The Spread of the Black Death in London

New Mexico

Supercomputing Challenge

Final Report

April 7, 2010

Team 37

Desert Academy

Team Members:

Katie Boot

Sara Hartse

Teachers:

Thomas Christie

Jocelyn Comstock

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1. Executive Summary

The objective of our project is to model the development of the bubonic plague in London for the duration of the primary outbreak in 1347 that lasted into 1350. We are applying epidemiology to the pandemic and analyzing the consequence it had on general social classes, for example the peasant's mortality rate versus that of the nobles and higher classes.

We chose this topic because we are interested in epidemiology, and wish to know how and why past societies were affected by circumstances that can be encountered today. We are also curious about the spread of the bubonic plague in past communities versus its spread in modern communities. If we can accurately replicate the Black Death, we could continue with the project and model a version of the Black Death in the modern-day London community. This would enable us to compare the spread of the plague in modern times to that of the past.

While our final model does not reflect the degree of complexity we originally intended, it takes into account the chances of infection, recovery and death, the geometry of 14th century London and the fact that the disease was initially brought to London by ships. We were able to determine model parameters, such as probability of recovery and the infection rate, that provide model results which correspond to historical data to a relatively high degree. This information will allow us to continue to use this model and add more elements in the future.

2. Introduction

A. Goal

Our goal for this project is to create a model of the bubonic plague in London and have it produce historically accurate figures, specifically with regard to the rate of death and overall rate of infection. We should be able observe the effect of the plague and its variations in different sectors of London. We ultimately want this model to be used to compare the effect of the plague on different social classes, comparing the mortality rates of peasants to aristocracy, or different professions such as the clergy or farmers.

B. Hypothesis

We predict that if we successfully create and calibrate our model so that it gives historically accurate results, then we will be able to see trends of people of higher class surviving longest and members of the clergy dying first. Furthermore, we predict that agents who start off in more crowed areas, especially near the Thames, will die more swiftly than those in more isolated areas.

3. Description

A. Biology

The bubonic plague, also known as the Black Death in the mid-fourteenth century, is derived from a bacterium called *Yersinia pestis* (*Y. pestis*), and is spread by the bite of an infected flea, *Xenopsylla cheopis* (the rat flea). The term "bubonic plague" comes from the most recognizable symptom, buboes, which are lymph nodes that become inflamed and swell to a substantial size. Victims of the plague generally die within three to seven days of infection. The reason for the plague's lethality is that humans rarely have immunity to it, and once contracted, the plague usually spreads too quickly throughout the body for one's immune system to react to it. However, if a person survives the plague they would probably never contract it again.

The bubonic plague cannot disseminate directly from person to person, but it can develop into two other forms of plague, septicemic and pneumonic. Septicemic plague is developed through blood poisoning, and cannot spread from person to person. Pneumonic plague, derived from pneumonia, is communicable through people and can circulate quickly through a populace by means of coughing, and can cause death in three days or less. During the Black Death, the pneumonic plague worked with the bubonic plague and caused approximately half of the total plague-related deaths.

Though the bubonic plague can be detrimental to a human population, it usually only occurs in rodents. This disease is only dangerous when it mutates and breaks out of its out biological group (rodents) and infects other groups (humans). Fleas spread the illness from infected rats to healthy rats by biting them and transferring some of their blood. Rats can transfer the plague to humans by biting them, in which case the plague is administered directly into the body.

Rats are the preferred host of the *Xenopsylla cheopis,* but if the rat population happened to decline, the fleas would be forced to find new hosts such as humans and livestock. The plague can also spread when the bubonic plague mutates into the pneumonic plague, which can move from person to person.

B. Background

Thought to have originated in East Asia, the outbreak of the bubonic plague was devastating for the European population. It was the first major disease to reach Europe in centuries. The plague first appeared in Europe in 1347 and swept through the populace for the next two and a half years, killing over 25 million people CITE – where is this data from? With a preliminary population of approximately 7 million, England's inhabitants declined as the plague killed almost half of its citizens. All of the social classes were affected, though the peasants were the most susceptible due to unhealthy living conditions and overpopulation. Only a few members of the nobles and royal family died due to the plague. The loss of the peasant class caused a great decline in food production, which contributed to the famine already sweeping the countryside, thus killing more people.

