Smallpox Martyr Bio-Terrorism Scenario Modeling Computer Systems Lab 2009-2010

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Abstract

This project models a martyr-type scenario in which a small terrorist group infiltrates a city after infecting themselves with a weaponized or vaccine-resistant strain of variola major. Agents attack hospitals (passing as flu sufferers), airports, subway stations, and large buildings. Panic begins to spread as the population realizes that medical facilities have been targeted. With the disease and panic spreading, the city shuts down; the infrastructure collapses and disease control units cannot intervene. After some time, control of the city is regained and quarantine is implemented or a new vaccine to counter the modified strain of smallpox is developed, produced, and distributed en masse. After this point, the danger from the attack drops to zero as the remaining survivors have nothing else to fear from the now obsolete virus weapon.

1 Introduction

1.1 Actual Situation

If smallpox was released into a population, the result would be a global spread and the virus would cause hundreds of thousands or even millions of fatalities. The long incubation time of smallpox would make the spread of the disease from town to town and country to country a common occurrence. Smallpox cannot be aimed or targeted; once released, it will infect and kill indiscriminately; the group releasing the disease would also harm their own families, friends, and allies. Despite these dangers, there are factions whose only goal is to cause panic and death; if these groups successfully obtain smallpox they pose a great threat to the world.

"Although... stocks of smallpox virus legally exist only at the two World Health Organization [WHO] repositories (the Centers for Disease Control and Prevention [CDC] in Atlanta, Georgia, USA, and at the State Research Center of Virology and Biotechnology, also known as Vector, in Koltsovo, Russia), it is of concern that undeclared stocks may exist at military sites within the former Soviet Union, or that they were transferred from the Soviet program to programs in Iraq, Iran, North Korea, or elsewhere. The probability that such stocks exist is impossible to assess, but the catastrophic consequences of a smallpox release in a biological attack cannot be discounted" (Jahrling, Huggins, Ibrahim, Lawler, and Martin 220).

1.2 Scenario

The scenario I am modeling is not considered in "Smallpox and its Eradication;" the conclusion of the passage involving a biowarfare attack using smallpox states that an attack would be unlikely (Fenner, Henderson, Arita, Jezek, and Ladnyi 1344). However, this conclusion was made in the days after the eradication, before bioengineering was as easy and possible as it has become in recent years, and before terrorist groups, willing to sacrifice lives without strict regard for whose lives were being sacrificed, were known to hold any significant power in the modern stage. My scenario considers a vaccine-resistant strain and a well-planned, independent attack by a small group of terrorist extremists; the danger from this threat has greatly increased in recent years. According to Soderblom, this case is surprisingly likely and has the potential to kill millions of people around the world.

1.2.1 Liklihood of an Attack

"Intelligence agencies and international relations scholars are concerned that Russian researchers of the former Biopreparat [now Vector], many of whom are unemployed... and feel disenfranchised, could be tempted to smuggle and sell smallpox to those terrorist groups with the financial resources and microbiological expertise to use it, or further weaponize it. Marvin Cetron, president of Forecasting International Ltd, a risk assessment company working with both the US Defense Department and the FBI, has stated, "I think the chance is about eighty percent of terrorists obtaining smallpox..." the potential for a serious smallpox attack is frighteningly feasible" (Soderblom 3).

1.2.2 Execution of Attack

"In this scenario, two 'smallpox infected suicide terrorists' strategically target doctors' offices... to obtain a medical certificate to explain their absence from work... They blend in with people suffering flu symptoms in the waiting room, but they are already effectively spreading smallpox amongst staff and patients... Smallpox is delivered to the target city through... another infected set of suicide terrorists passing on smallpox through exhaled droplets. Mass terror is created by the paradox that smallpox needs to be contained and treated, yet the mass smallpox infection of patients and staff at hospitals causes citizens to stay away from medical facilities.
Large segments of the community avoid medical treatment. The strain placed on the infrastructure of the city brings it to a halt: planes do not arrive or leave, police at roadblocks turn back fleeing residents, and the "terror" caused by the bio-terror attack is unmatched by any previously experienced health catastrophe. The economy is brought to a standstill and the bioterrorists now have political influence as they have demonstrated their capacity to inflict terror. Worse still... the smallpox is a weaponized variant... for which there is no vaccine. Thus the containment of infected people proves to be impossible even though WHO vaccines arrive quickly" (Soderblom 8-9).

1.2.3 Reaction to Attack

My simulation assumes that the attacked population would panic, and, as the city shuts down, chaos would spread. At this time, people would group together with others and avoid those who appear to be dangerous; with a fear of infectious diseases, those showing a full body rash that the media has declared as dangerous would be avoided if possible (Soderblom 8). They will remain within the boundaries of the closed section of the world during the simulation; it is assumed that if one person were to leave, another would enter at the same time from another region, to fill the same place.

1.2.4 Vaccine Resistant Smallpox

The smallpox strain used could be the weaponized India-1 vaccine-resistant strain from Vector, in Russia, that scientists admit was lost from the 20-ton vats that were being used to manufacture the biological agent, and several countries other than the US and Russia are suspected to have strains either of India-1 or another sample of smallpox, including Iran, North Korea, and Iraq (Preston 95-99).

If the strain used is not India-1, it would likely be a bioengineered virus, produced from insertion of the human IL-4 gene into a smallpox strain, which could be created in as little as four weeks, by using the book "Current Protocols in Molecular Biology," and would cost "about a thousand dollars for each strain. Virus engineering is cheaper than a used car, yet it may provide a nation with a weapon as intimidating as a nuclear bomb" (Preston 222, 225). A virus engineered with the mouse IL-4 gene infected 100 percent of the mice who were either mousepox-resistant or previously immunized with vaccinia, a live virus with an almost nonexistent fatality rate that is a powerful vaccine against smallpox. "The pox-resistant mouse never stood a chance with only ten particles of the engineered virus in its blood" (Preston 225-226). The accepted infectious dose of smallpox is less than 5 virions, and the average case inhales much more than that infectious dose, so the test did not use extreme numbers of infectious particles.

An assumption made is that this case would hold true in other species as well, eliminating the possibility of using the vaccinia vaccine to stop the outbreak. "The main thing that stands between the human species and the creation of a supervirus is a sense of responsibility among individual biologists... No nation that wanted to have nuclear weapons had a problem finding physicists willing to make them" (Preston 228). All it would take is one person with a purpose, or recruited to a cause, to create a biological weapon that would resist any immunization that the world could supply.

1.3 Background

Smallpox, also known as variola major, is a fast-spreading disease with a 100 percent susceptibility rate in humans who have not been immunized in the past 10 years. Only military, healthcare, and laboratory personnel are currently immunized.
Smallpox has a fatality rate between 30 and 40 percent and spreads like wildfire both locally and globally, traveling around the world in a month because of the 2 week incubation period in which no symptoms are shown from the infected person, who moves to uninfected cities or healthy areas of a population before the sudden development catches the surrounding area by surprise, creating many more victims for the disease. The disease spreads further when an infected person travels to another city or country. In today's world of long commutes, frequent vacations, and business trips, smallpox would travel around the world incredibly quickly, making quarantine almost impossible. Thus, the infection caused by terrorists in an airport would spread between many major cities throughout the world, creating millions of cases and deaths; the result would be a global spread within a matter of weeks (Preston 232).

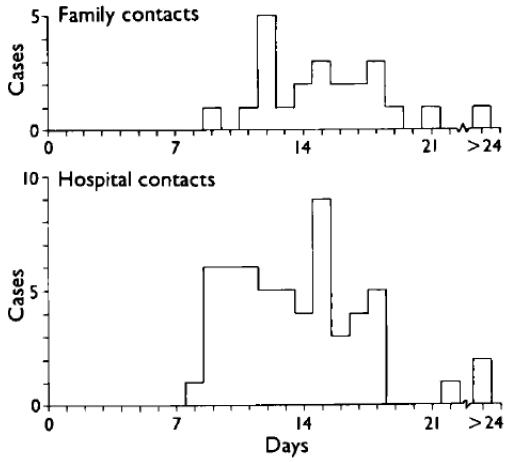


Figure 1: The number of infections from one case of smallpox who remains at home is much lower than from one case who seeks medical help at a hospital; hospitals are more susceptible to mass infection.

If shown the above data, very few, if any, infected people would seek any medical treatment at all (Soderblom 8). The likelihood of smallpox spreading to others through face to face contact during transit or in buildings would then increase, as the layouts of many buildings, apartments, and other large enclosed areas are susceptible to spreading smallpox over a large area, as was the case in the Meschede hospital in Germany in 1970, in which one victim, confined to his room, infected 16 people who had not seen his face or been in that room (Fenner et al. 193; Preston 47).

