we dangerously assumed that the immune system of every member in the population was completely healthy. Additionally, the model is unrealistic because, unless we are modeling the propagation of a disease exclusively through rural, country, areas whose population are very sparse, any given member in a fixed population is likely to contact several, if not hundreds of people a day through the workplace and running errands outside of the house. It is not very realistic to assume that each individual in a large population only contacts two people on a daily basis. In the last exercise of the project, the spread of an infectious disease from a single source was studied while varying the population size, percentage of the population that was vaccinated at the beginning of the simulation, and the probability of infection upon contact. These simulations approximately simulated the "SIR" model, where each member of the population was allowed to contact a fixed (6), but randomly chosen, number of other members in the population on a daily basis. A number of simulations were run to study the relationship between the duration of the disease propagation and the percentage of the population vaccinated for a fixed population size and probability of infection upon contact. It was determined that the relationship between the two quantities was indeed independent of the population size and probability of infection upon contact as expected. To study the relationship in detail, four simulations were run for a fixed population size of 100000, and fixed probability of infection upon contact of 50%, while varying the vaccination percentage of the population. Extracting the data from emacs, and importing into an excel spreadsheet produced the following table of values.

Contact Number	Probability of Transmission	
100000	50	
Duration of Simulation (Days)	Vaccination Percentage	Duration of Simulation (Days)
11	0	14
11	25	16
12	50	22
12	75	35
14	90	90

Figure 20: Table of Sample Output for Exercise 5: Contagion Simulation (Large Population Size (100000), Probability of Neighboring Infection: 50%, Vaccination Percentages: (0,90)%)

Generating a smooth line plot with data points included produced the graph shown in figure 21 below. As we can see from the graph, for a fixed population size of 100000, and infection probability of 50%, the duration of the disease propagation varies exponentially with vaccination percentage. An r-squared value of 0.8412 modestly reinforces this relationship. In general, then, for a fixed population size, and infection probability upon contact, the duration of the disease propagation will have an approximately exponential relationship with the vaccination percentage.

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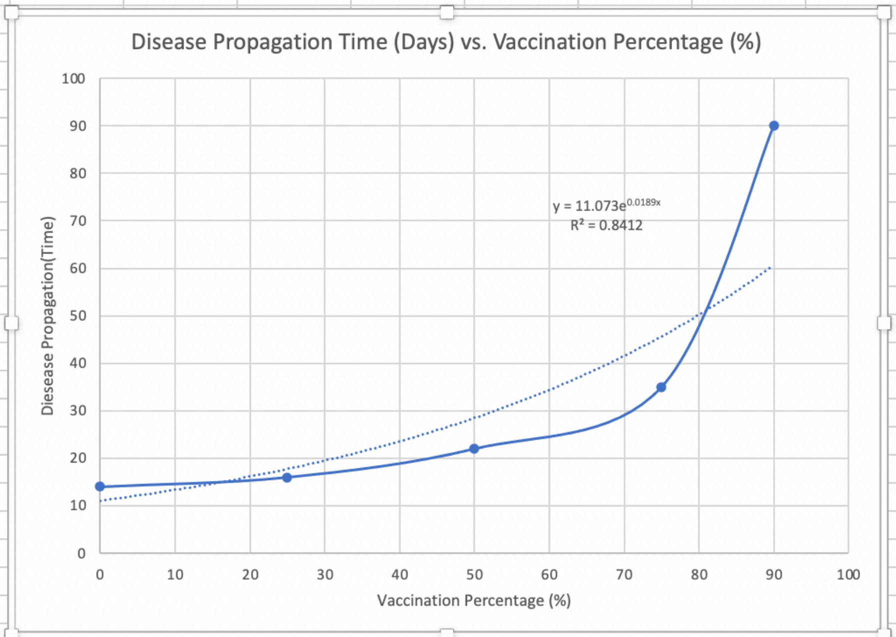

Figure 21: Exponential Relationship Between Vaccination Percentage (%) and Duration of Disease Propagation (days) for fixed population size of 100000 and probability of Infection of 50%

The second objective of the study in exercise 5 was the concept of “Herd Immunity”. “Herd Immunity” is a theory that states that if a large enough number of a population is vaccinated from a particular disease, then some people who are not vaccinated will never end up contracting the disease. In this project, the relationship between vaccination percentage (for values greater than 95%), and contagiousness of the disease (probability of infection upon contact) was studied for the condition of “Herd Immunity” for a population size of 100000. Extracting the data from emacs, and importing into an excel spreadsheet produced the table in figure 22 below.

