WHEN CAN WE LEAD A MASK-FREE LIFE AGAIN?

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Introduction

Coronavirus (COVID-19) caused by Sars-Cov-2, is an infectious disease that is transmitted airborne. Many people who suffer from the disease will experience either mild or severe respiratory symptoms, that include fever, dry cough, or even shortness of breath.[1] Due to the mRNA nature of the virus, multiple mutations occur that cause the virus to be more deadly. As of 10 May 2021, there are a total of 6600 mutations of the virus.[2] The WHO has classified it as a pandemic. The Logistic model is used to project the vaccination rates. Usually, the relationship between time and the vaccination rate is nonlinear. An upper limit is present in the case that is being looked into. Compared to linear regression, there is little to no assumption of homogeneity of variance, which provides a more accurate projection.[3] Simulation is also used to find the new reproduction number after the herd immunity, as found from the logistic model, is reached. Together, the appropriate vaccination rate, date and new reproductive number of the virus when no one wear's masks can be found, which allows us to predict when mask wearing can be optional in Singapore.

Application of Mathematics

To start off with the projection, a logistic model is used. Under normal circumstances, the vaccination rate V is proportional to the size of the healthy population. As the vaccination drive is implemented, more people will get to know about the vaccines. Number of healthy people who take the vaccine will increase exponentially. However, it is not realistic as there will be a limit to the number of eligible people. For more accurate projections, we assume that the relative growth of total vaccination rate, $\frac{dV}{dt}$, decreases when they reach the maximum healthy population of Singapore. According to the recent vaccination drive, students aged under 12 are not allowed to take the vaccine. 85% of people aged 65 and above are healthy and is eligible for the vaccine .[4] We assume that all people between the age of 12 to 65 are eligible for the vaccine.[5] The equation for eligible individuals are as follows:

$$L = 1 - \frac{N_{<12} + 0.15N_{>65} + N_f}{N},$$

where:

L is the total percentage of eligible individuals,

$N_{<12}$ is the number of residents below age 12,

$N_{>65}$ is the number of residents above age 65,

N_f is the number of foreign workers in Singapore,

N is the total population of Singapore.

After further calculations, we deduced that $L = 0.9056262359$.

We estimate that 90.56% of the population is healthy to take the vaccine. The equation for the rate of vaccination, also known as the logistic differential equation, is connected as follows:

$$\frac{dV}{dt} = kV(1 - \frac{V}{0.9056})$$

To obtain an equation for V, we integrate by separating the variables.

