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Simulating the Progression of the COVID-19 Pandemic and Analyzing the Effects of Vaccination

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Abstract: With thousands of COVID-19 cases on the rise, The project look back and see that it has already been more than a year and a half since the first COVID-19 case has been recorded. After months and months of the raging pandemic, many begin to wonder: what will it take to end it? As scientists and researchers scramble to come up with a global solution, many begin to educate themselves on the topic. In our paper, done by weeks of research, analysis, simulations, and coding, we look and touch upon the progression of COVID-19. Beginning with basic research, the project looked at the different types of vaccines that are being distributed, and found articles that mentioned the best way to end the pandemic worldwide. Along with basic research came simulating situations of the pandemic: this was done with none other than the programming language, Javascript, which was chosen for the fact that our simulation was going to be mostly web-based. Based on prior simulations, we came up with a model that was both accurate and visually intuitive. The project then used the simulation to obtain results and graph data. From the graphs that we obtained and kept, we were able to discuss and talk about the results that came up from it, such as analyzing the spread of the virus through different levels of masked or vaccinated individuals. From the basic steps of learning how to code to learning how to make graphs to represent the pandemic, we are able to grasp our current situation as well as educate others and ourselves on the biggest global concern today.

Keywords: COVID-19, Simulation, Vaccination, Pandemic, Modeling

1. Introduction

The recently discovered Coronavirus disease (COVID-19) has caused a global pandemic. With a high contagion rate, most people infected experience mild to moderate respiratory symptoms that do not require special treatment. However, those with affected immune problems such as diabetes or cardiovascular disease are prone to much more lethal symptoms. Transmission has been prevented through information, hygiene, and social distancing. Governments around the world for the beginning of the pandemic have controlled the virus spread through frequent masks, contact tracing, and quarantines. As COVID-19 vaccines are rolling out, it is more important than ever to make sure that herd immunity can be acquired through vaccinations to save as many lives as possible [1].

Access to vaccination is critical in the end of the pandemic. Even with those vaccinated, governments still recommend COVID-19 guidelines such as wearing masks, cleaning our hands, and physical distancing, because research is still ongoing as to how much protections vaccines protect against transmission [2]. In this paper, we will be analyzing through simulations the effects of vaccination rates, fatality rates, and mask rates on the spread of COVID-19.

2. Background Knowledge

2.1. Simulations

As the COVID-19 pandemic is continuing to threaten citizens, people have made simulations of COVID-19 pandemic that contain many variables referring to the situation they are in. In this project, we referenced 3 main simulations that were used as the basis for our model.

Simulation done by Joe Jox, Youjin Shin, and Armand Emamdjomeh (Feb. 16, 2020) [3] contained three variables being infected, recovered, and dead, giving each of them different colors to show difference and see the result after the simulation is done. The simulation had a circle shape and used a grid model. It also gave two comparison Measles and Evola virus with different rates of fatality and spread speed. It was also giving hypothesis simulation for cases in quarantine making a black lined wall between the outer space making the infected one not being able to spread.