The people of the middle ages had no effective way of treating the plague and it was not until antibiotics were developed that there was any way of stopping it at all. People blamed the plagues outbreak on a couple factors, including "bad air," witches, astrology and a rare alignment of planets. Many people believed the Black Death signaled the end of the world, or the apocalypse. Others thought that the Jews had created the plague as a way to destroy the Christian world. Thousands of Jews and other minorities were killed and tortured by the panicked masses of Europe, especially in England. England was already experiencing its own hardships when the plague hit in 1347. The various harvests had been almost completely destroyed by rains, winter was approaching, and the lower classes, such as peasants, were slowly starving to death.

The plague hit the hardest in large cities, of which London is a prime example. The plague reached London through the rats that inhabited trading ships carrying goods from Asia. Once the ships docked, the rats and fleas dissipated into the city, infecting both humans and rats as they went. London was overwhelmed by a combination of pneumonic and bubonic plague. Nearly 50% of London's population succumbed to the plague, and thousands more died of starvation and other causes. By late 1350, the plague had subsided, but outbreaks would continue for the following three hundred years. It was not until the mid-1600s that the plague would be mostly eradicated.

C. Significance

The Black Death had many consequences and produced many changes that would make a huge difference in European life. It was a turning point of the development of human civilization. For example, it led to the decline of the religious dogma that had controlled most societies for centuries. It caused people to have a greater interest in the study of science and medicine, which continued to philosophy, art, and a new era of invention. Trade expanded and eventually more efficient trade routes were searched for, leading to the discovery of America. The epidemic also eliminated serfdom in much of Europe. After a great quantity of the lower class peasants was killed by the plague, peasants were no longer thought of as personal property, but as individuals, and necessary for a society to flourish. Although the Black Death had many negative results, it brought about an adjustment in lifestyle that changed the way people thought and behaved, and eventually, the course of civilization itself.

The plague has emerged in the human population quite a few times throughout history, but the most famous and widespread outbreak is the epidemic that occurred from 1347 to 1350. This is the outbreak on which our project is based. The bubonic plague is still a common problem in the world today, and is currently the cause of major epidemics in regions such as Uganda, Kurdistan, and northern India. Also, as of late, bubonic plague has been found increasingly in the United States, especially the Southwest.