2 Smallpox

2.1 Progression of Infection

2.1.1 Incubation

A person does not realize he is infected until 10-14 days after exposure, when prodromal symptoms begin; the rash appears 2 to 4 days later. The first symptoms could appear, however, as early as 7 days after exposure, or as late as 17 days (Akhtar 23; Fenner et al. 5; "Medical Management of Biological Casualties Handbook" 62; Gober and Werth; "Smallpox," Utah Department of Health; "Smallpox Information Center"). This phase is part of what makes smallpox so devastating; during 2 weeks, infected people may travel, infecting others in different places ("Smallpox", WHO).

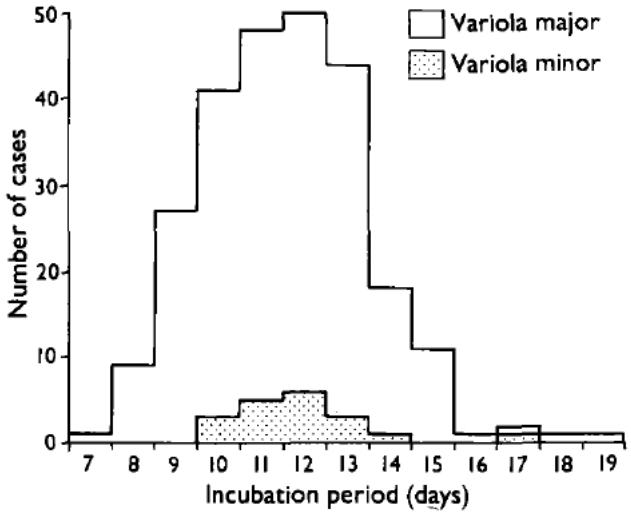


Figure 2: The above graph shows a case study of several hundred people, exposed to smallpox, in which the length of time from initial exposure to the beginning of prodrome symptoms was recorded.

The mean of this data is 11.5 days and the standard deviation is 1.1 days. It will be modeled by a normal distribution curve (Fenner et al. 188).

2.1.2 Prodrome

The prodrome or preeruptive stage of the illness starts abruptly, with a fever of (101-104F), malaise, headache, muscle pain, prostration, and often nausea, vomiting, and backache. The person appears quite ill. The prodrome usually lasts 2 to 3 days, with a mean of 3 days, and a standard deviation of about 8 hours. The person is not contagious until the end of the prodrome, when lesions develop in the mouth (Akhtar, 27; Atkinson et al. 283; Gober and Weese; "Smallpox," Utah Department of Health).
During the prodrome, the rash has not yet begun, and diagnosis of a smallpox victim is difficult at this time, as symptoms closely resemble the flu. If someone suffering from smallpox is towards the end of the prodrome, placing him or her into a clinic or hospital with flu victims results in the highest infection rates of any realistic situation. The next day, when he or she is diagnosed because of the beginning of the rash, he or she may have already infected tens of flu patients. These now infected flu patients will recover from the flu, and as the smallpox prodrome begins after a two week incubation period, they will likely be treated for relapse, perhaps in different hospitals or clinics, and the cycle continues. After the prodrome ends, the centrifugal rash of smallpox forms.

2.1.3 Rash

During the rash, all pustules and marks progress at the same speed; unlike chickenpox, in which pustules may form next to a scab (Atkinson et al. 283-284). This is an average

Day of Rash	Rash Characteristics
1	Macules and rash spread throughout body to concentrated areas on extremities (hands, feet, head) but covers entire body; macules begin to form papules.
2-3	The rash raises as the papules progress slowly to form vesicles.
3-5	The fever returns in full force as vesicles begin to form pustules.
6-12	The pustules have formed: raised, round, tense, and firm to the touch.
13-20	The pustules drain and form a crust. At this stage, infected people are no longer very contagious, and the fever drops off.
21-28	The crusts drop off and the victim is recovered.

Figure 3: Chart detailing rash progression created from data acquired from (Medical Management of Biological Casualties Handbook 63; "Smallpox Disease Overview," CDC)

progression of a case of ordinary smallpox; typically the victim will be fully healed between day 21 and 28 of the rash ("Smallpox Information Center"). The values will be modeled with a mean of 24.5 days and a standard deviation of 1.167 days from the beginning of the rash before recovery due to the first and last days of the end of the infection being 21 days and 28 days, from the beginning of the rash.

2.2 Forms and Fatality Rates of Smallpox

There are five recognized forms of smallpox (variola major) which have different symptoms, fatality rates, durations, and slightly different infectious rates.

1. Ordinary-type smallpox exists in about 85 percent of cases. "In fatal cases, death occurred between the 10th and 16th days of the illness" (Fenner et al. 22; Hong), due to toxemia ("Smallpox as a Bioterrorism Agent"). In "one to two weeks after infection as the bloodstream becomes overloaded with the virus" ("Dermatology", About.com), the disease "may be so severe as to cause death even before the rash is fully developed, but more commonly death, if it occurs, will be between the 11th and 15th day of the rash" ("Smallpox Information Center"). To model the fatality rate, a normal distribution with a mean of 13 days and a standard deviation of 1 day will be used so that the third standard deviation corresponds with the minimum and maximum values of 10 days and 16 days. The fatality rate of ordinary smallpox is 25 percent.

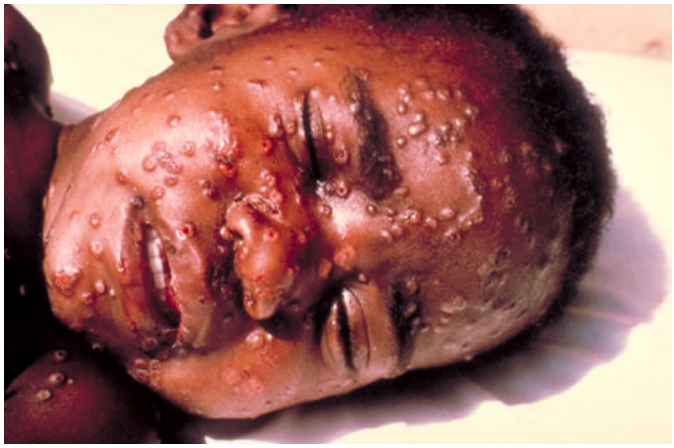


Figure 4: A case of ordinary smallpox

2. Confluent smallpox is a form of ordinary smallpox in which the rash is more severe, causing pustules to not harden and crusts to form a solid sheet over the body. About 8.5 percent of cases result in confluent smallpox. A victim remains infectious until complete recovery, and the fever does not drop until much later in the progression of the disease. In fatal cases, 'death often happens at the beginning of the crust' (Preston 45). Death occurs around day 13, where the pustules drain and begin to crust (Preston 231). To model the fatality rate, a mean of 13 days and a standard deviation of 1 day is used. The fatality rate for confluent smallpox is 62 percent (Fenner et al. 5).

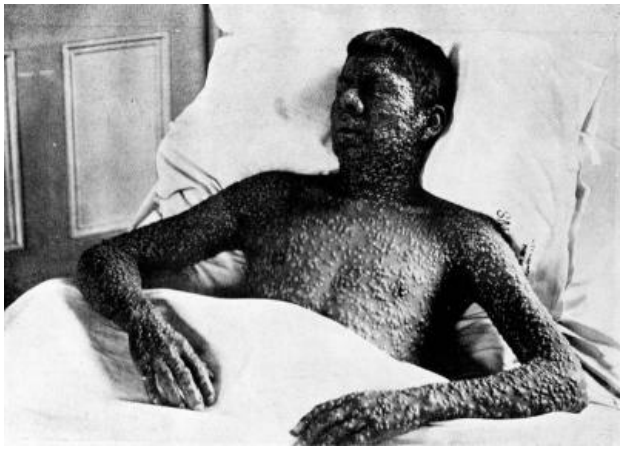


Figure 5: A case of confluent smallpox

3. Modified smallpox is a less severe form of smallpox, taking place in 2 to 3 percent of unvaccinated cases, modeled as 2.5 percent, and can be found in the recently vaccinated. It is less infectious than ordinary smallpox and progresses through the stages of rash quicker, with a half-length prodrome and a disease length of 14 to 18 days, with a mean of 16 days and a standard deviation of 0.667 days, but in other aspects, it follows the same progression. During the rash, the fever is reduced or nonexistent. The fatality rate for modified smallpox is 0 percent (Fenner et al. 5).