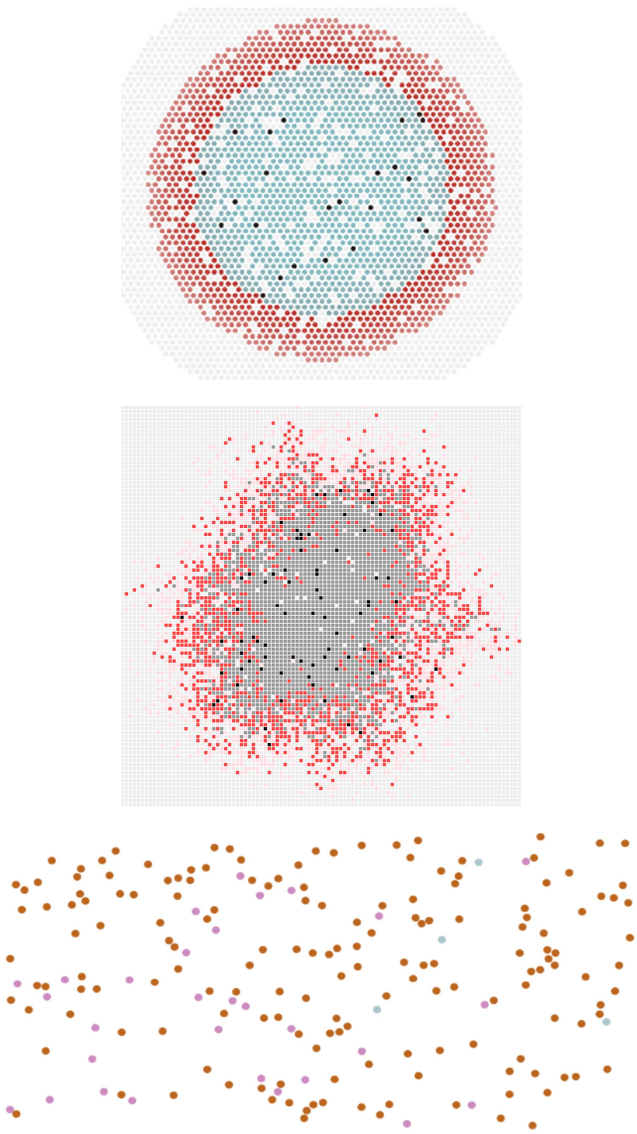


Figure 1. *(top) Circular grid simulation by Joe Jox, Youjin Shin, and Armand Emamdjomeh; (middle) Square grid simulation by Kevin Slimler; (bottom) Bouncing balls simulation by Harry Stevens.*

The second simulation was done by Kevin Slimler (March 16, 2020) [4] this simulation was a square shaped grid simulation that had four variables: susceptible (white color), infected (incubation period, no symptom, light red color), infected (with symptoms, red), recovered (grey), and dead (black). This simulation was made so that we can change the variable of the days in incubations and days with symptoms and the transmission rate (spreading rate). This simulation also produced a separate simulation of the number of other cases, taking into account factors other than simple infections. For example: hospital capacity, number of encounters, and travel.

The last simulation was done by Harry Stevens (March 14, 2020) [5]. Basic for simulation was ball movement. Balls collide with each other and walls bounce in different directions. When the infected ones with brown color collide with the susceptible with white color the susceptible turn brown, after a few seconds they turn to purple color meaning they are recovered. This simulation had many different variables such as putting a wall between certain places and opening it up or showing people staying at home by making them stop in certain positions when other susceptible and infected ones are bouncing around. Also, it had a simulation testing the effectiveness of social distancing which made all people stay separate from each other and also had those people staying still in certain places. It had a graph showing susceptible, infected, recovered, and dead as the time went.

2.2. Types of Vaccines

Currently, there are 5 main types of vaccines being distributed: Pfizer-BioNTech, Moderna, Johnson & Johnson, Oxford-AstraZeneca, and Novavax. All vaccines except the Novavax, which is still in clinical trial stage, have been approved for use under the European Union. Pfizer, Moderna, and Johnson & Johnson have been authorized by the FDA and are in use within the United States. Of these vaccines, Pfizer and Moderna are mRNA vaccines while others are protein vaccines [6].

The Pfizer vaccine is the only one that is recommended for minors under the age of 18. It is administered through 2 doses which are 21 days apart and has a 95% efficacy against COVID-19 [7]. It has been found to be 95% effective against Alpha and Beta strains of Covid, and 88% against the Delta mutation [8].

Moderna [9] is also administered in 2 doses, 28 days apart. It is 94.1% effective against COVID, but its effectiveness against COVID variants has not been proven [6]. Efficacy was also found to drop to around 86% for those who are 65 and older.

Johnson & Johnson, referred to as Janssen in Europe, is administered in a single dose. The FDA issued several warnings on the vaccine, as some rare cases of Guillain-Barre syndrome were reported after vaccine administration [10]. Severe blood clotting has also been observed in a few recipients [11]. Overall, its efficacy is around 76% [12], and proven to be effective against the alpha variant. The vaccine has also been reported to be effective against delta variants although there are minor controversies of how effective it is [13].

Oxford-AstraZeneca is lower in cost and can be stored or transported for longer than other vaccines [6]. It is delivered in two doses which are around 4 to 12 weeks apart and with a 76% efficacy. The vaccine was also proven to be 60% effective in preventing symptomatic disease for the Delta variant [8].

Novavax is administered in 2 doses, 3 weeks apart. The vaccine is still in clinical trial stage, and it was measured to have a 90% efficacy [6]. Novavax claims to have a 93% efficacy against predominant variants, but its effectiveness against the Delta variant has not been proven yet.

Amongst the variety of vaccines, we chose to include the Pfizer vaccine in our simulation and the experiments conducted in section III were based on the efficacy of the Pfizer vaccine.