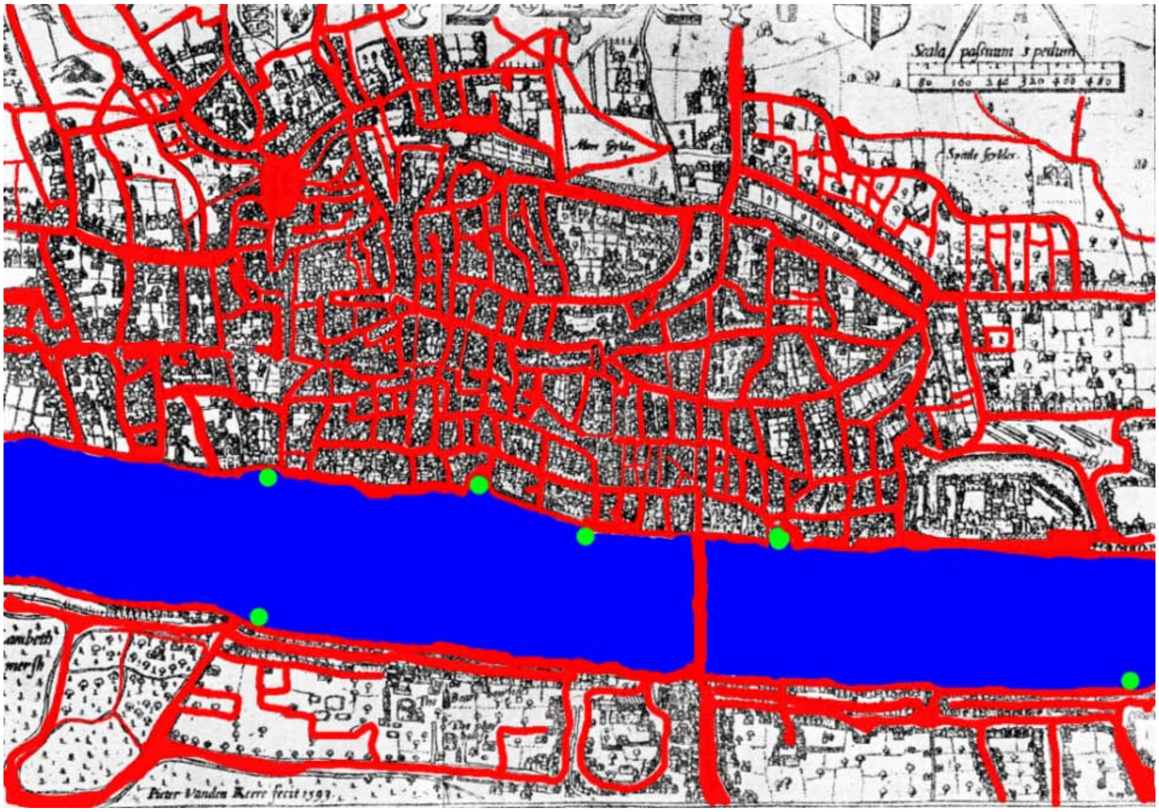
D. Model

We used Netlogo to model the spread of the plague in London. The basic function of our model is to create infected agents (rats), who start off at points along the Thames River. They dissipate randomly into "London" staying on specific paths and interacting with the human agents. There are about 7,000 human agents, each representing 10 of the 70,000 people living in London at the start of the Plague.

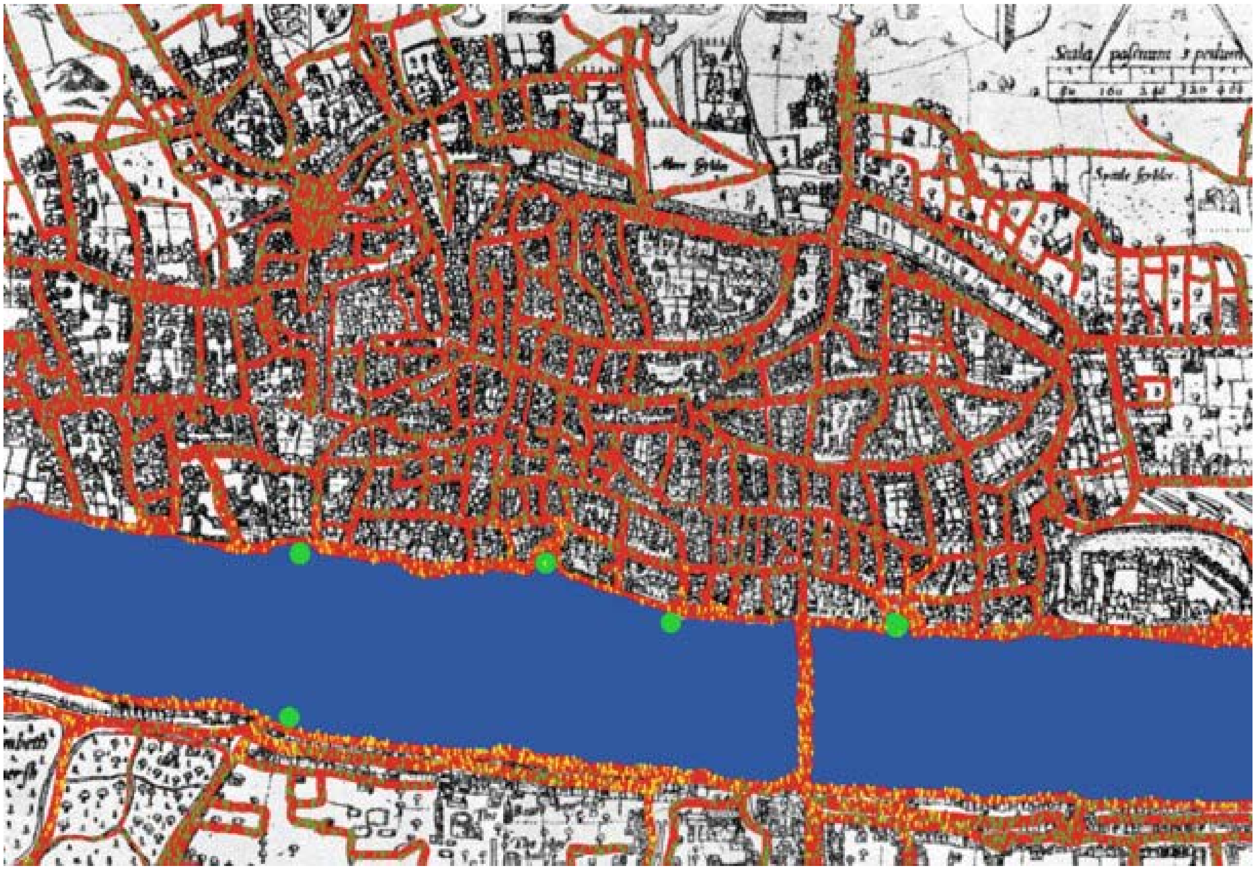
The sick rats are orange and they disperse through the London docks and infect the human and rat inhabitants of London through proximity. Healthy humans are green at first, and become yellow once they are infected. The infected agents generally live three to six more "ticks". Human agents do not spread the plague as quickly as the rats do, and can only infect each other pneumonic plague, which has a lower chance of transmission. If a human or a rat manages to recover (this is moderately unlikely), then they become immune and the agent is shown in grey.

