Infectious Disease Model

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December 5th, 2023

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Introduction:

Due to the recent COVID-19 pandemic, there has been a surge in the study of epidemiology. Predicting future outbreaks has increased in importance, and medical practitioners are actively looking for ways to prevent the possibility of another pandemic. This project simulates the spread of a disease from an initial source of infection. It aims to display the condition of a population daily, reporting the number of people that are susceptible, infected, recovered, or vaccinated. This model also incorporates potential mutations of the disease, further elongating its duration within the population. The goal of this project is to observe how different factors, such as vaccination rate, disease transmission rate, and mutation rate affect the spread and duration of a certain disease.

Test Cases:

Throughout the process of creating this model, numerous tests were run to make sure that the code was running correctly. The first test was a simulation of Joe, an individual who was infected on Day 3 with a disease lasting 5 days.

```
On day 1, Joe is susceptible
On day 2, Joe is susceptible
On day 3, Joe is infected
On day 4, Joe is infected
On day 5, Joe is infected
On day 6, Joe is infected
On day 7, Joe is infected
On day 8, Joe is recovered
```

The purpose of this test was to ensure that the `get_infected()`, `get_vaccinated()`, and `one_more_day()` methods were working correctly in the `Person` class. It also ensured that the `Disease` class was working properly as well. Catch2 test cases were then used at different points in the creation of the model serving as sanity checks. These tests varied from checking the functionality of the transmission rate to checking that the individuals were infected for the correct amount of time. As shown in the following output, all tests were passed:

```
Randomness seeded to: 363099835
===============================================================================
All tests passed (19 assertions in 8 test cases)
```

Simulation Results:

When beginning to create the model, it was assumed that there would be no contact between individuals within the population. In order to check that the `Disease`, `Person`, and `Population` classes were functioning properly, the following output was generated:

```
Initial State:
? ? ? ? ? ? ? ? ? ? 
After Infection:
? + ? ? ? ? ? ? ? ? 
Day 1: ? + ? ? ? ? ? ? ? ?
Day 2: ? + ? ? ? ? ? ? ? ?
Day 3: ? + ? ? ? ? ? ? ? ?
Day 4: ? + ? ? ? ? ? ? ? ?
Day 5: ? – ? ? ? ? ? ? ? ?
```

The “?” represents susceptible individuals, “+” represents infected individuals, “-” represents recovered individuals, and “x” represents vaccinated individuals. This simple simulation is the heart of this infectious disease model because it contains all of the basic methods needed to create a more complicated model. It shows that initially, 10 people were susceptible, when one got infected. Because, in this simulation, the individual is not capable of infecting others, they were sick for 5 days and then recovered.

Afterwards, interactions between members of the population were incorporated. Here are a few examples of the outputs with varying population size and contagion probability:

```
Simulation with Population Size: 20, Contagion Probability: 0.1
Day 1: ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ?
Day 2: ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ?
Day 3: ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ?
Day 4: ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ?
Day 5: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
Day 6: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
Day 7: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
Day 8: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
Day 9: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
Day 10: ? ? ? - ? ? ? ? ? ? ? ? ? ? ? ? ? - ? ?
```

```
Simulation with Population Size: 50, Contagion Probability: 0.3
Day 1: + + ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ?
Day 2: + + + ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + ? ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ?
Day 3: + + + + ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + + ? ? ? ? ? ? ? ? ? ? ? ? + + + ? ? ? ? ?
Day 4: + + + + ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? + + + + + + + + ? ? ? ? ? ? ? ? ? ? + + + + ? ? ? ? ?
Day 5: - - + + ? ? ? ? - - + ? ? ? ? ? ? ? ? ? ? ? + + + + - - - + + ? ? ? ? ? ? ? ? ? ? + - - - + ? ? ? ?
Day 6: - - - + + ? ? ? - - + ? ? ? ? ? ? ? ? ? ? ? + + + - - - - - - + ? ? ? ? ? ? ? ? ? + + - - - + ? ? ? ?
Day 7: - - - - + ? ? ? - - + + ? ? ? ? ? ? ? ? ? ? + + - - - - - - + + ? ? ? ? ? ? ? + + + - - - + + ? ? ?
Day 8: - - - - + ? ? ? - - + + + ? ? ? ? ? ? ? ? ? + - - - - - - - - + ? ? ? ? ? ? + + + - - - - + + ? ? ?
Day 9: - - - - + ? ? ? - - - + + ? ? ? ? ? ? ? ? + - - - - - - - - - + ? ? ? ? ? ? + + + - - - - - + ? ? ?
Day 10: - - - - - ? ? ? - - - + + ? ? ? ? ? ? ? ? + - - - - - - - - - + ? ? ? ? ? ? + + - - - - - - + ? ? ?
```