2.3. How to End COVID-19

The longer an epidemic spreads throughout populations, the number of people in that population left to infect decreases. However, contagious outbreaks such as COVID-19 and measles have been prevented and contained through vaccinations. The measles outbreaks have been contained once 86% of children under 2 years old globally have received measles vaccinations. The life cycle of an epidemic goes as: they go up, growth rates slow, peak number of infections, and then a decrease in infected people. Epidemics don't have to be waited out; quarantine and personal hygiene effectively limits the ability of pandemics to rapidly spread. In a simulation done by the Washington Post, a third of people who hypothetically got a disease that wore masks and gloves decreased the spread of the disease. Quarantines proved effective as they limited the number of people exposed to the disease. Governments have used quarantines, masks, and social distancing to try to contain the COVID-19 outbreak, but as long as there are people that do not follow these guidelines, the pandemic may take a much longer time to end than it could. [3]

One aspect of concern that may draw is the new wave of more infectious variants across the globe. Potential herd-immunity timelines are changing as data shows variants may reduce vaccine efficacy. If the new variants pose as a minor factor or are contained easily, herd immunity is much more likely. However, if the new variants are much more impactful, the timeline could significantly delay into 2022. [14]

3. Method

3.1. Tools

The programming language used to build the simulation was Javascript. Javascript was chosen as it is relatively easy to manipulate and is web-compatible, which was vital since the simulation was going to be web-based.

All coding was done through Visual Studio Code, an open source code editing software optimized for building web applications. Visual Studio Code was chosen since it was advantageous in many ways: it was free and provided assistance through tools such as auto-indentation, bracket-matching, or syntax highlighting. Codes were tested though running the command, npm-start and any errors were debugged. To ensure that codes for all research group members were identical, Github was used. Codes that worked the best were pushed into the main branch, and other group members merged their codes with the main branch.

3.2. Modeling

Grid model is a default model for creating simulations that take place on a grid / tortus topology [16]. In prior simulations [3, 4] grid model was used for accurate mathematical and statistical results. The downside of these grid models is that it does not account for the randomness of real life situations and it is not very intuitive when observing the spread of COVID-19. In the previous study study [5], Stevens uses a more random and intuitive approach which is modeling the agents as balls that are able to interact with each other and bounce around the environment. In our simulation we chose a combination of both approaches. We use the bouncing balls model in order to achieve an amount of randomness and interactions between agents, but also position the balls in close proximity. This limits the balls from moving around the environment too much and sacrificing accuracy when collecting data. The result is a grid environment where each individual agent is able to penetrate or travel to other regions and also interact with or contage other agents. It beautifully resembles that of a cell-like structure or ishihara test.

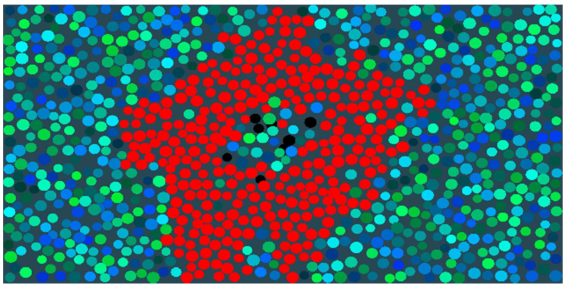


Figure 2. *Bouncing balls + grid simulation.*

Each ball represents an individual agent. Balls are given a random color between green and blue. Infectived agents are shown as red while dead agents are shown as back.

3.3. Performance and Scalability

PIXI.js is a 2D WebGL renderer used to animate scenes of graphical objects. You can load, move and rotate images, and change their color. You can also add graphic objects to a container and move the container as a unit. PixiJS' strength is speed. When it comes to 2D rendering, PixiJS is the fastest one. Other advantages that PixiJS has is that it is applicable to multiple platforms, simple as well as powerful, easy to use and learn, and has full multi-touch input recognition. We used PixiJS to tint a ball, shape a ball, and load the graphics and container. PixiJs was the best fitting rendering engine for 2D so it was able to hold a large amount of agents in the simulations. Using PIXI.js and its WebGL based rendering engine, we were able to simulate agents up to a number of 100,000. However this was bottlenecked by the computations that needed to be conducted in order for the simulation to run. Due to this, the number of agents was limited to 1000, a hundredth of its potential capacity.