$$\frac{dV}{dt} = kV(1 - \frac{V}{0.9056})$$

$$\frac{1}{V(1-\frac{V}{0.9056})} \cdot \frac{dV}{dt} = k$$

$$\int \frac{1}{V(1-\frac{V}{0.9056})} \cdot \frac{dV}{dt} dt = \int k\, dt$$

$$\int \frac{dV}{V(1-\frac{V}{0.9056})} = \int k\, dt$$

$$\int \frac{dV}{V} + \int \frac{dV}{0.9056 - V} = kt + c$$

$$ln|V| - ln|0.9056 - V| = kt + c$$

$$\ln\left|\frac{0.9056-V}{V}\right| =- kt - c$$

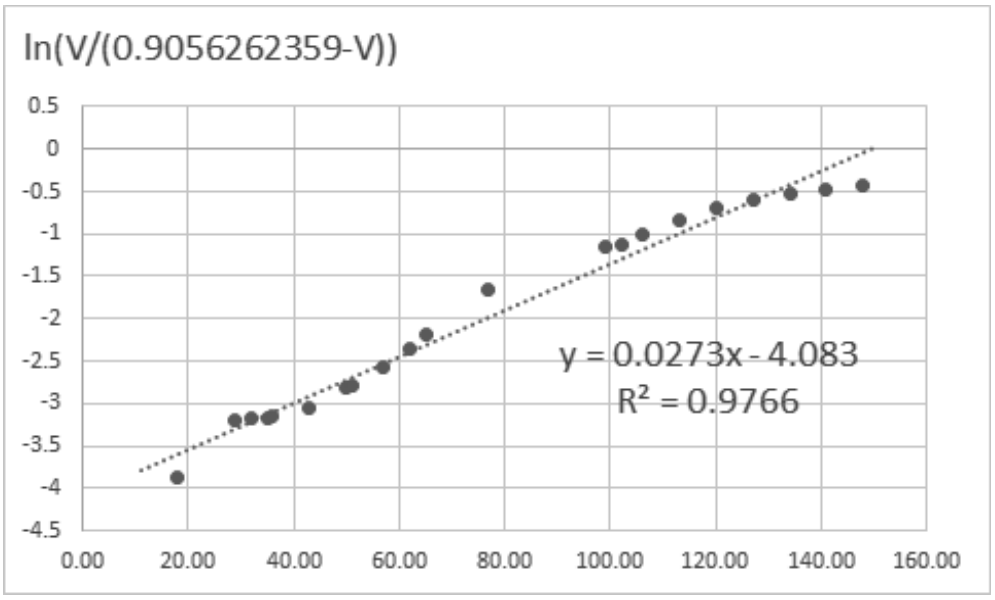
$$\frac{0.9056-V}{V} = \pm\, e^{-kt-c}$$

$$V = \frac{0.9056}{1+e^{-kt-c}}$$

We rejected the case where denominator is $1\text{-}e^{-kx-c}$ since $V < 0.9056$
Domain of t : [-20 ,∞]
Range of V: [0 , 0.9056262359]

For ease of projection, the equation for V will be linearised into the following:

$$ln(\frac{V}{0.9056-V}) = kt - c$$



The graph above shows the vaccination rate plotted against time for double-dosed vaccine.

$$ln(\frac{V}{0.9056-V}) = kt - c$$

$$ln(\frac{V}{0.9056-V}) = 0.0273t - 4.083$$

By comparison, $k = 0.0273$, $c = 4.083$
Do take note that t is the number of days after 31 Jan 2021 .

Only data from 31 Jan 2021 onwards is taken due to little amounts of data available before this date. Because of the small database, projection will be inaccurate due to it being affected by minor outliers.

The original equation is shown below:

$$V = \frac{0.9056}{1+e^{-0.0273t-4.083}}$$

where V is a function with properties as shown:

$$\left\{\begin{matrix} 0, if\ t < 0 \\ \frac{0.9056}{1+e^{-0.0273t-4.083}}, if\ t \geq 0 \end{matrix}\right\}$$

Herd immunity is a concept used by many countries to decide on their next step. Herd immunity works through achieving a threshold immunity that is able to theoretically cut the transmission chain of the infectious disease. It can be obtained through natural infection or vaccination.[6] The threshold immunity, when high enough, protects most, or even all the people in an area. However, the latter notion would very much depend on the duration of individual-level natural or vaccine-induced immunity. Assuming that the vaccine is completely effective, the reproduction rate of the virus is connected as follows:

$$R = sR_o,$$

where
R is the reproduction number,
s is the susceptible percentage,
R_o is the basic reproduction number of the infectious disease.

For a transmission chain to be cut, $R < 1$. Students aged 12-16 are only allowed to take Pfizer BionTech Vaccine and is recommended for the public has an efficacy of 80% for their first dose[11].People who are vaccinated will be less susceptible to the virus. $s = 1 - 0.80V$. Based on a research using the Fudan single- and multi-chain CCDC model, R_o for Sars-Cov 2 is estimated to be 3.32[7][8]. The equation can be rewritten as:

$$R = sR_0$$

The efficacy of double-dose Pfizer Vaccines are 95%.

$$s = 1 - 0.95V$$ [12]

$$3.32 \times (1 - 0.95V) < 1$$

Range for V is (0.7355738744, 0.9056262359)
Herd immunity requires around 73.6% of the population to have double-dosed vaccinations.

We can evaluate the time it takes to reach herd immunity by substitution of values.

$$ln(\frac{0.7355738744}{0.9056262359-0.7355738744}) < 0.0273t - 4.083$$

$t > 203.2067611$

$t = 204$(rounded up to nearest integer)

Therefore, the date where herd immunity will be reached is 23 August 2021.