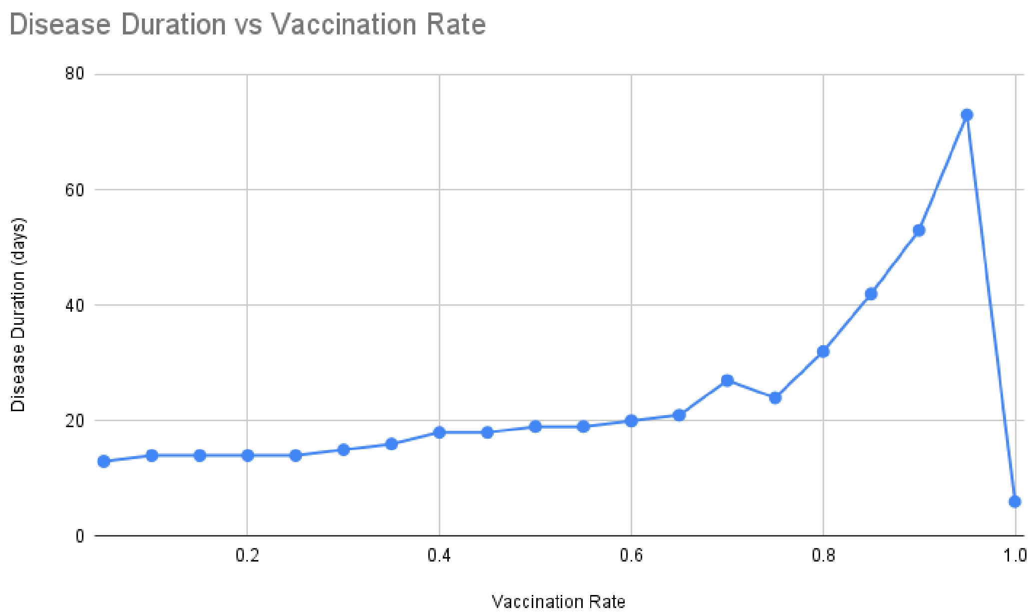
These results show that because individuals can only infect their neighbors, people can escape getting sick. If an individual fails to infect their neighbor before recovering, every individual after them will not be infected either. This is in large part due to the less than 100% infection rates. Vaccination was then added to this model as well. Here are some more outputs including vaccination:

```
Simulation with Population Size: 20, Contagion Probability: 0.1
Day 1: + ? ? ? ? + x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 2: + ? ? ? ? + x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 3: + ? ? ? ? + x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 4: + + ? ? ? + x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 5: - + ? ? + - x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 6: - + + ? + - x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 7: - + + ? + - x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 8: - - + ? + - x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 9: - - + + - - x ? ? ? ? ? ? ? x ? ? ? ? ?
Day 10: - - - + - - x ? ? ? ? ? ? ? x ? ? ? ? ?
```