In order to solve the bottleneck problem we needed a more efficient way of computing the simulation. Spatial hashing is a process by which a 3D or 2D domain space is projected into a 1D hash table. The environment is divided into a grid of cells and each cell holds the agents that it spatially contains or is adjacent to. By saving the agents into each of its respective cells, we can massively reduce computation time. Previously, in order to implement interactions between agents, we needed to correlate each ball with every other ball in the environment. This resulted in a computation time of O(n2). However, by only looking at adjacent balls that inside nearby cells we reduce the computation time to O(logn) or O(n). Using spatial hashing, we were able to reach numbers of agents by 10,000 (10 times the quantity of the previous method).

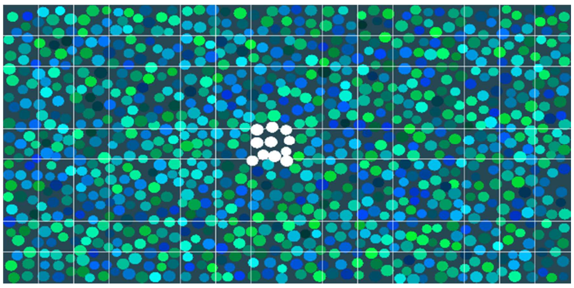


Figure 3. *Spatial Hash integrated with simulation.*

The environment is divided into a grid of cells and each cell holds the agents that it spatially contains or is adjacent to. The white balls indicate the balls that are held by the respective cell.

3.4. Interactions and Sequences

There are three main methods (bounce, contage, and update condition) that are taking a big part in showing interactions and sequences between balls and their conditions. These methods use different colors, the ball's velocity, and different conditions: has Mask, vaccinated, and dead (fatality).

First, the bounce method uses the velocity implemented in the code and it shows the movement of the ball bouncing to each other. It also prevents the ball from looking like it is laying over the ball. For simplicity, we assume a perfectly elastic collision and use the following formula:

$$v_{Af} = \left(\frac{m_A - m_B}{m_A + m_B}\right) v_{Ai} + \left(\frac{2m_B}{m_A + m_B}\right) v_{Bi}$$

$$v_{Bf} = \left(\frac{2m_A}{m_A + m_B}\right) v_{Ai} + \left(\frac{m_B - m_A}{m_A + m_B}\right) v_{Bi}$$

Eq 1. Formula for solving the final velocities of a collision.

For a perfectly elastic collision, mA and mB are equal and velocities are simply exchanged.

Next, the contage method as it says contage the ball when they hit each other by turning the other ball to red color. Masked and vaccinated property makes a difference by making the chance to get infected lower. This probability was calculated by taking into account the ability of masks to reduce the amount of aerosols being leaked into the environment. An agent wearing a N95 mask will leak 70% less aerosols into the environment and also have 99% less aerosols leaked into the mouth and nasal parts. An agent will have immunity over infection with an efficacy of 95% [6]. Masked people have a white border line and vaccinated people have a yellow border line showing the difference between those two properties in the experiment.

Lastly, the update condition method updates the condition of the infected by changing its condition and color so when they are recovered they change the color into the original color showing that they are recovered and in the graph it shows the recovered ones as purple color. Also, this condition takes part in checking dead people by turning their color to black and the fatality rate is changeable on the settings.

3.5. GUI

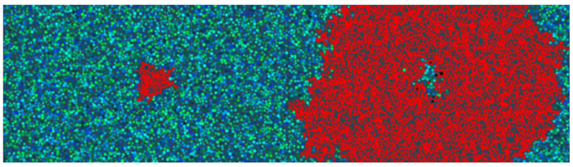
To allow users to run the simulation in different conditions, a graphical user interface (GUI) was added. The GUI included 2 parts: one that enabled users to manipulate input settings, and one that showed a live graph of the number of infected, susceptible, dead, and recovered. The input settings tab consisted of 3 slider bars for the percentage of masks, vaccination, and fatality. Each slider had a range from 0 to 100. Options to enable or disable graph stacking and showing fatality were also added to the input settings tab. This feature was used to create and run different scenarios, which enabled us to compare results and determine the effects of vaccination, mask percentages, or fatality had on the spread of the virus. The live graph was designed so that it would display accurate statistics of a certain point when the user puts their cursor over it (Figure 1). This feature was used to determine the maximum number of infected in a scenario, or find any other interesting points.