4. Development

Throughout the course of this project we learned a lot about epidemiology as well as NetLogo, the program we used to model the Black Death. First, we created a basic epidemiology model. After we had agents infecting and recovering, we added some factors that are more specific to the plague. For example, we changed the model so that rats were the original infected agent and the spread of the sickness depended on their movement and behavior.



One of our main challenges was incorporating a map of London into the model. We tried many different things, until we eventually colored in a fundamental map of fourteenth-century London using the GIMP photo-editing program. We colored in as many streets as we could, making sure that all the major roads and public areas in London were covered. We used red for this task, giving specific paths for the agents to move along and make contact with each other. We colored the Thames River blue and the docks green, and imported the patches from the image into our model. This allowed us to make the agents responsive to the patch colors. The next step was to enable the “human” agents to move along the roads and remain on the red patches, avoiding the blue Thames River and the green docks. We used a piece of code that asserted when the setup button is hit the “human” agents automatically determine the color of their current patch. If the patch color is not red (the color of the roads) then the agents continue to move randomly until they move on to a red patch. We used a similar procedure to have the "rat" agents start off at specific colored points, namely the docks, which are the green patches in the model. These were placed at all the major docks along the London section of the Thames River, where the infected rats exit ships, and spread the plague among the human populace.



This is a screenshot of the model in the earlier stages of the epidemic.

5. Results

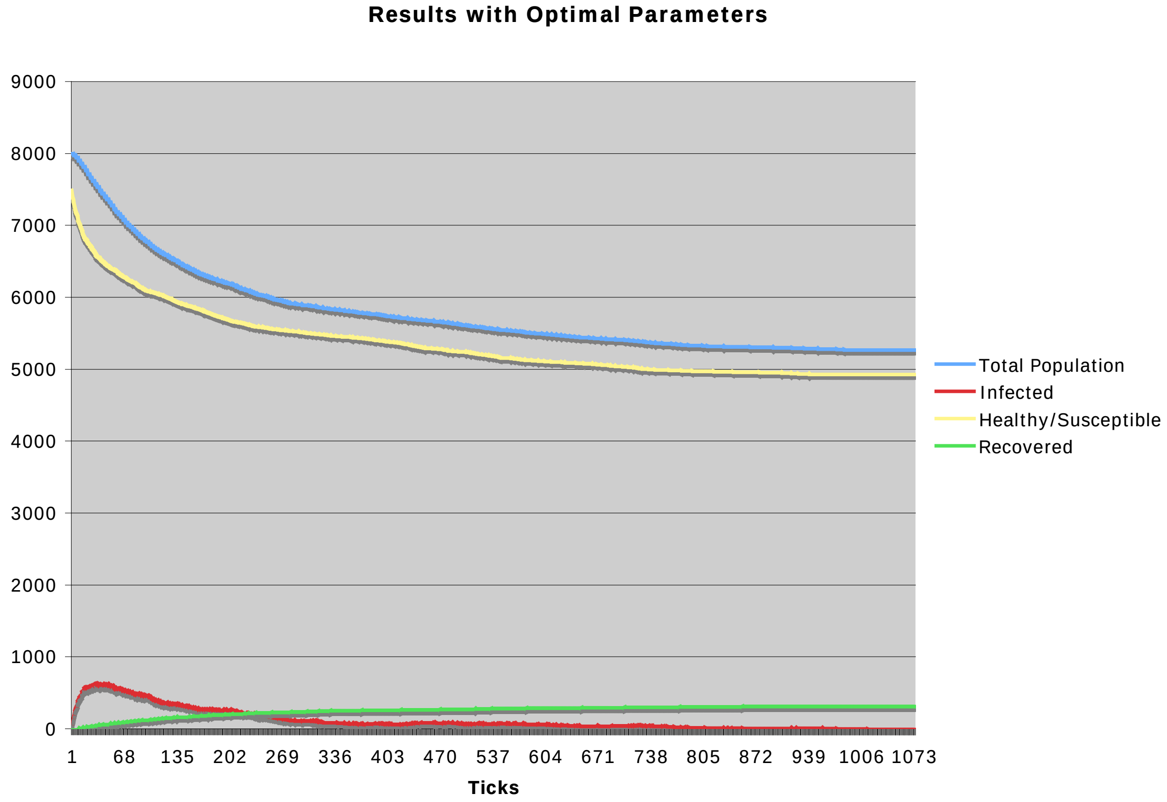
A large part of the modeling process has been tweaking various features of our model in an effort to make it as accurate, yet as functional as possible. Adjusting the size of the interface was a delicate matter; at one point there were so many pixels in “London”, that none of the agents ever had a chance to interact. We fixed this by shrinking the number of pixels and adding a variable that increased the infection radius, expanding the area surrounding an agent in which they could infect someone else.