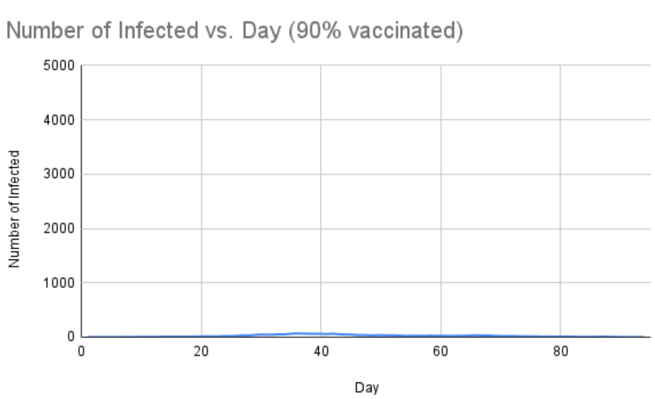
```
Simulation with Population Size: 50, Contagion Probability: 0.5
Day 1: ? ? ? ? ? ? ? ? + + ? ? x ? ? ? x ? ? ? ? ? ? ? ? x ? ? ? ? ? + + ? + + ? ? + + ? ? + x ? ? ? ? ? x
Day 2: ? ? ? ? ? ? ? ? + + + ? x ? ? ? x ? ? ? ? ? ? ? ? x ? ? ? ? + + + + + + ? + + + ? ? + x ? ? ? ? ? x
Day 3: ? ? ? ? ? ? ? + + + + + x ? ? ? x ? ? ? ? ? ? ? ? x ? ? ? + + + + + + + + + + + ? ? + x ? ? ? ? ? x
Day 4: ? ? ? ? ? ? ? + + + + + x ? ? ? x ? ? ? ? ? ? ? ? x ? ? + + + + + + + + + + + + + ? + x ? ? ? ? ? x
Day 5: ? ? ? ? ? ? + + - - + + x ? ? ? x ? ? ? ? ? ? ? ? x ? + + + + - - + - - + + - - + + - x ? ? ? ? ? x
Day 6: ? ? ? ? ? ? + + - - - + x ? ? ? x ? ? ? ? ? ? ? ? x ? + + + - - - - - - + - - - + + - x ? ? ? ? ? x
Day 7: ? ? ? ? ? + + - - - - - x ? ? ? x ? ? ? ? ? ? ? ? x + + + - - - - - - - - - - - + + - x ? ? ? ? ? x
Day 8: ? ? ? ? ? + + - - - - - x ? ? ? x ? ? ? ? ? ? ? ? x + + - - - - - - - - - - - - - + - x ? ? ? ? ? x
Day 9: ? ? ? ? ? + - - - - - - x ? ? ? x ? ? ? ? ? ? ? ? x + - - - - - - - - - - - - - - - - x ? ? ? ? ? x
Day 10: ? ? ? ? ? + - - - - - - x ? ? ? x ? ? ? ? ? ? ? ? x + - - - - - - - - - - - - - - - - x ? ? ? ? ? x
```

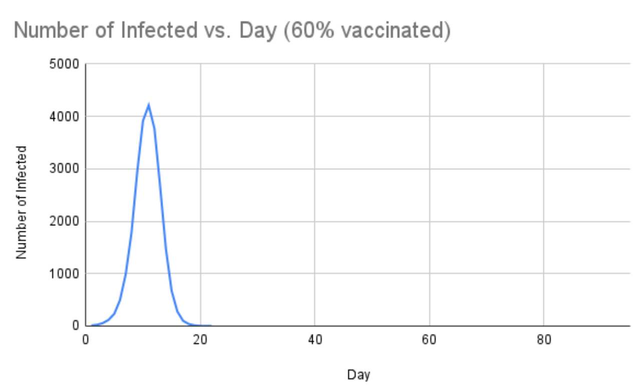
In these cases, people beyond the vaccinated individuals cannot be infected either. Vaccinated individuals end up creating a barrier blocking others from getting infected. This model is unrealistic because a vaccinated or recovered individual should not be able to prevent half the population from getting infected, for example. In a realistic model, an individual's recovered or vaccinated status should not affect another individual's status.

Furthermore, random interactions between individuals were then added. So, instead of only infecting their neighbors, individuals can now infect random people within the population. After testing many vaccination rates for a fixed transmission probability, a trend in the duration of the disease can be observed. A population of 15,000 was used.



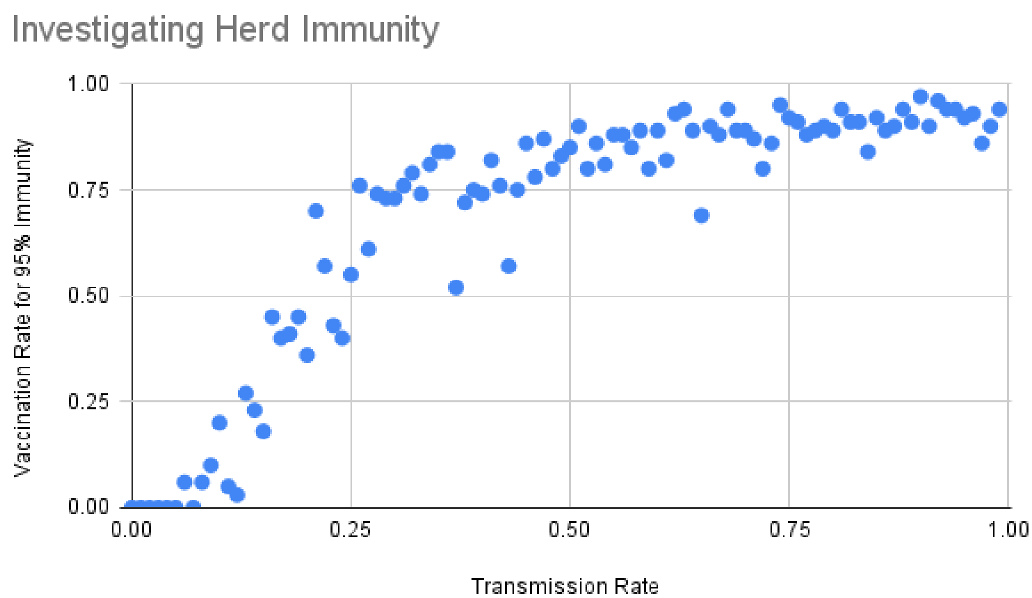
The duration of the disease increases as the percent vaccinated increases, except when the vaccination rate is 100%, when there are no susceptible individuals. This is because infected individuals can interact with vaccinated individuals as well. As the vaccination rate increases, the infected individual is less likely to interact with susceptible individuals. Thus, it takes longer for the susceptible population to get infected and then recover. This also ties back into the "flatten the curve" ideology that public health officials would refer to during the COVID-19 pandemic. As the vaccination rate increases, the duration of the disease increases, also meaning that less people are sick at one time.