Figure 6: A case of modified smallpox

4. Flat or malignant smallpox, or blackpox, occurs in about 7.5 percent of cases in which the fever does not drop off with the beginning of the rash, severe toxemic symptoms are shown, the rash becomes increasingly severe on the mouth and tongue, making infectivity higher, and the pustules do not rise or harden. The rash feels velvety and the skin separates in sheets, often slipping off of the victim. There is no fluid in the skin lesions, and toxemia couples with respiratory failures in fatal cases. In fatal cases, death 'usually occurred between the 8th and the 12th day' (Fenner et al. 31-32). To model the fatality rate, a mean of 10 and a standard deviation of 0.667 days will be used to represent minimum and maximum values of 8 days and 12 days. The fatality rate for malignant smallpox is 95 to 100 percent, which will be represented as 97.5 percent.

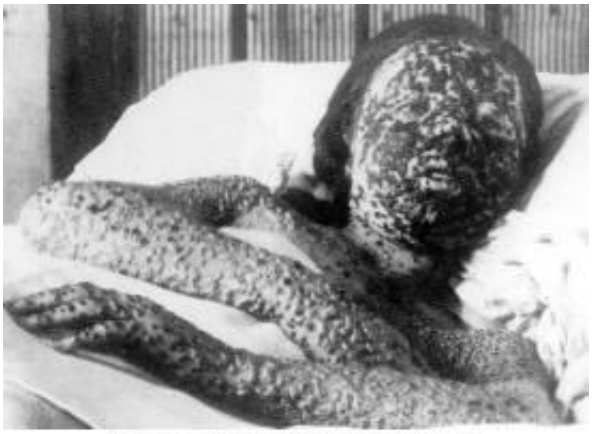


Figure 7: A case of malignant smallpox (blackpox)

5. Hemorrhagic smallpox occurs in 5 percent of cases and is accompanied by severe bleeding into the skin. The prodrome is twice the length of the other forms of smallpox, ending between day 5 and day 8, which greatly increases the chance of infecting others before the rash develops and the victim is diagnosed. The symptoms are severe and do not wane until the end of the infection. In fatal cases, death often occurs suddenly between day 5 and day 7 of illness, with records from day 4 to day 9, during the last days of the prodromal period. (Akhtar, 42; 'Bioterrorism Update, Smallpox;' Fenner et al. 32-34, 37; 'Smallpox,' CDC). To model the fatality rate a mean of 6.5 days and a standard deviation of 0.833 days correspond with values of 4 days and 9 days. The fatality rate of hemorrhagic smallpox is around 98.5 percent.

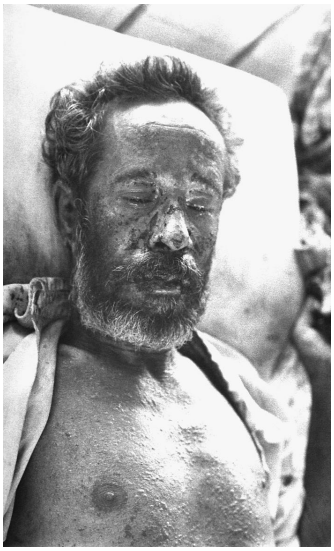


Figure 8: A case of hemmorhagic smallpox

(Akhtar 41-45; Atkinson, et al. 284-285; Center for Biosecurity, University of Pittsburgh Medical Center [UPMC]; Fenner et al. 4-5, 22, 32-34, 37).

2.3 Infectivity

2.3.1 Susceptibility

'The outbreak [of variola major] grows? in an exponential rise, expanding at a faster and faster rate? it quickly gives way to branching chains of explosive transmission of a lethal virus' (Preston 48). Unfortunately, historical data are available only from periods with substantial immunity either from vaccination or from having survived natural infection. In the absence of natural disease and vaccination, the global population is significantly more susceptible (Center for Biosecurity, UPMC).
Inoculation has ceased for the public since the Eradication in 1980, and the vaccine only lasts with any potency for 3-5 years ('Vaccine Overview,' CDC). Therefore, the public is, except for military personnel, healthcare workers, and laboratory staff engaged in work with vaccinia and related viruses, 100 percent at risk for infection with smallpox. Despite the few who have recently received the vaccine, the risk of a vaccine-resistant virus being introduced is high, so initial immunity is excluded from the model.

2.3.2 Rate of Infectivity over Time of Infection

Persons carrying the virus during the incubation period cannot infect others. 'The maximum infectivity of cases of smallpox was during the first week of rash? when the lesions? were releasing virus into the secretions of the mouth and pharynx?. cases remained infectious until the last scab had separated? but the level of infectivity fell off greatly? during the latter part? of the disease' (Fenner et al. 189).
While smallpox is highly communicable 'from the appearance of enanthema until day 10 of the rash' (Gober and Weese) and transmittable until the scabs fall off (Akhtar 20), it 'is most infectious during the first 7 to 10 days following rash onset' ('Smallpox Disease Overview,' CDC). 'In short, there are roughly 8-9 days of serious infection possibility with smallpox, 3-4 days in which infection is a low probability, and approximately 12 days in which smallpox infection is no threat to others' (Feasel), because when 'scabs formed, infectivity waned rapidly' (Smallpox Information Center).
Infectivity for smallpox during the prodrome begins at a very low value for the first 2 days, then rises quickly during the third and fourth days. Infectivity continues to increase during the first week of rash, when the virus is released via the respiratory tract. Peak infection rates occur 7 days after the beginning of the rash and drop quickly after day 10 or 11, reaching lower values around day 12 or 13 and continuing to drop until around day 20 with the exception of confluent smallpox, in which the infection rate does not significantly drop off until the scabs form and cover the sores; when the scabs form, the infectivity of a victim is very low. Although patients remain contagious until the scabs fall off, the large amounts of virus shed from the skin are not highly infectious; exposure to patients in the late stages of the disease is less likely to produce infection in other people (Center for Biosecurity, UPMC). Those with a severe rash (hemorrhagic, malignant, or confluent) are more infectious than those with a slight rash (Akhtar 96).

Because of the lack of available data to create a function to fit a graph, I created my own quartic function model for the contagion of a victim over time for confluent smallpox and nonconfluent smallpox, which peaks around t=7 days, drops off at a somewhat steep rate after day t=10, and decays exponentially for the remainder of the days until t=20, at which point the simulation assumes a much lower infection rate, as scabs have formed. The equation is -5.715*10-5*t4+0.002557t3-0.0383t2+0.181t+1. The equation for confluent smallpox does not drop off at the same rate after day t=7; instead, it maintains a gradual decline and reaches a similar low point around t=20. The equation is -2.3564*10-5*t4+0.00163t3-0.0346t2+0.181t+1.015. For hemorrhagic and malignant smallpox cases, the first equation was multiplied by 1.1.

2.3.3 R-zero, the Rate of Infectivity per Infected Person

In the past, patients suffering from variola major became bedridden early and remained so throughout the illness. Therefore, the spread of infection was limited to close contacts within a small vicinity. However, the estimated R-zero value, or the number of people infected from one case, has been estimated to be between 3 and 20, where an R-zero of 5 or more would spread 'explosively,' and would cause 'millions of smallpox cases in a few months? It has taken the world twenty years to reach roughly fifty million cases of AIDS. Variola could reach that point in ten or twenty weeks' (Preston 47-48). Some experts have estimated that today's rate of transmission would be on the order of 10 new infections per person (Center for Biosecurity, UPMC). 'Other? experts disagreed with one another, sometimes sharply, but in general they found that smallpox would spread widely and rapidly? 'Our general conclusion was that smallpox is a devastating biological weapon in an unimmunized human population... If you look at the real-world data from a 1972 outbreak in Yugoslavia, you find that the multiplier of the virus was ten... Basically, if you don't catch the first guy with smallpox before he kisses his wife, it goes out of control. We could be dealing with hundreds of thousands of deaths. It will absolutely shut down international trade, and it will make 9/11 look like a cakewalk. Smallpox can bring the world to its knees" (Preston 213).
According to Preston's experts and the UPMC Center for Biosecurity, if the first person with smallpox is not quarantined before he infects another, there will be no method of stopping it from continuing to spread. If the first person or people do not want to be stopped, as in a bioterrorist attack, the disease will spread globally, killing hundreds of thousands of people. After every 2 weeks, the number of people infected increases: 10 to 100 to 1000 in the span of a month. R-zero was 10 in an era of mass vaccination; in a population with a 100 percent susceptibility rate, R-zero will likely be higher, but the R-zero of the model will remain at 10, and the number of others infected beyond R-zero=10 will assumedly travel to many places (Preston 232), and spread the infection to other cities, states, provinces, countries, and continents. The simulated infection rate will be 9¡R-zero¡11 to account for differences in exact populations and situations, but it will be focused around an R-zero of 10, as the predictions show.