Infectious rates alone cannot single-handedly determine when we can start putting off our masks. Other factors such as infection rates, which are caused by many environmental factors have to be taken into consideration. With many assumptions being made, it decreases the accuracy of the projections. Still, it will give an informed result.

Advanced Application of Mathematics

While a logistic equation provides a good estimation of vaccination rates due to an observable trend, the number of infections per week is less predictable, with too many factors in play. Real life infection spreads are a lot more unpredictable and random, just like in a simulation. A simulation would hence be much more suitable as it would take a smaller scaled version of real infection rates and sufficiently predict the probability of infection of every contact.

In coding a simulation, some factors that are produced are:

- ❖ Range of virus transmission is a 1m radius circle, twice a person's length.
- ❖ Recovery rate or the time taken to be removed from the simulation is 2 weeks, the typical time taken before symptoms show up.[10]
- ❖ Movement speed cannot be given an accurate number and hence we put it as a fixed, unchanged value, assuming that the lockdown and safe management measures are unchanged.
- ❖ The population density, number of people in a simulation is 20, assuming the variable case of an office, where there is an average of 20 people[13].
- ❖ All cases start off with the introduction of an infected person, to be referred to as patient zero.

With the above, the code for one person in the simulation is in appendix A.

Having these assumptions in place, a first simulation is conducted with fixed factors and a dependent variable of time taken for all to be infected, where those infected will not continue to infect other people. The independent variable is the probability, which can be found through a study that assessed airborne SARS-CoV-2 levels in a hospital in Wuhan, China, and found concentrations in the range of 20 virus particles/m^3 in medical staff offices and meeting rooms.The results of the current research also show that on average 1,000 virus particles are transmitted during an infection, from which an assumption is made that the transmission of an average 1,000 virus particles to an individual gives rise to a 100% probability of getting infected[9] .The Pfizer vaccine is 95.3% effective for people taking 2 doses while 1 dose provides at least 80% protection[14] . The surgical masks worn have a filtration rate of approximately 95%[15].

The probability of getting infected can be estimated and is hence displayed below.