The other variables that have taken more time to adjust are those of the chance of dying, chance of recovering, the infectiousness of the bubonic plague and the infectiousness of the pneumonic plague. Our ideal model ends with about 5% of the population recovered and immune, 45% dead and the remaining 50% still susceptible. To figure out the perimeters that would lead to these results we have repeatedly run the models using the “Behavior Space” feature of NetLogo over long periods of time, altering these variables in increments of varying sizes each time. In total, we ran the model approximately 4500 times, each time with varying parameters. We then analyzed this information in spreadsheet form and found the ideal values for these variables.

The following chart shows the closest values for the variables that we found after repeatedly running the model. None of the calculated variables were ideal. We were aiming for a survival rate of 50 to 60% and the closest runs were still 70%. Our reasoning for this is that the increments we adjusted the variable in had to be fairly large in order to keep the number of times we had to run the model down to 720 times per computer (we used 6 different computers overnight). These numbers all produced survival rates that were too high, but we were able to take the values for the variables and adjust them to create a model that produced results closer to the actual statistics of the Bubonic Plague in London.

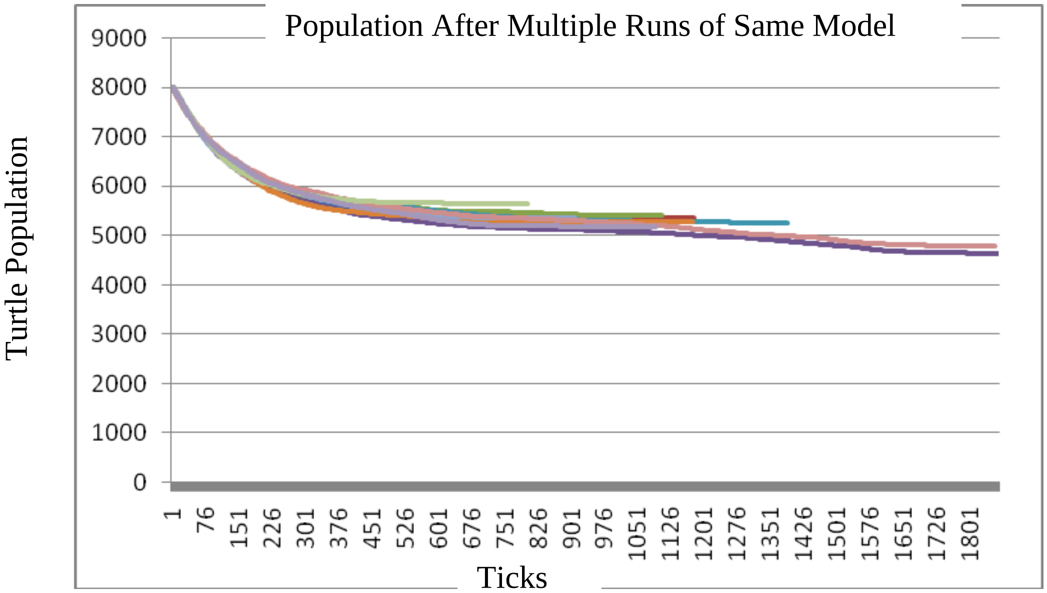
Run number	Infectiousness-pneumonic	Chance recover	Chance die	Infectiousness	Steps	End Count		%
212	65	2	9	15	498	6214	Survived	77.7
212					498	5971	Never infected	74.6
212					498	243	Recovered	3.0
220	65	2	9	95	480	6113	Survived	76.4
220					480	5852	Never infected	73.2
220					480	261	Recovered	3.3
454	70	2	9	35	570	6117	Survived	76.5
454					570	5871	Never infected	73.4
454					570	246	Recovered	3.1
700	75	2	9	95	513	6016	Survived	75.2
700					513	5755	Never infected	71.9
700					513	261	Recovered	3.3
935	95	2	9	45	924	6073	Survived	75.9
935					924	5821	Never infected	72.8
935					924	252	Recovered	3.2
936	95	2	9	55	501	6054	Survived	75.7
936					501	5775	Never infected	72.2
936					501	279	Recovered	3.5
938	95	2	9	75	470	6019	Survived	75.2
938					470	5772	Never infected	72.2
938					470	247	Recovered	3.1
939	95	2	9	85	399	6013	Survived%	75.5
939					399	5765	Never infected	72.1
939					399	248	Recovered	3.1
940	95	2	9	95	729	5738	Survived	71.7
940					729	5463	Never infected	68.3
940					729	275	Recovered	3.4