2.4 Transmission

2.4.1 Inhalation

Smallpox virions behave like smoke particles, and are almost the same size (Preston 47). If there was a fire in a building, anyone who smelled smoke would likely be infected if there was a smallpox patient instead of a fire in that room. The infectious dose of smallpox is between 1 and 5 virions, making the disease very contagious; it does not need to be concentrated in order to cause an infection (Preston 45).
'In the Meschede outbreak an electrician? was admitted 10 days later to the isolation ward of a large general hospital with a feverish illness that was suspected to be typhoid fever. He was confined to his room, and 3 days after admission developed a rash. Smallpox was confirmed? 2 days later and the patient was then transferred to the smallpox hospital. In spite of rigorous isolation of the patient (because of the suspicion of typhoid fever) and, after smallpox was suspected, the vaccination of all patients and nurses in the general hospital? 19 further cases of smallpox occurred there, on all three floors of the building in which the index case had been nursed? Seventeen cases occurred within one incubation period? The locations of these patients within the hospital are given in Fig. 4.9B, which also shows the results of tests on the carriage of smoke through the hospital' (Fenner et al. 192). Smallpox

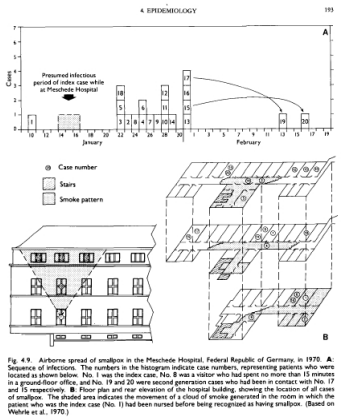


Fig. 4.9. Airborne spread of smallpox in the Meschede Hospital, Federal Republic of Germany, in 1970. **A**: Sequence of infections. The numbers in the histogram indicate case numbers, representing patients who were located as shown below. No. 1 was the index case. No. 8 was a visitor who had spent no more than 15 minutes in a ground-floor office, and Nos. 19 and 20 were second generation cases who had been in contact with Nos. 17 and 15 respectively. **B**: Floor plan and rear elevation of the hospital building, showing the location of all cases of smallpox. The shaded area indicates the movement of a cloud of smoke generated in the room in which the patient who was the index case (No. 1) had been nursed before being recognized as having smallpox. (Based on Wehrle et al., 1970.)

Figure 9: In the Meschede case, a smoke machine was used to recreate the possible spread of smallpox particles. This is the Fig. 4.9B described in the above passage (Fenner et al. 193).

is transmitted mainly from person to person by air droplets spread in face to face contact after fever has begun, but infection occurred in 16 cases from 1 isolated source without any face to face contact, over 3 floors of a building, and once when the infected person was visiting for less than 15 minutes in a hallway near the closed room of the infected, justifying an increase in the infection range of the model.

2.4.2 Contact Transmission

The disease can also be transmitted by contaminated clothes and bedding. Naturally, smallpox would be more infectious from direct contact with a victim than through contaminated clothing, but inhalation of smallpox virions is, more often than physical contact, the method of transmission (Center for Biosecurity, UPMC). Fenner discusses the transmission of smallpox through scabs on clothing or bed sheets: 'virus on such objects?, even when they were heavily contaminated? were of little importance in the transmission of smallpox in India? Virus in scabs rarely appears to have been a source of infection' (194). Virus transmission via infected clothing is a very minor risk, and contact transmission will not be included in the simulation.

2.4.3 Animal Transmission

Animals and insects play no role in transmission (Center for Biosecurity, UPMC).

2.4.4 Transmission Conclusions

The vast majority of smallpox infections were caused by inhalation of particles transmitted by coughing of those infected; infection rates are higher in closer proximity or upon more time spent near an infected person. In the model, the rate of infection is an exponential function: each unit that a healthy agent moves towards one who is infected while inside the infection range increases the likelihood of infection threefold.

2.5 Complications after Recovery

Between 65 and 80 percent of people who recover from smallpox will have some form of pockmarks on their faces. In 1-4 percent of recovered cases, either 'blindness from corneal scarring? [or] disfiguring or even physically debilitating dermal scarring' occur. (Medical Management of Biological Casualties Handbook 64). In 0.9 percent of survival cases, blindness occurs, typically in those recovering from confluent forms of smallpox (simulated by a vision of 0). In 1.7 percent of cases, arthritis develops (simulated by a movement reduced to one fifth) (Fenner et al. 47, 50).

3 Research, Modeling, and Simulation

3.1 Objectives

The purpose of the project is to use a Sugarscape based modeling system in Python in order to determine the probable death toll of a scenario that relates to the one described above depending on the time at which the situation is brought under control. When a successful quarantine has taken place or a vaccine has been developed and distributed, it is assumed no more infections will take place in the area. The statistics for infections, recoveries, and deaths will then freeze as the epidemic ends, except for the continued progression of the disease in those already infected. In my model of the scenario, the population is small, but the depiction of 5000 in the community is representative of the city. Only 5000 are simulated because of the limitation in computing power; while it would be useful to visualize the social network of an entire city, it is not necessary because the situation would be universal; the long incubation period coupled with a few attacks in key cities or airports would guarantee a similar case throughout the city and around the globe.

3.2 Rationale

Much research has been done in the field of epidemiology regarding smallpox, focusing on vaccination or the containment of an outbreak. Several government programs have made advances on simulating a smallpox outbreak from an accidental beginning, but no projects have dealt with the Soderblom scenario in which a planned suicidal bioterrorism attack involving smallpox takes place.

My research attempts to determine the fatality rate by percent in the city in which the attack and infection first takes place over time. It is assumed that similar scenarios will take place in other cities globally. The assumption is made that vaccination and containment are ineffective for the duration of the simulation due to the vaccine-resistant or bioengineered strain and the panic of the general population.

Although few studies detail the average time of death after the first symptoms, several individual points and generalizations are common. A normal distribution function is used as a model, with the mean as the middle of the data range and the third standard deviation on either end will be equal to the minimum and maximum values.

An assumption made is that people need to sleep and do not move from one social situation to another constantly. On average, a person would be in a unchanging position for 8-12 hours per day; the agent is motionless for two to three steps every six-step day. In the code, a random element is included in the movement, showing that some people are less inclined to social changes or more inclined to sleep than others.

With many sores on the feet of a smallpox sufferer, coupled with the symptoms and illness of the disease itself, someone infected with smallpox would likely move much less frequently than one who is not infected (Akhtar 72). This is modeled by showing that those infected with smallpox are 50 percent as likely to move around as a healthy person, and that those in the prodrome of smallpox are 60 percent as likely to move around.

3.3 Procedure and Methodology

The Python model is an agent-based social representation with circles as simulations of the people in the area; each location can either be occupied by an agent or empty. In an agent-based model, agents are used to simulate real people or things.
The model shows people who are near each other instead of showing where a person is in the city geographically. 2 agents close together simulates two people spending time in close proximity to one another in a situation in which one person would likely infect the other over a 4 hour period. If several agents are all very close, the model represents a location or event in which many people could potentially infect each other.

3.3.1 Methods, Techniques, and Construction of Program

These are the steps I have taken to create a program to simulate the above scenario:

- Create data points for the number of agents who are healthy, carrying the disease, in the prodrome of smallpox, exhibiting a rash, recovered/immune, and dead.

The Agent Class: defines the agent representation: the basis of the simulation.