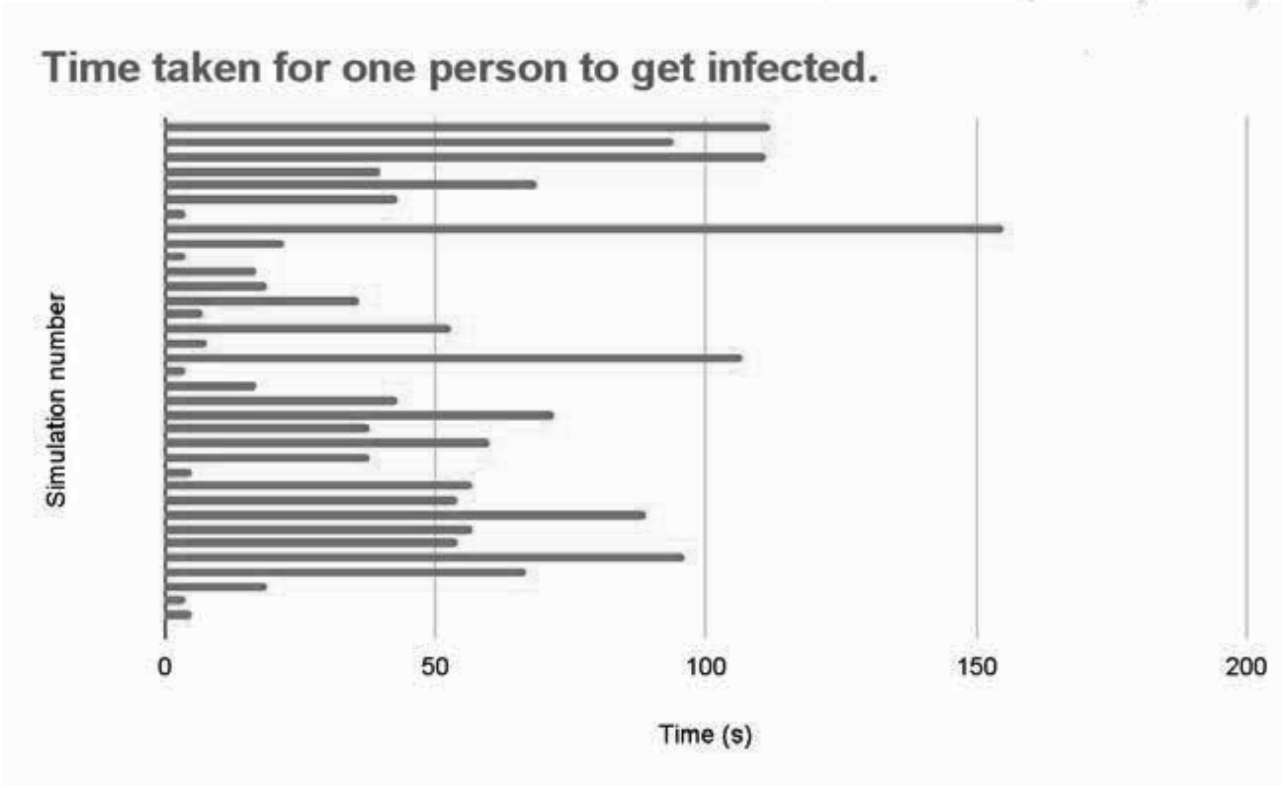
Conditions			
Mask-wearing (surgical mask)	1st Dose Taken	2nd Dose Taken	Estimated Probability Of Getting Infected
✔	×	×	1.68%
×	✔	×	1.995%
×	✔	✔	1.6747% (to 5 s.f.)
✔	✔	✔	1.68% × 1.6747% = 0.028135% (to 5s.f.)

The dependent variable would be the infectious phase of a person, T. A total of 35 simulations are conducted, and T would be taken to be the time spent for one person to affect another person within this simulation of 20 people (not including patient zero). The wearing of a mask will multiply a factor of 0.3 to the natural reproductive number of the virus ($R_0 = 3.32$)[16]. Hence, the new reproductive number of the virus when people are wearing masks would be 0.996. This means that one person will infect only another person in his or her infectious phase. This provides the rationale for conducting our simulations to conduct the time span to infect another person. The general code for tuning the variables for each person is in appendix B.

The results of the simulation timings (seconds) are in appendix C and listed below:

112 secs	38 secs	155 secs	57 secs	53 secs	4 secs	43 secs
94 secs	60 secs	22 secs	54 secs	8 secs	89 secs	54 secs

111 secs	38 secs	4 secs	96 secs	107 secs	7 secs	36 secs
40 secs	5 secs	17 secs	67 secs	4 secs	5 secs	4 secs
69 secs	57 secs	19 secs	19 secs	17 secs	72 secs	43 secs



As a simulation gives very varied results, there are many outliers from the data obtained. It would hence be best to pick the duration of infectious phase *T* from the median of the results provided.

The median is 43 seconds.
T = 43 seconds.

With finding this infectious phase T , the rest of the simulations will be run over a period of T before ending. A new variable, the number of infections caused by patient zero within time T is formed, will be referenced as I.

The second simulation would be used to find the number of people infected (I) by patient zero within the time limit of T. We also included the hypothesis of 73.6% vaccinated population represented by lowering the infected probability of 15 people in the simulation. In total, 70 simulations are conducted to obtain the most accurate result possible. The code for the second simulation is almost exactly the same as that in the first simulation. With one of the only changes being that each simulation ends at T = 43 instead of when everyone is infected.

The results are in appendix D and summarised below.

Number of infections (I)	Frequency (f)
0	51
1	18
2	1

As this simulation is about gaining the most accurate result, but has results of mostly the same numerical value, we chose to use the mean of the 70 values as the number of infections caused by patient zero within the time limit T, 43 seconds.