The variables that seemed to produce the most realistic results were infectiousness-pneumonic = 60, chance recover = 1, chance die = 5, infectiousness = 95. We decided to decrease the chance-die and chance-recover because the agents were dying so quickly that they could not move far enough to spread the sickness. Here is a NetLogo graph of the populations of the agents in our model while running it within these parameters.



Infectiousness-pneumonic = 60
Chance recover = 1
Chance die = 5
Infectiousness = 95

After running the model with in these parameters many times, we began to notice patterns within the behavior of the agents and how they interact with their environment. Because of the paths that agents have to follow, they take longer to spread the illness. Some agents who are on wider paths come into contact with many other agents and if they happen to be near the river, these are the first areas to be wiped out. The agents that live the longest are those that start out on smaller streets, farther away from the river. Because of this variation in terrain and the randomness of the agents' movement, different trials of the same parameters often produced slightly different results. The following graph records the populations of the agents over ten different runs.



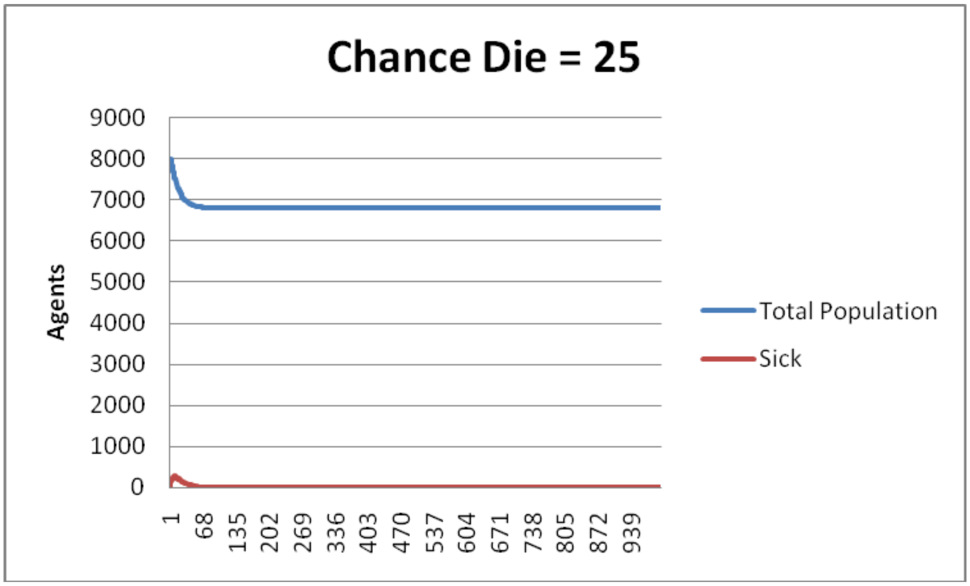
6. Conclusion

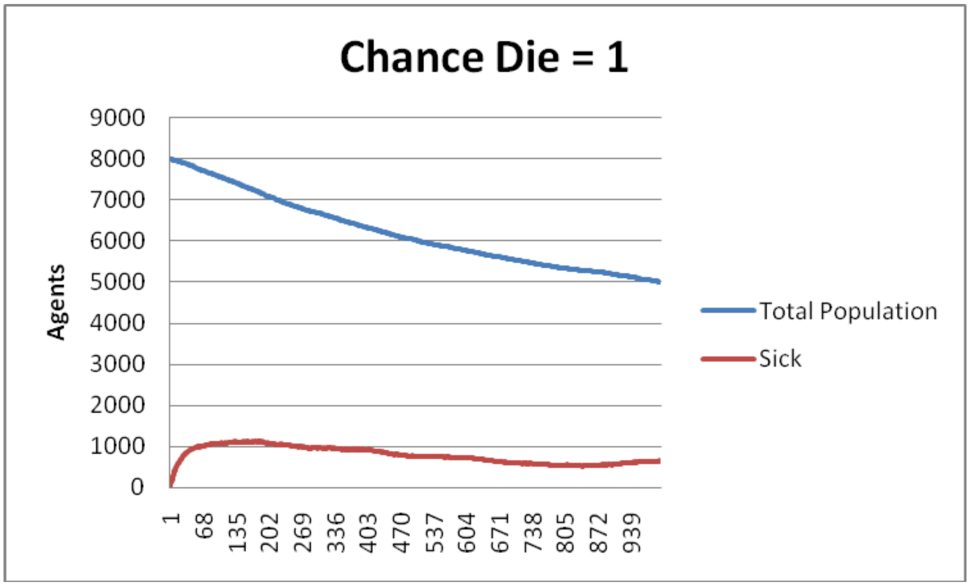
We were not able to get as far with our project this year as we had planned. As explained earlier, we managed to create a working base model of London and the plague, but we were not able to go into as much detail as we had originally intended. We did not finish making different agent behaviors to represent social classes. However, we were able to learn a lot about the epidemiology behind the Bubonic Plague and how the landscape of London affected that.

Our hypothesis that agents in wider, more crowded areas, especially those close to the Thames would die more quickly was correct. Agents in these areas transmitted the disease very quickly, causing the count of sick agents to spike. We observed that it only took a few infected agents to enter one of these areas and almost everyone would become sick. This was also true for very isolated areas, but these areas also had the highest rate of survival, because they had such limited interaction with the other inhabitants of the model.

While we were trying the correctly calibrate the model and pick values for the variables that would generate historically accurate results, we learned quite a bit about epidemiology in general. We learned that a higher chance of death was not necessarily the way to make an epidemic worse; high chance of death, at least in our model, caused almost all infected agents to die before they could infect anyone else. We discovered that the key to a long lasting and dangerous epidemic is relatively low chance of death and very high infectiousness. This creates a disease that, like the Bubonic Plague, is very contagious, but does not kill all of its victims immediately, allowing it spread it to many other people. This is shown in the following graphs.