4. Experiments and Analysis

4.1. The Spread

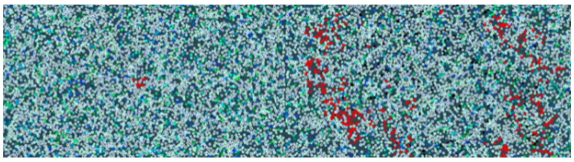
Through adjusting our simulation with code, we were able to see the general results of how the virus spread with a certain community of 5000 different individuals. Usually, we made it so that the outbreak would begin in the center of the simulation, and those who were infected were highlighted with red.

In our simulation, we also put the option to adjust the number of masked and vaccinated individuals, as well as putting the fatality percentage rate. For masked individuals, we put their color as white, while putting vaccinated individuals as yellow. To represent those who died, we put those individuals in the color of black, unable to move once after. Depending on what percentage we put for masked or vaccinated individuals, we saw an immense difference in how quickly the virus was able to spread.



(left) The outbreak (right) The progression of the spread

Figure 4. *The spread of the virus with 5000 agents.*



(left) The outbreak (right) The progression of the spread

Figure 5. *The spread of the virus with 5000 agents that are 80% masked.*

As we can see from comparing Figures 4 and 5, a highly masked community will not only take longer for the virus to spread, but also the number of agents that are contaged will be reduced significantly. Both simulations were run with the outbreak at the direct center of the environment. However, the position of the outbreak can also affect how the virus is to spread and the shape of the graph.

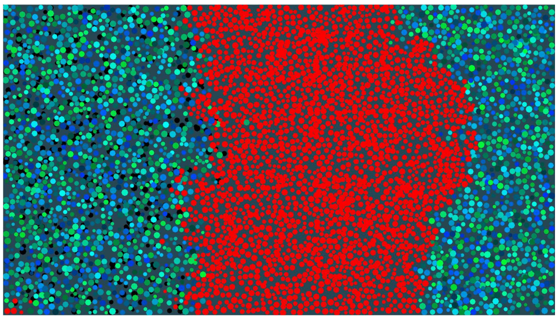


Figure 6. *Spread of the virus when outbreak is from the left side of the environment.*

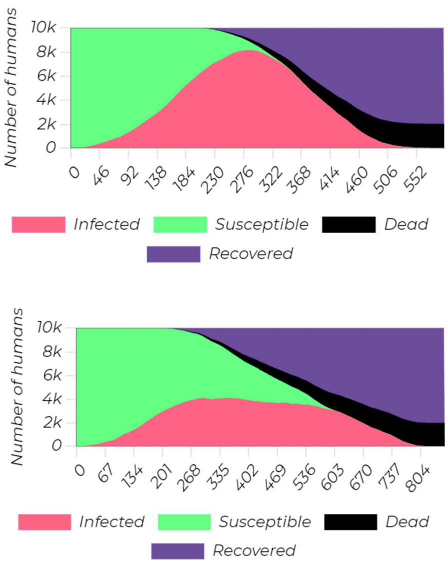


Figure 7. *(Top) Graph of the spread when outbreak is from the center of the environment; (Bottom) Graph of the spread when outbreak is from the left side of the environment.*

When the outbreak of the virus is on the furthest left side of the environment, the peak of the infection is lower but the length of the virus is longer. This is because as the virus travels across the environment, it turns into a consistent wave as shown in Figure 6. When the spread is in the shape of Figure 4, the number of infected increases exponentially due to the circular shape of the spread. However Figure 6 shows the shape of the spread to be more of a rectangular shape, therefore resulting in a linear increase. This linear increase is countered by a linear decrease at the end of the spread as the life of the virus ends and the agent's conditions are resolved to either dead or recovered.

4.2. Vaccination

We ran experiments to understand the effect of vaccination on the community. For all the simulations conducted, the fatality percentage was fixed to 20%. According to Figure 8 as vaccination percentage increases the maximum number of infected ones decreases at a slower rate, showing an exponential curve ending out at 0. This shows that after a certain threshold of vaccination is met, the community will reach herd immunity and slow down the rate of infection. That threshold is typically said to be around 60 ~ 70% which coincides with our graph.