The mean is 0.28571428571429

The mean, 0.285714 (6 s.f.) would be taken as R_M, the reproduction rate of the virus when everyone is wearing masks, and where there is herd immunity. Thus, to find the reproduction value of when people are herd immunized and do not wear masks, substitute R_M= 0.285714 and $\theta = 0.3$, since the wearing of masks decreases the reproduction value to 0.3 times its original[16], into the equation below.

$$R_M = \theta R_0$$
$$\theta = 0.3$$
$$R_M = 0.3R_0$$
$$0.285714 = 0.3R_0$$
$$R_0 = 0.952 \text{ (3 s.f.)}$$

Since $R_0 < 1$ it indicates that each existing infection results in less than one infection. This indicates that virus outbreaks would be under control and it is then suitable for people to remove masks. Therefore, the simulation proves that at a vaccination rate of 73.6%, it will be an appropriate time for mask wearing to be optional in Singapore.

Some challenges and issues with using this simulation model[17] is that it is almost impossible to factor in every single variable in real life due to the lack of data and is not feasible. This includes new variants sprouting, varying types of vaccines used and different social lives amongst different people. Even when we manage to make mask wearing optional, the virus can mutate and leave us with deadly, less predictable variants that are not factored into such a simulation. This model can hence only be modelled after some basic and important variables which we have mostly assumed values for, since accurate information like the actual probability of infection in different locations can hardly be found. That is why the simulation model is not 100% foolproof, and is only used as a method of additional proof, against what we have originally concluded upon, on 23 August 2021, where 73.6% of the population have double doses of vaccines, there is herd immunity and mask wearing can be optional.

Conclusion

In conclusion, we used a logistic model to project vaccination rates and to find the date at which Singapore reaches herd immunity, and a simulation model to find the new reproduction value of the virus after reaching the herd immunity levels as stated before. We then concluded, with finding that herd immunity is when 73.6% of the population has double doses of the vaccine, on 23 August 2021, finding the median infectious phase of a person in the simulation to be 43 seconds and hence obtaining the new simulated reproductive value when everyone does not wear masks, 0.952. Since the new reproductive number is less than 1, it means that existing infections result in less than one new infection, and that the spread of the virus can be manageable. Therefore, with our prediction, we hypothesise that mask-wearing can be made optional earliest on 23 August 2021.

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17. COVID-19 spread simulation (2021, June) https://f15hygames.itch.io/spread-simulation

Appendix A
Code for one person in the simulation

```
using System.Collections;
using UnityEngine;

public class unit : MonoBehaviour
{
    //movement variables
    private Rigidbody2D rb;
    public float speed= 3;

    public Vector2 minPos;
    public Vector2 maxPos;
    private Vector3 nextPos;

    //infection variables
    public bool infected = false;
    public bool removed = false;
    public bool vaccinated = false;

    public float infectionRadius = 0.4f;
    private bool infected = true;
    public LayerMask whatIsInfected;

    //depends on mask rate
    public float probabilityOfInfection = 0.5f; //where 1 is 100%

    //display
    private SpriteRenderer sr;

    // Start is called before the first frame update
    void Start()
    {
        rb = GetComponent<Rigidbody2D>();
        sr = GetComponent<SpriteRenderer>();
        sr.color = Color.blue;
        infect = true;
```

```
  nextPos = new Vector3(Random.Range(minPos.x, maxPos.x), Random.Range(minPos.y, maxPos.y), 0);
  }

  // Update is called once per frame
  void Update()
  {
    //random movement about a fixed area
    if(transform.position == nextPos)
    {
      nextPos = new Vector3(Random.Range(minPos.x, maxPos.x), Random.Range(minPos.y,
maxPos.y), 0);
    }
    transform.position = Vector3.MoveTowards(transform.position,nextPos,speed*Time.deltaTime);

    //if infected
    if (removed) { sr.color = Color.black; }
    else if (infected) { sr.color = Color.yellow; }
    else { sr.color = Color.white; }

    if (infected && recovery)
    {
      StartCoroutine("RemovedTime");
    }
  }

//FixedUpdate is called once every few frames
  private void FixedUpdate()
  {
      //check if person is within the radius of an infected person
    if (Physics2D.OverlapCircle(transform.position, infectionRadius, whatIsInfected) &&(infect))
    {
      //randomly generate a number to determine if gets infected
      if (Random.Range(0f, 1f) < probabilityOfInfection)
      {
        infected = true;
        infect = false;
        //gameObject.layer = LayerMask.NameToLayer("Unit");//currently cannot infect people - set to
infected unit when can
        StartCoroutine("Timer");
      }
    }

  }
}
```