In these two graphs, the first is one in which the chance of dying was very high. The second had much lower chance of dying, but despite the low chance of death about 2,000 more people died in this simulation than in the previous one. The high chance of death in the first run meant that infected people died very quickly, before they could infect anyone else. The number of infected people spiked rapidly and then bottomed out. The lower chance of death in the second run kept the sickness around much longer, infecting many more people, eventually leading to more deaths. When calculating the parameters for our final model we actually had to raise the chance of death to have a higher survival rate.





Our final model is not entirely realistic, in that it is still missing a few key factors. The main way that we think it could be improved is by adding an incubation period for the agents. A period of time in which they are contagious but are not showing symptoms would greatly help us achieve our goal of realism. We could also improve the circulation of the agents to make the spread of the plague more realistic. We could do this either by making people walk on “tracks” instead of randomly “wiggling” through the streets, or by making them walk further between each proximity check.

There are many ways that we can expand and use this model in the future. The most immediate thing we would like to do is complete our goals for this year by adding different types of “human” agents to represent the different social classes with different movement patterns and trying to model the varying effects of the Bubonic Plague on them. We are also interested in modeling the bubonic plague on a much smaller scale, looking at the interaction between *Yersinia pestis*, *Xenopsylla cheopis* (the rat flea), rats and humans, as well as what causes *Yersinia pestis* to break out of its biological group of rats and move on to infect humans. What we accomplished this year has given us a good base model of the Bubonic Plague in London and a good point at which to start further investigation.

7. References

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When creating this project we referenced several models in the NetLogo model library including Virus and African Plains, though the code in our model is all written by us. We would like to thank all the people who helped us and gave us feedback throughout the course of this project; we could not have done it without them.