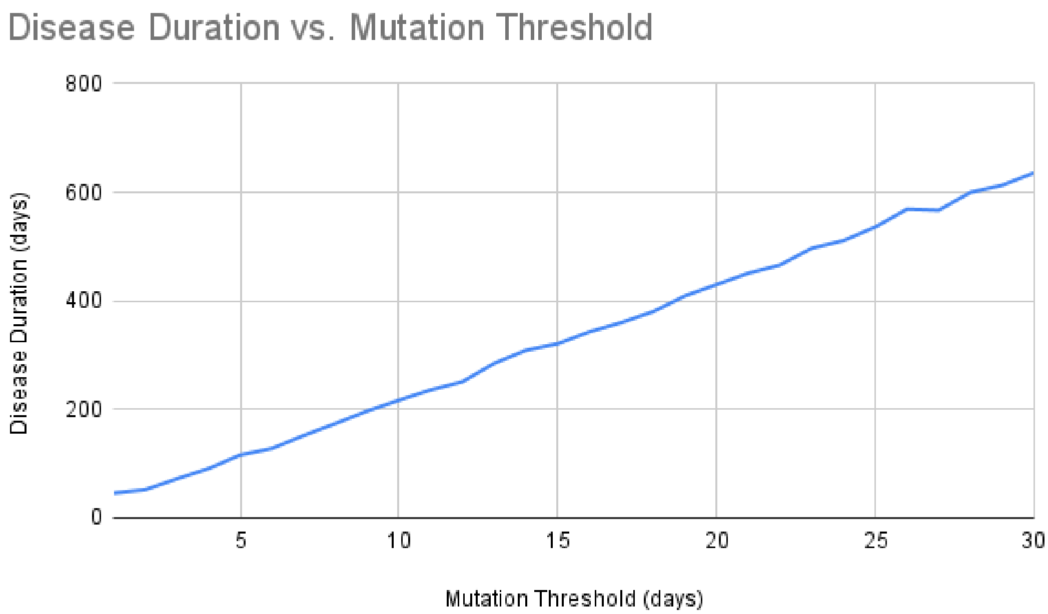
These graphs include data from the above simulation and show that as the vaccination rate increases, the number of people infected at one time decreases, thus flattening the curve. During the pandemic, this made hospital beds and doctors more accessible due to the significant decrease in the number of people sick at once.

In order to further investigate the effects of vaccination rate on the population, herd immunity was analyzed. The goal was to have the probability of being not vaccinated, yet never getting sick, to be over 95 percent. The transmission rate was then varied to see what vaccination rate would be needed to achieve this. A population of 10,000 people was used to model a relatively larger population as well as prevent long run times.