- At the beginning of the world, the agent will either be healthy or an infected terrorist.
- The agent can see randomly 3, 4, or 5 spaces away. If the agent sees another agent, the movement of that agent will be influenced accordingly. The numbers were chosen in relation to the maximum range of infection, 4 spaces. Some people have greater situational awareness than others and will be able to detect a potential threat before it becomes an actual threat, while others are unaware even after the threat has passed.
- The agent will have a random element accounting for 30 percent of the tendency of the agent to move, showing that some people are more inclined to be socially active.
- Agents, at the beginning of the program, are not immune but can become so later.
- Terrorist agents determine the length of time before they enter the prodrome.
- The disease information array is created, with 6 pieces of information:
    1. The stage of infection of the agent (healthy, carrier, prodrome, infected, or recovered)
    2. The type of smallpox that the agent is infected with (ordinary, confluent, modified, malignant, hemorrhagic), with an empty string (") if the agent is not infected
    3. The status of the infection with regards to appearance: if the agent appears sick (is either in the prodrome phase or exhibiting a rash), this is stated here
    4. The time (in days) that the agent has been in the current stage of infection
    5. The time (in days) at which the agent will progress to the next stage of the disease

6. The time (in days) at which the agent might die from smallpox

Infection of Other Agents:

- During an agent's move, every agent within 4 spaces (infection range) is processed. Before the agents can be processed, however, the state of the current agent must be evaluated to determine the potential risk factors for the other agents. Depending on the length of time that the agent has been infected, the potential risk can be high or low.
- If the infected agent is in the prodrome phase, the risk of infection is low. However, as the agent endures the prodrome for longer periods of time, the risk for infection rises.
- If the infected agent is exhibiting signs of the smallpox rash, the value differs greatly. An agent with ordinary or confluent smallpox has a multiplier of 1.0, where an agent with hemorrhagic or malignant smallpox has a multiplier of 1.1, accounting for the increased infectivity. Those with modified smallpox have a 0.2 multiplier to account for lower risk.
- The duration of the rash is factored in: the equations shown in the bottom of the 'Rate of Infectivity over Time of Infection' section on page 14 are used.
- For each agent within the infection range, a random number is compared with a factor defined by 3 to the power of the distance between the two agents * the aforementioned risk factor * a common multiple which was changed to obtain an R-zero of 10. A lower multiple is used to determine risk of infection for those who have recovered.
- If the random value is higher than the multiplied factor, the agent will not be infected.
- Otherwise, the agent will become infected. The agent takes on one of the forms of smallpox, with a probability based on the information on pages 9-12. The newly infected unit then becomes a carrier of smallpox.

Agent Disease Progression:

- Increase the time since the beginning of the stage of infection by one sixth of a day.
- If that time is after the point at which the agent would die, set the state of the infection to 'dead' and remove the agent from the simulation.
- If the time is after that when the agent will progress to the next phase of the disease, check which part of the disease the agent is currently in.
- If the agent is merely carrying the infection without symptoms, change the data set to 'prodrome,' visible, no time since start of phase, and the time at which the agent will progress again as detailed in the description of the form of smallpox on pages 9-12. If the agent is infected with hemorrhagic smallpox, there is a large chance of fatality during the prodrome, represented with a change in the time until death.

- If the agent is in the prodromal phase, all points change as stated above except that 'prodrome' changes to 'infected' and a value showing when the agent will die is created.
- If the agent is already infected and has survived until this point, it recovers and becomes immune. 'Infected' becomes 'immune', the agent is no longer showing visible signs of the disease, will not progress, and will not die. The potential long-term effects of infection will be calculated; blindness, which reduces the vision of the agent to zero, and severe arthritis, which cuts the tendency of the agent to be socially active to one fifth.

World Progression (4 hours or 1/6 of a day):

- The agent views each location which it can see that contains another agent.
- The agent considers the disease of the viewed agent (a more severe form of the disease has a greater influence on the agent viewing it), the proximity of the agent (an infected agent immediately next to the agent viewing it will cause a greater response than one far away), and the possibility that the other agent may be friendly (agents, like people, tend to gather in groups for comfort) when deciding how and where to move.
- The tendency to avoid a victim in the prodromal stage will be 40 percent, the tendency to avoid a victim suffering from smallpox with the ordinary or modified rash will be 60 percent, and the tendency to avoid a victim with a confluent, flat, or hemorrhagic rash is 90 percent. Those already infected are not influenced by illness around them, but will avoid those who are not apparently infected to avoid infecting others. To account for human error and ignorance, these tendencies are not guarantees of the movement.
- A possibility to not move is added to represent an unchanged social status.
- Infected and prodromal agents will be less socially active because of the malaise and other symptoms during the prodrome and the more severe symptoms during the rash stage of the infection: agents in the prodrome will move 60 percent as often and agents exhibiting the rash will move 50 percent as often as they normally would.

World Formation and Display:

- After the creation of the agent class is completed, a Sugarscape model of a square, 200x200 world is formed. 10 terrorist agents, in the carrier stage of the infection, are inserted into random locations, followed by 4990 healthy agents for a sum of 5000.
- During each time step, each agent moves in the manner described above.
- The world is redrawn. Agents that have moved are now shown in different locations; agents that have progressed in the disease or become infected are now different colors:
  - Green agents are healthy.

  - Yellow agents are infected with smallpox but do not show any symptoms.
  - Orange agents are currently in the prodromal phase of the infection.
  - Red agents are exhibiting a fully formed smallpox rash.
  - Blue agents have recovered and are now immune.

- histogram shows the number of agents in each of the above categories as well as the total number of living agents (white) and the total number of dead agents (gray). It updates every step to show the 800 most recent steps, or last four and a half months.

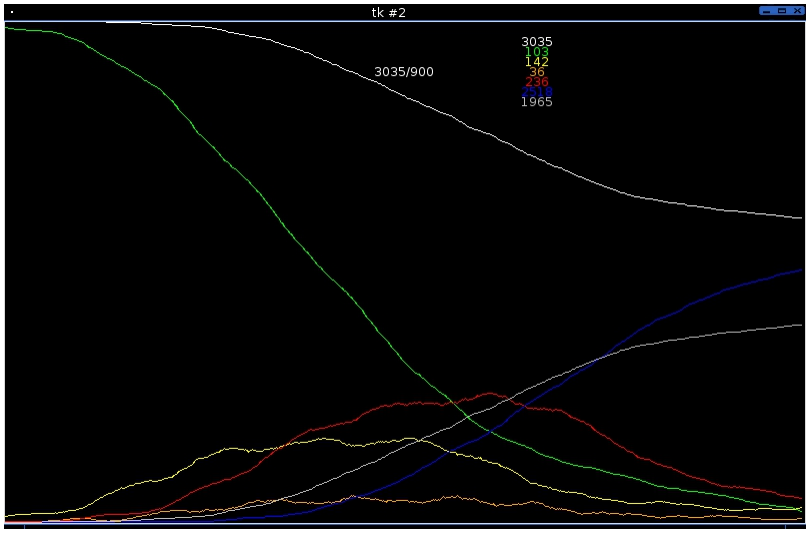


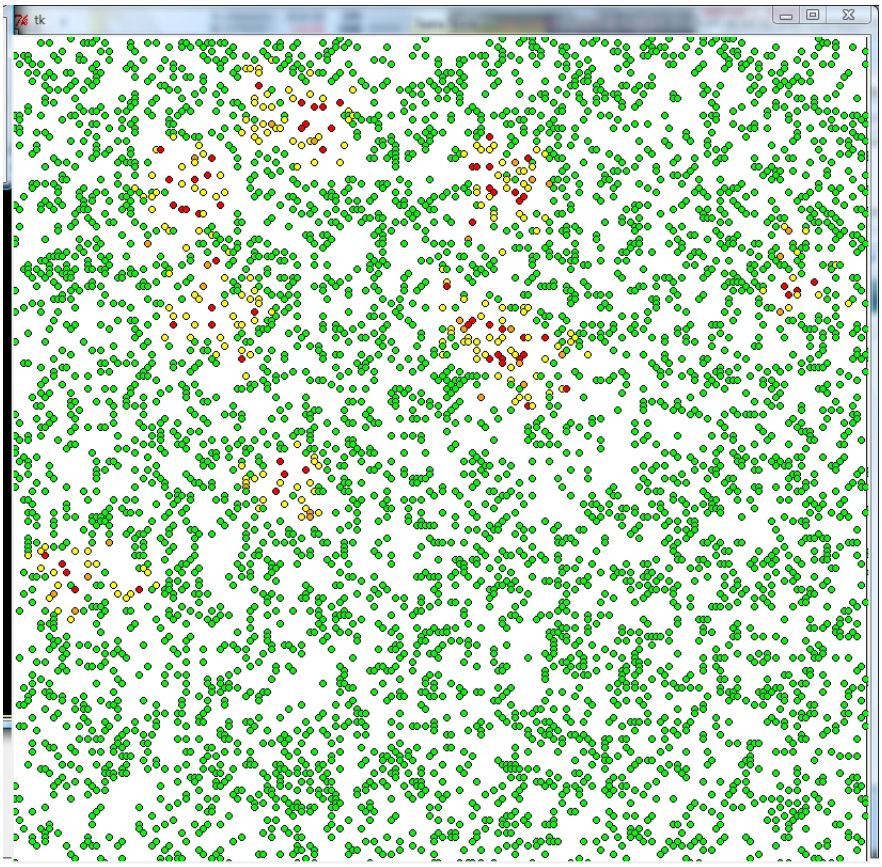
Figure 10: The histogram described above starts around 15 days and ends at 150 days.