Appendix B

General code to manage all people in the simulation

```
using System.Collections;
using UnityEngine;
using UnityEngine.UI;
using System.IO;
using UnityEngine.SceneManagement;

public class UnitController : MonoBehaviour
{
//general values
    public int noOfInfected = 1;
    public int noOfRemoved = 0;
    public int noOfSusceptible = 1;
    public int totalPpl = 0;

    public Component[] units;

    public float dayTime = 50f;
    private bool day = false;
    public int days = 0;

    private float timer = 0f;
    public int sec = 0;

    [Space]
    public Slider proximity;
    public Slider recoveryRate;
    public Slider movementRestrictions;
    public Slider infectionRate;
    public Slider infectionVaccinatedRate;
    public Slider vaccRateDose;

    public Slider totalNumber;
    public GameObject unit;

    public Text consoletext;

    [HideInInspector]
    public int simul;

    // Start is called before the first frame update
```

```
void Start()
{
    units = GetComponentsInChildren<unit>();
    totalPpl = units.Length;
    days = 0;

    totalNumber.value = 20;
    SpawnUnits();

    noOfInfected = 1;
    noOfSusceptible = 1;

    StartCoroutine("SimulationTime");

        int test = PlayerPrefs.GetInt("Simul Number") + 1;
    PlayerPrefs.SetInt("Simul Number", test);
    Time.timeScale = 1;
    ended = false;
}

// Update is called once per frame
void Update()
{
    timer += Time.deltaTime;
    sec = (int)(days*dayTime) + (int)(timer % 60);

    units = GetComponentsInChildren<unit>();
    totalPpl = units.Length;

    //for each day
    if (day == false)
    {
        day = true;
        StartCoroutine("dayClock");
    }

    //changing values in units
    foreach (unit unit in units)
    {
        unit.infectionRadius = proximity.value;
        unit.removedTime = recoveryRate.value * dayTime; //daytime would be the accurate 1 day
        unit.speed = movementRestrictions.value;
        //unit.probabilityOfInfection = infectionRate.value;
```

```
        if (unit.vaccinated == true)
        {
            unit.probabilityOfInfection = infectionVaccinatedRate.value; //if vaccinated at one dose
        }
    }

    noOfInfected = 0;
    foreach (unit controller in units)
    {
        if (controller.infected == true)
        {
            noOfInfected++;
        }
    }
    noOfSusceptible = totalPpl - noOfInfected;


    if (uc.noOfInfected <= 0 && ended == false)
    {
        //stop simulation and print result
        Time.timeScale = 0;
        PrintResults();
        ended = true;
        //load next simulation
        SceneManager.LoadScene(SceneManager.GetActiveScene().buildIndex);
    }


}

public void SpawnUnits()
{
    for(int i = 0; i < totalNumber.value; i++)
    {
        GameObject obj = Instantiate(unit,this.gameObject.transform.position,Quaternion.identity);
        obj.transform.parent = this.gameObject.transform;
        if ((i / totalNumber.value) < vaccRateDose.value)
        {
            //if less than infection rate, gets the infectionRate of a vaccinated person of dose 2
            obj.GetComponent<unit>().probabilityOfInfection = infectionVaccinatedRate.value;
            obj.GetComponent<unit>().vaccinated = true;
        }
        else
        {
```

```
                obj.GetComponent<unit>().probabilityOfInfection = infectionRate.value;
                obj.GetComponent<unit>().vaccinated = false;
            }
        }
        totalPpl = units.Length;
        Debug.Log("Spawned " + totalNumber.value + " units");
        consoletext.text = "Spawned " + totalNumber.value + " units";
    }

    private IEnumerator dayClock()
    {
        yield return new WaitForSeconds(dayTime);
        days++;
        //to check number of infected
        noOfInfected = 0;
        noOfRemoved = 0;
        foreach (unit controller in units)
        {
            if (controller.removed == true)
            {
                noOfRemoved++;
            }
            else if (controller.infected == true)
            {
                noOfInfected++;
            }

        }
        day = false;

        noOfSusceptible = totalPpl - noOfRemoved - noOfInfected;
        consoletext.text = "SEC" + sec + " SUSCEPTIBLE: " + noOfSusceptible + " INFECTED: " +
noOfInfected + " REMOVED: " + noOfRemoved ;

    }
    static void WriteString(string input)
    {
        string path = "Assets/Resources/simul.txt";
        //Write text
        StreamWriter writer = new StreamWriter(path, true);
        writer.WriteLine(input);
        writer.Close();

    }
```

```
//to end each simulation once time is up, and print the time taken for it
  IEnumerator SimulationTime()
  {
    yield return new WaitForSeconds(43);
    PrintResults();
    SceneManager.LoadScene(SceneManager.GetActiveScene().buildIndex);
  }
}

  public void PrintResults()
  {     WriteString("Test " + PlayerPrefs.GetInt("Simul Number") + " INFECTED: " + (noOfInfected
-1)); //write only at the end of a simulation
  }
```