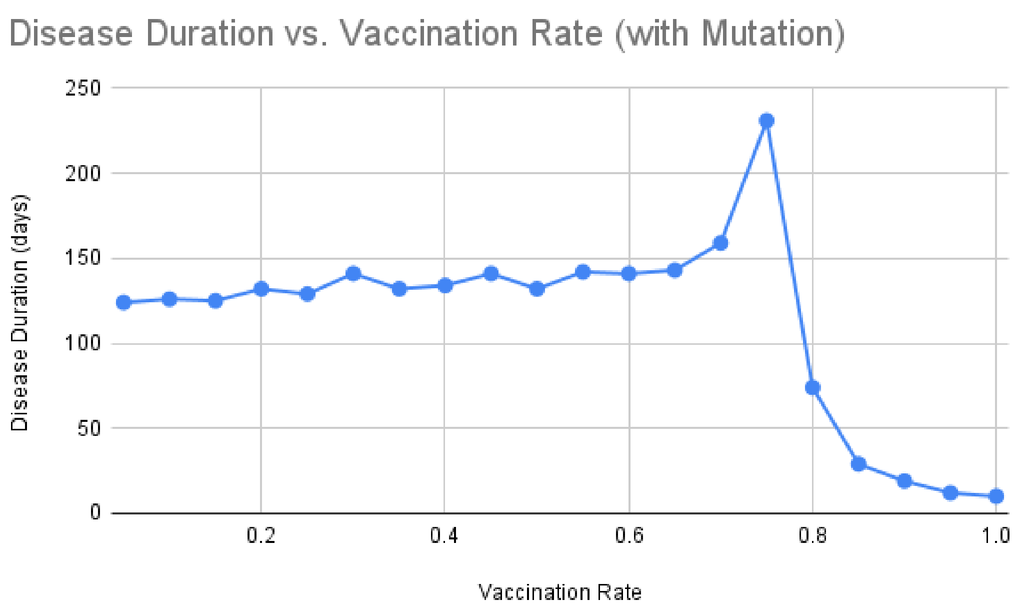


When looking at the results, it can be concluded that as the transmission rate increases, a higher vaccination rate is needed to achieve herd immunity. This is because as the transmission rate increases, it is more likely that individuals will get infected, indicating that more vaccinated individuals are needed to combat the increase in the infected population. This data depicts the reason why medical practitioners and public health officials aim to vaccinate as many individuals as possible in a population. The higher the number of vaccinated individuals, the more likely it is to achieve herd immunity. It also increases the number of people that are susceptible to the disease, but never get infected to protect people that did not get vaccinated.

Finally, mutations of the disease were also added into the model. Although this model currently is not very realistic, it models the basic concepts of mutation. A mutation threshold was assigned in the code to determine after how many days the disease would mutate. Furthermore, a variant limit was also added in order to prevent the model from running indefinitely. A variant limit also makes the model more realistic because in most cases, there are a limited number of variants per mutation.



This graph shows that as the mutation threshold increases, the disease stays in the population for a longer period of time. This is because if the disease takes longer to mutate, it will take the disease longer to reach the variant limit in order to stop spreading throughout the population.



When comparing this graph to the previous “Disease Duration vs. Vaccination Rate” graph without mutation, a similar trend can be observed. The duration gradually increases, reaches a peak, and then rapidly decreases. This further supports the idea that, even with mutations, as the vaccination rate increases, the disease stays in the population longer. This, in turn, also reduces the number of individuals infected per day and continues to “flatten the curve”.

Ethics:

Ethics plays a key role in the study of infectious diseases and vaccination, with this simulation project highlighting key ethical considerations. The simulation raises questions about individual responsibility in the context of potential pandemics, particularly in the context of vaccination. The simulation results emphasize the need for the collective responsibility to get vaccinated throughout a potential pandemic. The exploration of herd immunity emphasizes the ethical imperative of achieving high vaccination rates to protect both vaccinated and unvaccinated individuals. When a few individuals decide not to get vaccinated in a situation like this, it increases the risk of other people getting sick as well. Even though nothing necessarily happens to the individuals making this decision, they are putting others at risk. The inclusion of mutations in the model introduces additional ethical dimensions, highlighting the ongoing need for diligence when facing evolving pathogens. These ethical considerations depict the societal impact of individual choices and emphasize the importance of community-wide cooperation to mitigate the risks of potential outbreaks.

Conclusion:

Ultimately, using the results from the experiments run throughout this project, it can be concluded that the vaccination rate holds the largest influence in the spread of the disease throughout the population. Factors such as population size, disease transmission rate, and mutation threshold hold far less influence in how the disease affects a population. Thus, this ties back into the ethics of this infectious disease model. Given that vaccination rate greatly reduces the number of individuals getting infected and increases the duration of the disease, it is vital for people to get vaccinated. Specifically, the model's exploration of herd immunity reinforces the ethical necessity of achieving high vaccination rates. Individual decisions of not getting vaccinated greatly increases the risk of others getting sick. This simulation highlights the ethical significance of individual choices and stresses the societal impact of widespread cooperation in mitigating the risks and consequences of potential outbreaks.

References:

Eijkhout, Victor. *Introduction to Scientific Programming in C++17/Fortran2008*. Vol. 3, 2023.