4 Conclusions

4.1 Unaltered Run Data

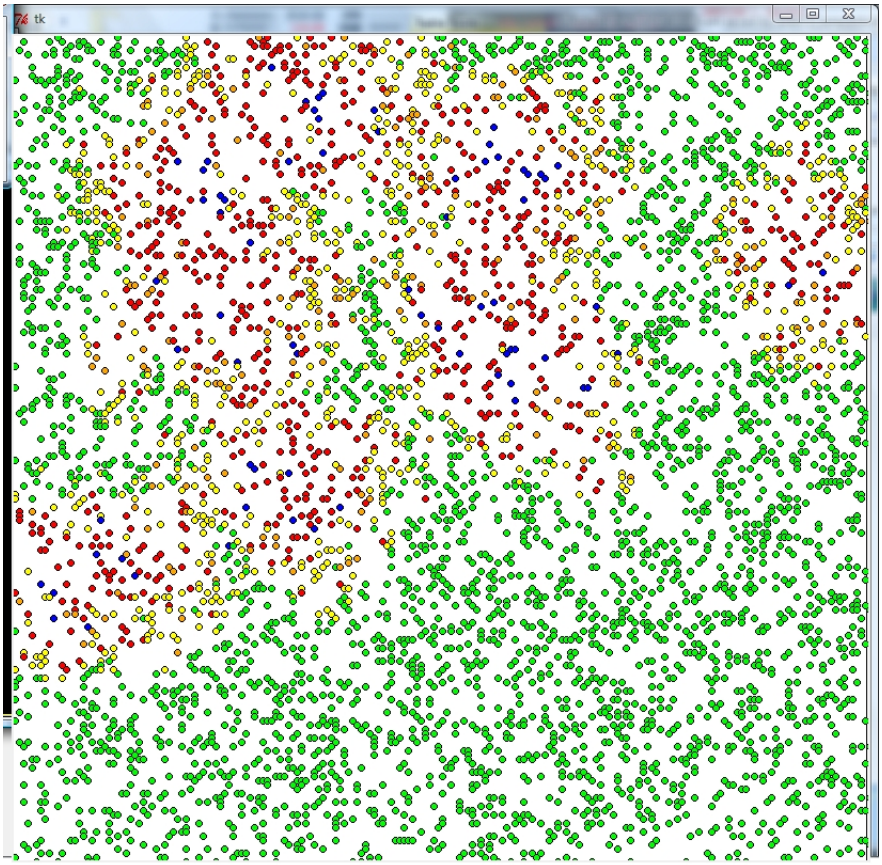
In this section, no quarantine or vaccine was used.
The data from the trial runs are accompanied with a screenshot of the program at a point in time close to that shown in the data tables. After 10 trial runs with 10 terrorists in the scenario, the results were as follows:
Out of 5000 people in the modeled location:
After 1 month (180 steps = 30 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	4709	217	33	39	0	2
2	4732	189	24	53	0	2
3	4716	202	28	51	0	3
4	4650	252	34	62	0	2
5	4721	189	45	44	0	1
6	4694	205	39	60	0	2
7	4710	211	22	56	0	1
8	4713	197	30	58	0	2
9	4678	218	34	67	0	3
10	4724	188	39	47	0	2
Average	4704.7	206.8	32.8	53.7	0	2



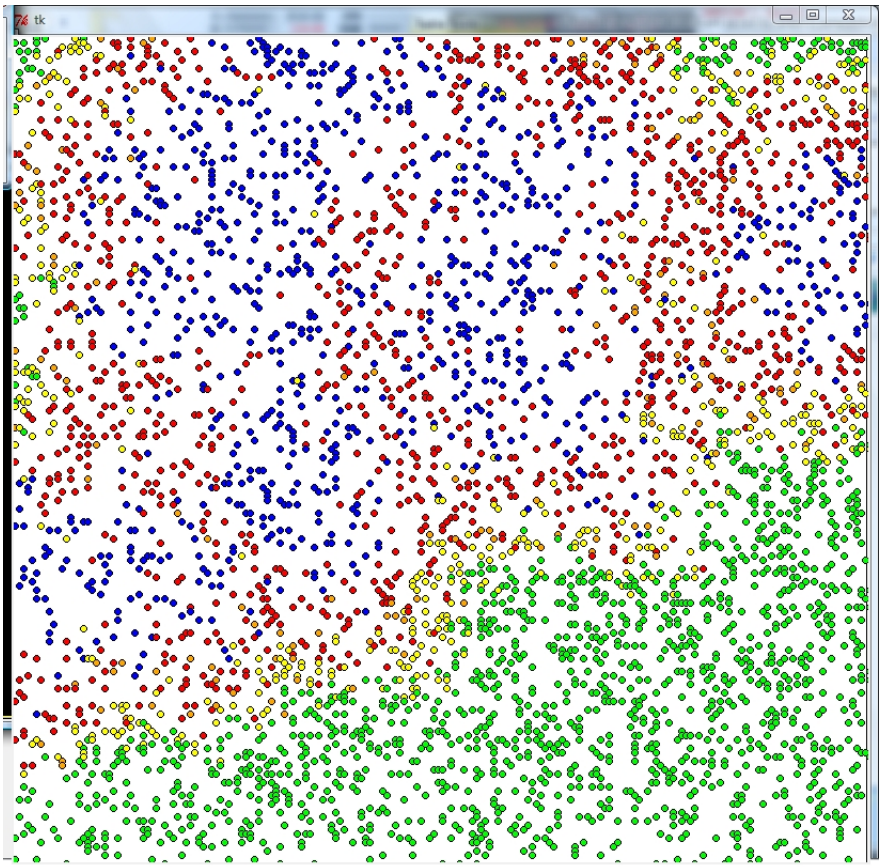
After 2 months (360 steps = 60 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	3313	660	156	669	54	148
2	3341	612	183	666	65	133
3	3117	753	184	718	58	170
4	3072	638	194	814	83	199
5	2996	781	229	769	68	157
6	3085	748	184	732	63	188
7	3030	733	225	791	63	158
8	3046	785	227	712	61	169
9	3005	753	205	786	75	176
10	3058	751	214	753	83	141
Average	3106.3	721.4	200.1	741	67.3	163.9



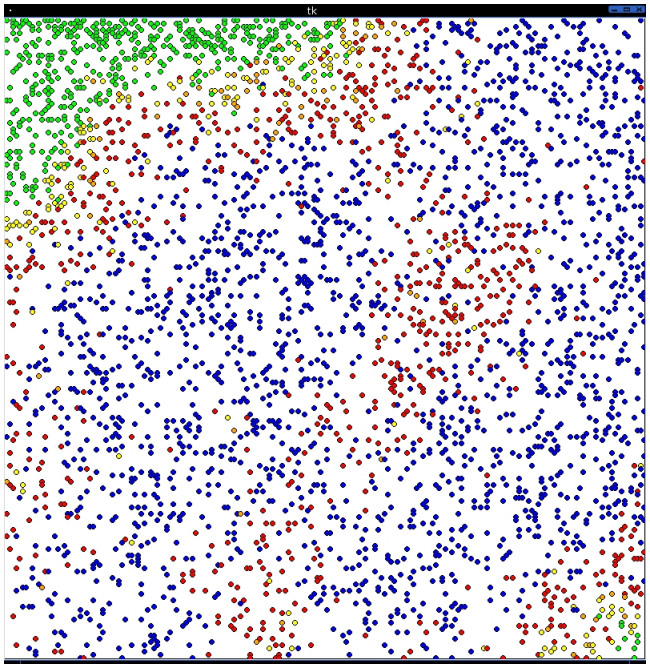
After 3 months (540 steps = 90 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	1643	614	160	1155	716	712
2	1691	601	185	1093	749	681
3	1044	796	236	1415	787	722
4	1319	632	188	1186	837	838
5	1183	681	191	1215	880	850
6	1006	703	234	1399	823	835
7	1542	484	167	1140	858	809
8	1067	622	223	1429	804	855
9	1154	679	190	1318	835	824
10	1039	672	240	1379	885	785
Average	1268.8	648.4	201.4	1272.9	817.4	791.1