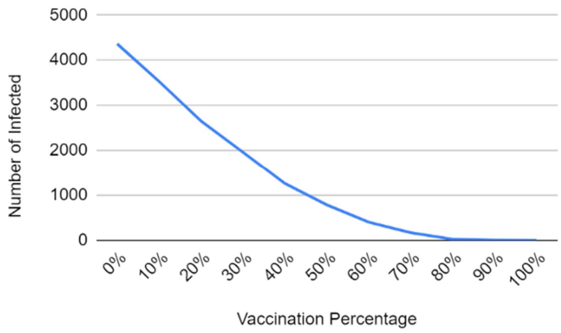


Figure 8. *Maximum number of infected by vaccination percentage.*

According to Figure 9, as vaccination percentage increases the total time of the experiment increases until 70% where it peaks and then decreases until it reaches almost no change in 90 ~ 100%. This is because up to 70%, the vaccination works more as a cushion to slow down the spread of the virus but once it reaches herd immunity, the spread of the virus is reduced so much that the life of the virus catches up with it, killing the virus entirely. The virus is therefore not able to last for a long time and the simulation ends.

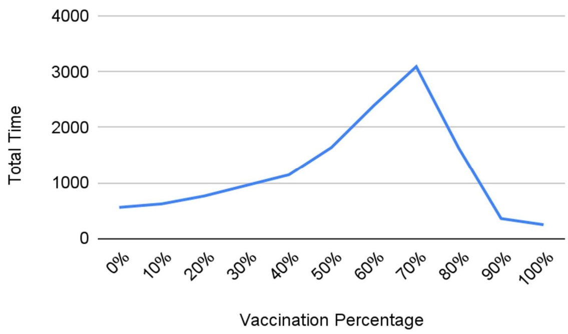


Figure 9. *Total time by vaccination percentage.*

According to Figure 10, as the vaccination percentage increases, the number of susceptible increases at a steady rate until 60% and grows faster after until 80%. The number of susceptible increases and it stays almost the same from 80% having 0.02% or lower amount of those infected or dead. As the slope of the graph increases from 60% we can see that due to herd immunity even though not all of the susceptibles are vaccinated, a large portion of the people are protected and this also can mean that the effectiveness of the vaccination substantially increases after 60%.

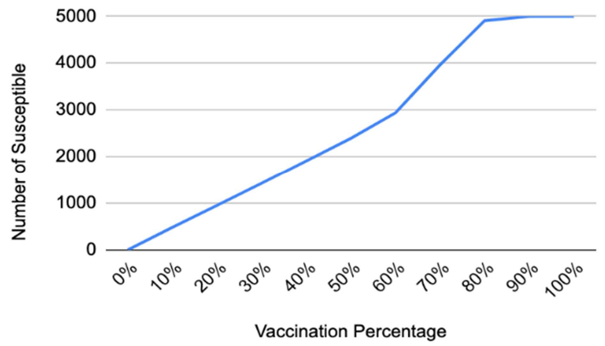


Figure 10. *Number of susceptible by vaccination percentage.*

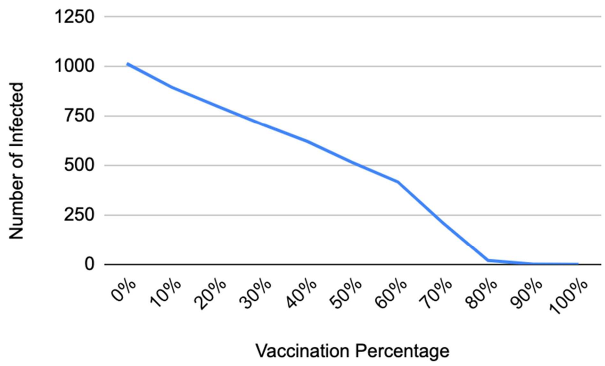


Figure 11. *Number of dead by vaccination percentage.*

According to Figure 11, as vaccination percentage increases the number of dead people decreases till 80% and stays similar in 80~100%. Also, the slope of the graph was decreasing much faster from 60% showing that after 60% of people vaccinated it decreases the number of deaths much more than before 60%. This means vaccination causes less casualties when there are more than 60% of the citizens vaccinated.

4.3. Masks

In order to test how different mask percentages affected the number of infected when the majority of the population was vaccinated, the simulation was run with different mask percentages at 60, 70, 80, and 90% vaccination rates. Fatality rate was fixed to 20%, and the mask percentage was increased by 50 (0, 50, 100%). For each category, 5 trials were run and the median of the maximum number of infected were calculated to create a line graph.

Most people were infected when 60% of the population were infected and nobody was wearing masks (an average of approximately 450 people). However, with only a 10% increase in vaccination percentage, the number of infected were cut down by around 67%, to a little less than 150 people.