Relationship between Prob of Infection and Percentage of Vaccination for Herd Immunity	
Contact Number	
100000	
Probability of Infection (%)	Percentage of Vaccination(%)
20	99
15	98
10	97
5	96
2.5	95

Figure 23: Table of Sample Output for Exercise 5: Contagion Simulation (Large Population Size (100000) for Herd Immunity Condition

Developing a smooth line plot inclusive of data points, produced a linear relationship where the required percentage of the population that must be vaccinated to prevent any spread of an infection increases linearly with an increase in the probability of infection for high vaccination percentages ranging between 95% and 99%

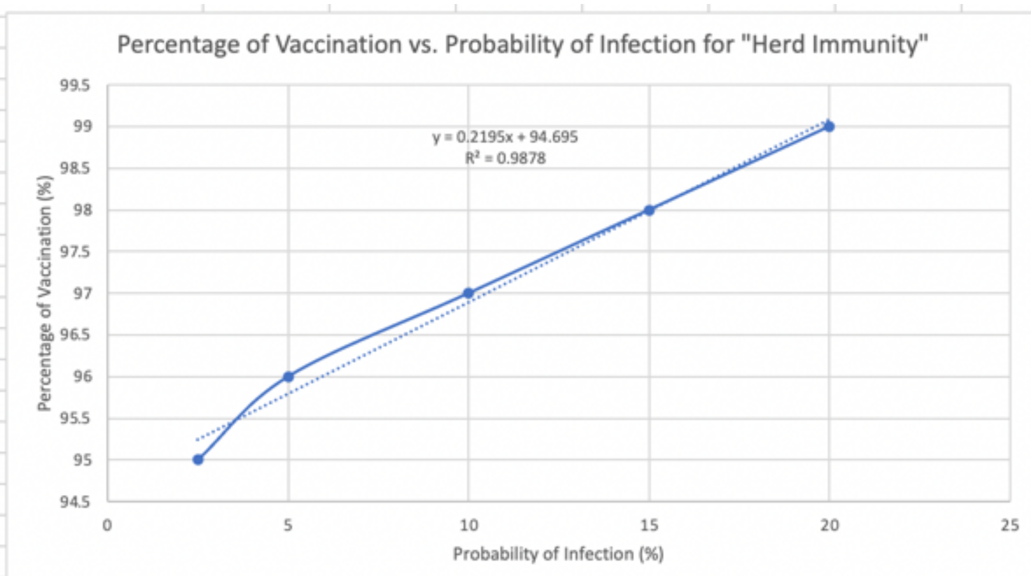

Figure 24: Percentage of Vaccination vs. Probability of Infection for "Herd Immunity" Condition

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Conclusion

A number of simulations were run to study how a disease propagates from a single source through a population while imposing different parameters such as varying vaccination percentages, probabilities of infection, and method of contact (neighboring, random). Upon completion of exercise 3, where the propagation of the disease was studied from a single, and randomly-generated, source in the population without vaccination, it was confirmed that the maximum number of infected persons in the population during any particular day was 10, and that when the infection spread to a member at the boundaries of the population, that number dropped to five as expected. In exercise 4, a more realistic, but still hardly relevant, simulation was developed by imposing vaccination on varying percentages of the population at the beginning of the disease propagation. It was determined that vaccinating an increasing number of members of the population exponentially decreased the propagation time in which a disease would spread from a single source, and through neighboring contact. In review, this model was determined to be unrealistic because in the real-world, people will contact much more than just a couple of members in the population a daily basis. Furthermore, it is not reasonable to assume that every member in a population can fight off a disease in an equal amount of time, and with the same result. Individuals with pre-existing health conditions, of different genders, and different age groups will be of varying susceptibility. In exercise 5, a number of simulations were run to study the spread of an infection, again from a single source, with varying infection probabilities and vaccination percentages, but with a different mode of contact. In these simulations, which are best approximated by the "SIR" model, each member of the population was free to come into contact with six, randomly chosen members of the population each day. It was determined that for a fixed population size, and infection probability, the duration of infection propagation through this mode of contact has an exponential relationship with the vaccination percentage. The concept of "Herd Immunity" was then studied to examine the relationship between vaccination percentage, and probability of infection upon contact for conditions where the infection is never spread from the original source to any member in the population. It was determined that for large vaccination percentages (95-99 %), there is a linear relationship between the vaccination percentage and probability of infection.