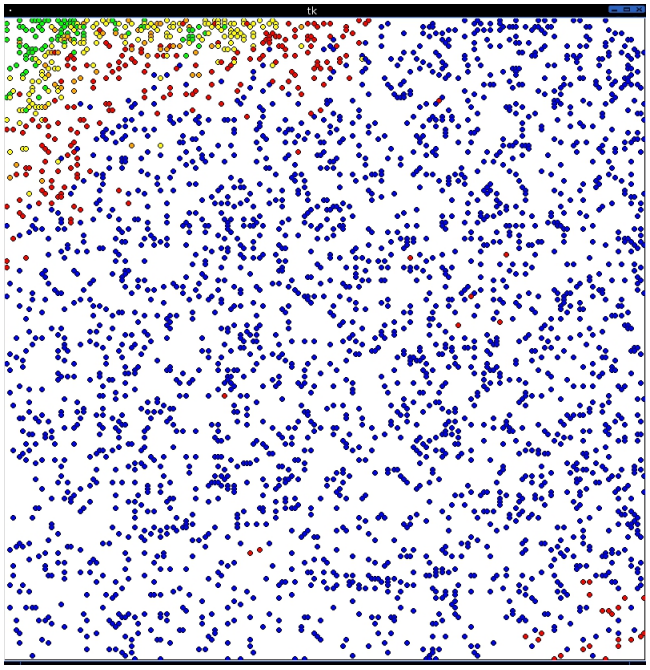
After 4 months (720 steps = 120 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	332	435	148	990	1811	1284
2	568	422	109	844	1815	1242
3	174	250	83	880	2178	1435
4	365	196	81	936	1950	1472
5	80	270	120	1030	2030	1470
6	34	147	117	970	2159	1573
7	716	289	87	677	1930	1301
8	269	197	61	797	2198	1478
9	129	309	110	915	2060	1477
10	213	188	89	865	2198	1447
Average	288	270.3	100.5	890.4	2032.9	1417.9



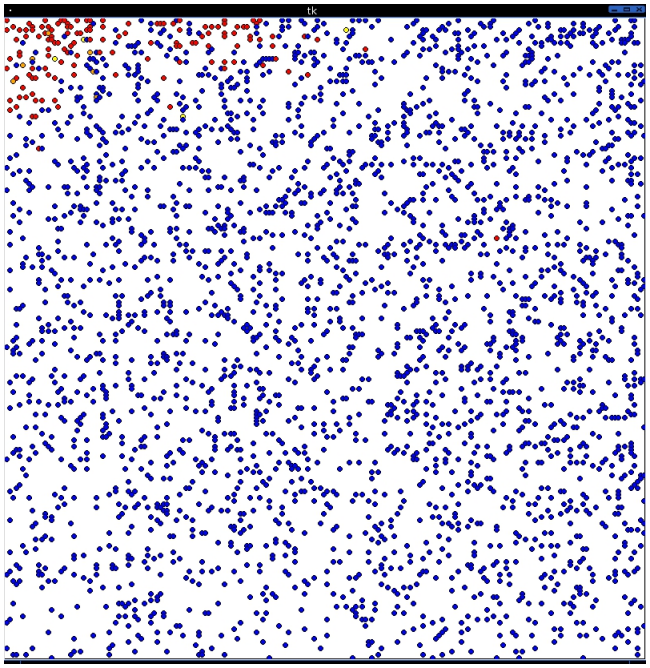
After 5 months (900 steps = 150 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	39	69	29	403	2722	1741
2	69	91	44	573	2620	1603
3	3	20	11	241	3020	1705
4	101	57	25	282	2778	1757
5	0	2	4	206	2987	1801
6	2	1	4	109	3067	1817
7	302	127	40	387	2590	1692
8	63	51	27	223	2936	1700
9	0	4	6	257	2915	1818
10	36	38	26	213	2995	1692
Average	61.5	46	21.6	289.4	2863	1732.6



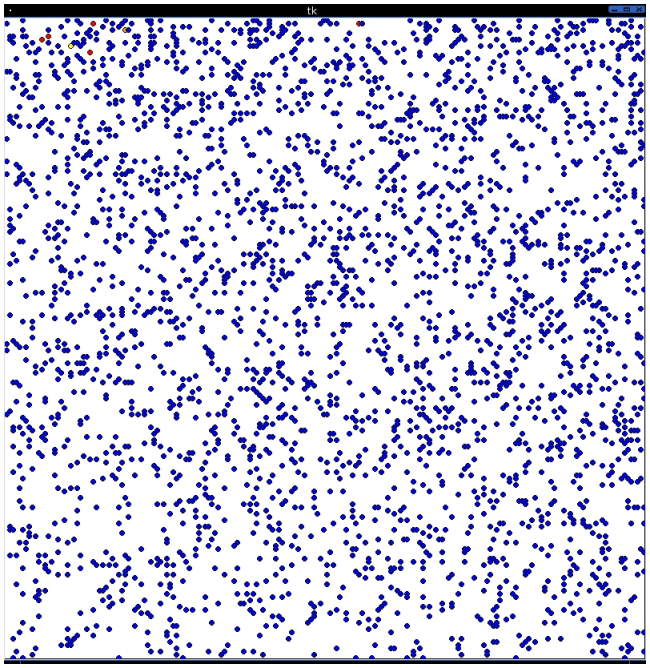
After 6 months (1080 steps = 180 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	2	11	8	59	3094	1826
2	4	16	7	83	3135	1755
3	0	0	0	15	3238	1748
4	3	20	13	85	3042	1837
5	0	0	0	4	3177	1819
6	2	0	0	1	3175	1822
7	19	100	38	196	2955	1692
8	5	15	6	61	3149	1764
9	0	0	0	3	3161	1836
10	1	3	2	48	3199	1747
Average	3.6	16.5	7.4	55.5	3132.5	1784.6



After 7 months (1260 steps = 210 days):

Trial	Healthy	Carriers	Prodrome	Infected	Immune	Deaths
1	0	0	1	6	3158	1835
2	0	0	0	10	3212	1778
3	0	0	0	0	3252	1748
4	0	0	0	9	3122	1869
5	0	0	0	0	3181	1819
6	2	0	0	0	3176	1822
7	0	3	2	73	3149	1773
8	0	0	0	9	3208	1783
9	0	0	0	0	3164	1836
10	1	0	0	2	3240	1757
Average	0.3	0.3	0.3	10.9	3186.2	1802



4.2 Summary

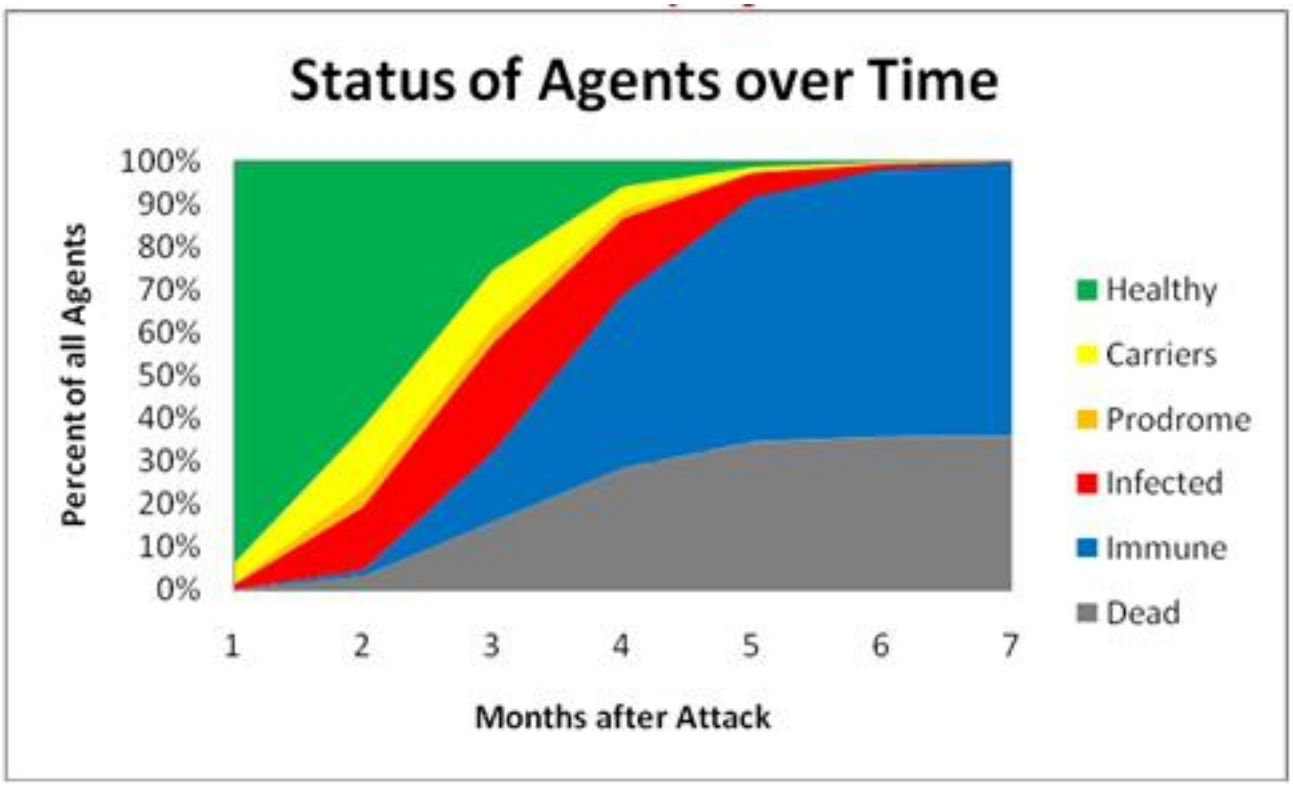


Figure 11: The above graph shows, by percent, the relationships between the numbers of healthy agents, agents carrying smallpox, agents in the prodrome of smallpox, agents exhibiting a rash, agents who have recovered, and agents who have died over a seven month time span.