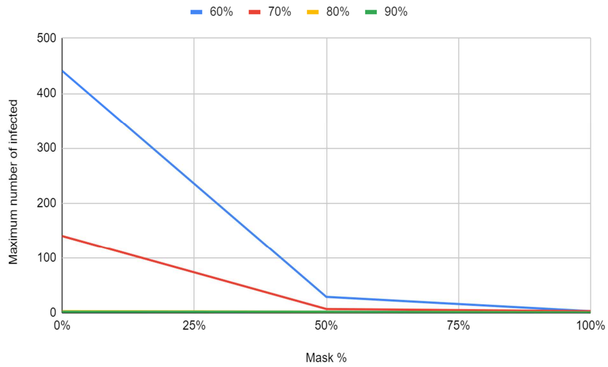


Figure 12. *Maximum number of infected are compared for different mask percentages and vaccination rates.*

The infected count also decreased the fastest when 60% of the population were vaccinated. Half of the population wearing masks resulted in a significant decrease in the infected count, from almost 450 to around 40. When vaccination rate was 70%, the infected count dropped from around 140 to 0 with a 50% increase in mask prevalence. Meanwhile, when 80 and 90% of the population were vaccinated, the number of infected were around 0 regardless of mask percentage. It suggested that the spread of COVID-19 could effectively be halted if very high percentages of the population are vaccinated.

The x-axis represents mask percentage, while the y-axis represents the mean maximum number of infected per frame. Different lines represent different vaccination rates.

4.4. Perimeter

In this situation, we made our simulation so that we would have our outbreak begin in the middle, with a circumference (like a circle) around the outbreak. We had our minimum radius with 300 pixels, and made 4 different situations, with the maximum pixels per simulation increase by 100 pixels. Every time we increased the maximum number of pixels by 100, the circle (which essentially represented the vaccinated individuals who were circling the outbreak) would get thicker and thicker, meaning more and more vaccinated individuals would act as a barrier against those who were infected.

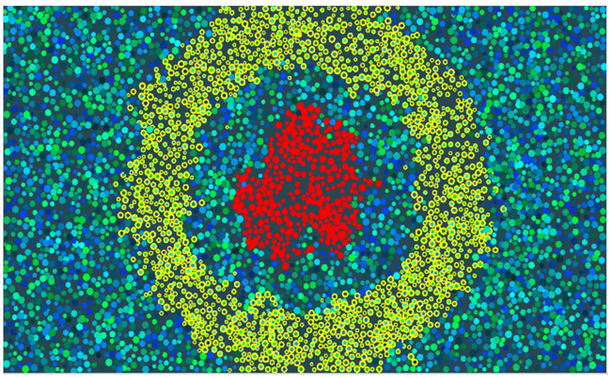


Figure 13. *Simulation of outbreak with a vaccinated perimeter.*

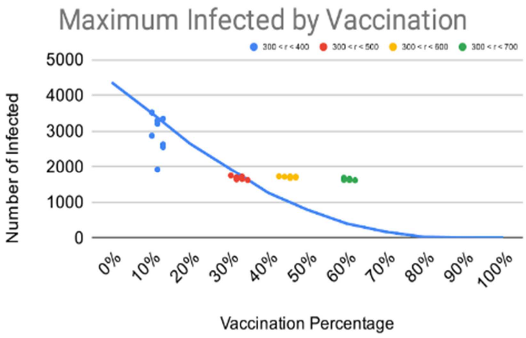


Figure 14. *Maximum number of infected by vaccination percentage.*

(blue line) randomly vaccinated agents
(dots) vaccinated agents in a perimeter

According to Figure 14, we can see that when the radius is between 300 and 400 pixels, the maximum number of infected people varies. Specifically, the range for the maximum number of infected individuals in this simulation was between 1,255 infected people to 2,771 people. But when we continue to look to the right of Figure 14, we can see that when the maximum radius continues to increase by 100 pixels, the overall maximum infected is consistent at around a total of 1,000 people.

The left of Figure 15, we can see how there are 2 waves, and we see that the second wave is a lot bigger than the first. The second wave represents the infected individuals that bled through the vaccinated individuals who acted like a barrier around the outbreak. Because the outbreak was able to bleed through the "wall", those who were not vaccinated outside the barrier caught the virus very quickly, and thus, caused a massive second wave.

However, the right of Figure 15 shows that there is only one wave towards the beginning, which most likely represents the infected individuals who got infected from the first outbreak. We can see that there is no second wave unlike the left, and this means that the infected individuals were not able to bleed through the vaccinated barrier.