Appendix C

Exact number of seconds taken for all 20 people to get infected by patient zero in the simulation.

Test1 Seconds: 112
Test2 Seconds: 38
Test3 Seconds: 155
Test4 Seconds: 57
Test5 Seconds: 53
Test6 Seconds: 94
Test7 Seconds: 60
Test8 Seconds: 22
Test9 Seconds: 54
Test10 Seconds: 8
Test11 Seconds: 111
Test12 Seconds: 38
Test13 Seconds: 4
Test14 Seconds: 96
Test15 Seconds: 107
Test16 Seconds: 40
Test17 Seconds: 5
Test18 Seconds: 17
Test19 Seconds: 67
Test20 Seconds: 4
Test21 Seconds: 69
Test22 Seconds: 57
Test23 Seconds: 19
Test24 Seconds: 19
Test25 Seconds: 17
Test26 Seconds: 43

Test27 Seconds: 54
Test28 Seconds: 36
Test29 Seconds: 4
Test30 Seconds: 43
Test31 Seconds: 4
Test32 Seconds: 89
Test33 Seconds: 7
Test34 Seconds: 5
Test35 Seconds: 72

Appendix D
Exact number of people found to be infected by patient zero in the simulation.

Test INFECTED: 0
Test INFECTED: 0
Test INFECTED: 1
Test INFECTED: 1
Test INFECTED: 0
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Test INFECTED: 0
Test INFECTED: 0
Test INFECTED: 1
Test INFECTED: 0
Test INFECTED: 0
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Test 7 INFECTED: 0
Test 8 INFECTED: 0
Test 9 INFECTED: 0
Test 10 INFECTED: 0
Test 11 INFECTED: 0
Test 12 INFECTED: 0
Test 13 INFECTED: 0
Test 14 INFECTED: 0
Test 15 INFECTED: 0
Test 16 INFECTED: 0
Test 17 INFECTED: 0
Test 18 INFECTED: 1
Test 19 INFECTED: 0
Test 20 INFECTED: 1
Test 21 INFECTED: 0
Test 22 INFECTED: 2
Test 23 INFECTED: 0
Test 24 INFECTED: 1
Test 25 INFECTED: 0
Test 26 INFECTED: 0
Test 27 INFECTED: 1
Test 28 INFECTED: 0
Test 29 INFECTED: 0
Test 30 INFECTED: 0
Test 31 INFECTED: 0
Test 32 INFECTED: 1

Test 33 INFECTED: 0
Test 34 INFECTED: 0
Test 35 INFECTED: 0