8. Code

The following is the code that runs our model. The text preceded by “;;” is an explanation of the procedure underneath it.

```
turtles-own [sick?
immune?
dead?
sick-count]
globals [infection-range
  seperation-range
  ]

to setup
  import-pcolors "LondonMap.bmp"
  clear-plot
  reset-ticks
clear-turtles
setup-turtles
update-plot
set infection-range (sqrt 2)
set seperation-range (sqrt 2)
scatter-to-roads
go-to-ships
end



to go
  tick
  exit-ships
move-turtles
infect
infect-pneumonic
infect-from-patches
update-plot

if ticks mod 3 = 0 [check-death]
if ticks mod 5 = 0 [recover]
end

;;this makes the agents move to red patches, the roads

to scatter-to-roads
  ask turtles [
```

```
    while[pcolor != 14.9][
      set xcor (random 1024) - 512
      set ycor (random 1024) - 512
    ]


  ]
end

;;this makes this infected rats start at the green ports along the Thames
to go-to-ships
  ask turtles [if (color = orange)
    [while [pcolor != 64.9] [set xcor (random 1024) - 512 set ycor (random 1024) - 512]]]
end

;;this makes the rats leave the ships quickly when the model begins to run
to exit-ships
  ask turtles with [color = orange]
  [while[pcolor != 14.9]  [forward 1]]
end


;;this sets up all of the different agents and whether or not they start sick
to setup-turtles
  set-default-shape turtles "person"
  crt 7000

  [setxy random-xcor random-ycor
    set sick-count 0
    set immune? false
    set size 5
   ifelse (who < 0)
[get-sick]
[get-healthy]
]
  set-default-shape turtles "rat"

crt 500
[
setxy random-xcor random-ycor
set sick-count 0
set immune? false
set size 2

get-healthy-rat
```

```
]
set-default-shape turtles "rat"
crt 500
[
setxy random-xcor random-ycor
set sick-count 0
set immune? false
set size 2

get-sick-rat

]

end

;;defines a sick human
to get-sick
set sick? true
set immune? false
set color yellow
lt random 10
end

;;defines a sick rat
to get-sick-rat
set sick? true
set color orange
lt random 10
end

;;defines a healthy rat
to get-healthy-rat
set sick? false
  set immune? false
  set sick-count 0
  set color green
end

;;defines a healthy human
to get-healthy
  set sick? false
  set immune? false
  set sick-count 0
  set color green
end
```

```
;;the movement pattern for all agents
to move-turtles
 ask turtles
 [left random 30
  right random 30
  ifelse ((can-move? 1) and (  ([pcolor] of patch-ahead 1) = 14.9  or ([pcolor] of patch-ahead 1) =
64.9 )) [
    forward 1
  ] [
    right 180]
  ]
end


;;agents infect each other depending on their proximity and the value of infectiousness slider
to infect
  ask turtles with [color = green or color = violet] [if ((any? (turtles in-radius infection-range)
with [color = orange]) and ((random-float 100) < infectiousness)) [
    set color yellow ]]
end

;;human agents infect each other with the pneumonic plague depending on proximity and the
value of the infectiousness-pneumonic slider
to infect-pneumonic
  ask turtles with [color = green or color = violet] [if ((any? (turtles in-radius infection-range)
with [color = yellow]) and ((random-float 100) < infectiousness-pneumonic)) [
    set color yellow ]]
end


;;agents have the possibility to become infected from patches where other agents died
to infect-from-patches
  ask turtles [if pcolor = yellow [set color yellow]]
end


;;controls the populations graph
to update-plot

  set-current-plot "Populations"
  set-current-plot-pen "sick"
  plot count turtles with [color = yellow or color = orange]
  set-current-plot-pen "healthy"
  plot count turtles with [color = green or color = violet]
  set-current-plot-pen "total"
```

```
  plot count turtles
  set-current-plot-pen "recovered"
  plot count turtles with [color = gray]
end

;;sick agents have the possibility of dying. This procedure is run every 3 ticks.
to check-death
ask turtles with [color = yellow or color = orange]
[if (random-float 100.0) < Chance-die
[ set pcolor yellow die]]
end

;;sick agents have the possibility of recovering, when they recover they become gray and
immune
to recover
 ask turtles with [color = yellow or color = orange]
 [ if (random-float 100.0) < chance-recover
   [set color gray]]
   end
```