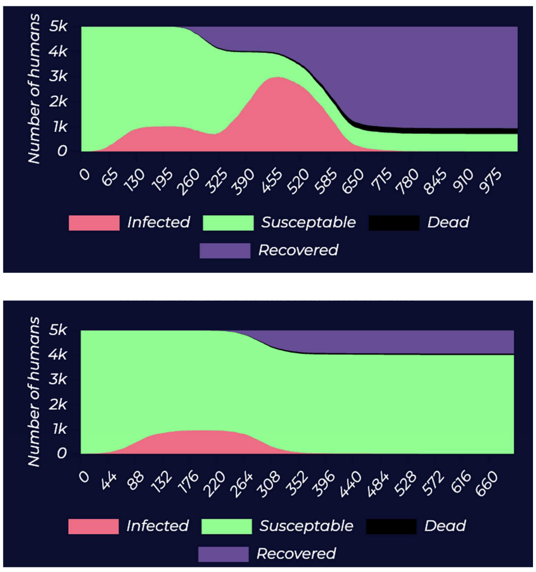


Figure 15. *(Top) Graph of the simulation with a vaccinated perimeter of 300 ~ 400px; (Bottom) Graph of the simulation with a vaccinated perimeter of 300 ~ 500px.*

4.5. Fatality

In order to test for different fatality rates around the world in terms of COVID-19, we decided to change fatality rates while keeping mask percentages and vaccination percentages consistent. To keep consistent with Korea's vaccination rates and mask percentages, we stuck to 70% vaccination and 30% mask rates. Then, we adjusted mortality rates: 5%, 10%, 18%, 40%, and 60% fatality rates. For each fatality rate, we ran the simulation 6 times each to find an average number of deceased, susceptible, and infected. Overall, we found that as fatality rates increased, the number of susceptible people also increased, although the number of dead did not linearly increase.

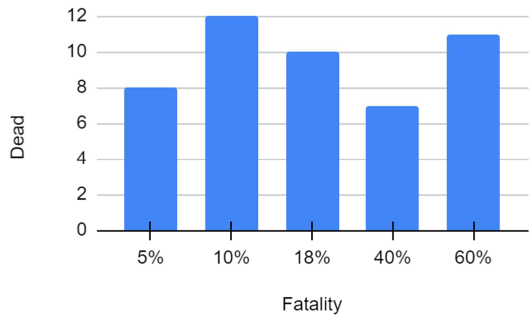


Figure 16. *Fatality Percentage compared with number of dead.*

In Figure 16, we compared the fatality rates to the number of dead in the simulation. In this graph, we found that the results did not coincide at a consistent rate, rather having numbers linearly. The range was from 7 dead and 12 dead, but 10% fatality rate had the most deaths compared to 40% fatality rate which had the least number of deaths.

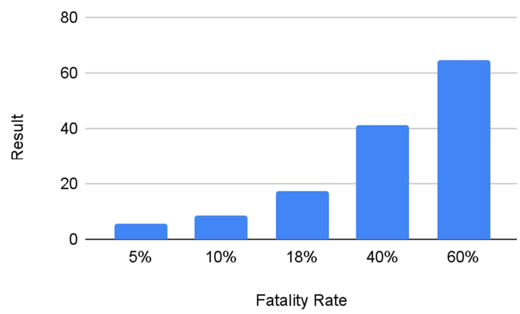


Figure 17. *Fatality Rate versus Result of Dead and Susceptible.*

In Figure 17, we compared fatality rates with the proportion of susceptible and dead numbers of people. These results were much more consistent with the fatality rates: as fatality rates increased, the results of susceptible and dead also increased at a consistent rate. This means that the simulation is accurately implementing the fatality rate. It is just that once the percentage of vaccination and masks reach a high enough value, the number of dead remains constant.

5. Conclusion and Future Works

Through our simulation, we found consistencies with vaccinations rates and those susceptible, infected, and dead. In this paper, we first talk about COVID-19 in general with current vaccines, vaccination rates, and overall background. Through the use of JavaScript programming with GitHub Desktop and Visual studio code, we built a simulation that would address vaccination rates, perimeter of people, fatality rates, and mask rates to find which would have the least susceptible, infected, and death rates. For future works, we can focus on running trials with different vaccination efficacies, such as Pfizer versus AstraZeneca. By running multiple different simulations, we can find the optimum circumstances to contain the new variants of COVID-19 and hopefully bring an end to the pandemic.

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