The graph is a representation of the population of the city. At the point in which control is regained, the quarantine will be effective and the newly developed vaccine will be given universally, stopping the spread of the disease. Therefore, given the data above, if control is taken and a vaccine is developed and distributed 1 month after the attack begins, the region will have a 6 percent infection rate, and most likely, around 2 percent of the population would die by the end of the outbreak. If the outbreak is stopped 2 months into the attack, 38 percent would be infected and about 13 to 14 percent would die. If the outbreak lasted for 3 months, 75 percent of the area would be infected and between 25 and 30 percent of the population would die. If control is not taken and a vaccine is not developed for 4 months or more, over 90 percent of the population would have been infected and between 30 and 40 percent of the population would die.

4.3 End Scenario Testing and Results

4.3.1 Expected Results and Value to Others

This project can be used to provide an understanding of the fatalities and infection rates of a population in a major city in the scenario described in the abstract.
The simulation shows the expansion of the infection over time and the statistics of the population after the beginning of the attack. Depending on how quickly control can be regained and how effective the quarantine effort or vaccination is, different percentages of a population could be saved from death or infection.

4.3.2 Quarantine Scenario

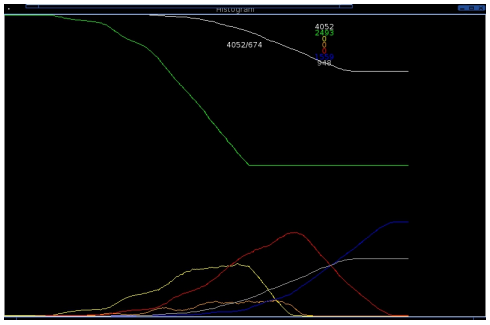


Figure 12: The quarantine simulation shows a world in which a military quarantine has isolated everyone from each other.

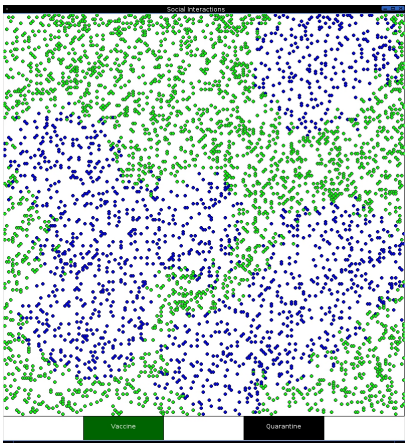


Figure 13: The visual representation stops moving, yet diseased agents continue to progress.

The population of the city has gone from 5000, the initial value, to 4052; a fatality rate of 20 percent. However, the population in this situation was quarantined after two months of the simulation, while the rate of infection was still increasing, which would lead to many more cases of smallpox and many more fatalities. Throughout the simulation, about half of the agents became infected, which raises the relative fatality rate to 40 percent.
After the quarantine was implemented, the number of healthy people leveled off at 2495, while, at the same time, the number of carriers no longer increases after that time, immediately after the number of infected people becomes greater than the number of carriers in the simulated world. From the graph, it is possible to notice the increases in the number of carriers, infected agents, and immune agents as they progress, defining the generations of infection. After the last generation becomes infected, defined by the time of quarantine, all of the values drop off after the generation progresses to the next stage of disease.

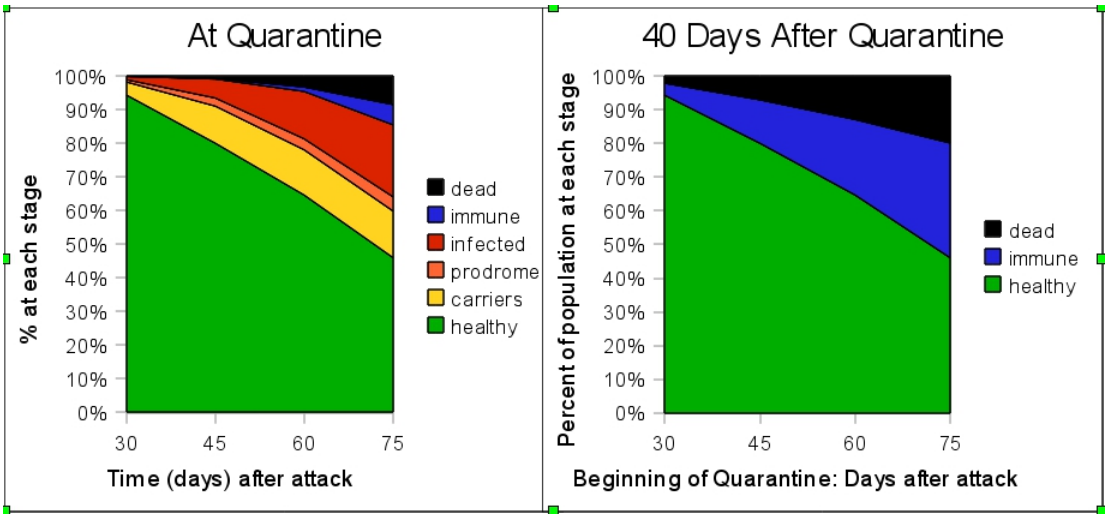


Figure 14: Results for Quarantine Simulation

The results from calculating several possible outcome times (30 days, 45 days, 60 days, and 75 days) ran 6 times to prevent outliers from significantly affecting the results are shown in appendix A.
The left graph shows the world immediately before the quarantine, and the right graph shows the world 40 days after, long enough to ensure that the remaining infected agents will survive for the remainder of the simulation. Therefore, the infected agents will be labeled immune.

Fatality rates for quarantine simulations:	Infection rates for the simulations:
30 days: 102 (2%)	30 days: 279 (6%)
45 days: 350 (7%)	45 days: 995 (20%)
60 days: 643 (13%)	60 days: 1766 (35%)
75 days: 992 (20%)	75 days: 2698 (54%)

Figure 15: Fatality and Infection Rates for Quarantine Simulation

The average fatality rate for the quarantine method is about 36 percent of the infected population, which increases over time.
This rate is relatively constant for all of the times at which the simulation is run.

4.3.3 Quarantine Data (Appendix 1)

4.3.4 Vaccination Scenario

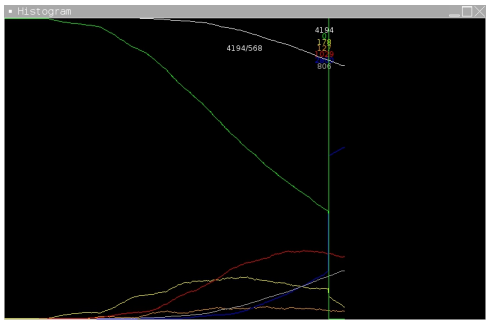


Figure 16: The vaccine simulation shows a world in which a vaccine to the weaponized smallpox has been created, produced, and distributed.

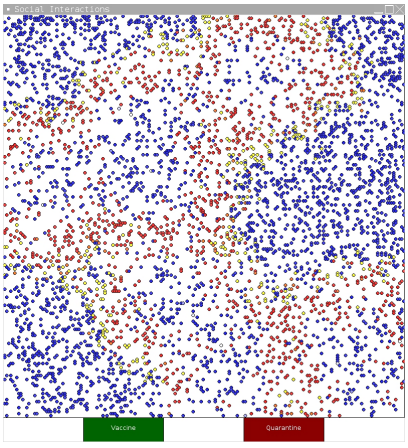


Figure 17: Diseased agents continue to progress, but some recover, and all healthy agents become immune.

The population of the city has gone from 5000, the initial value, to 4198; a fatality rate of 16 percent, and ultimately proceeds to a value of 3911, with an overall fatality rate of 21.8 percent. The total number of agents who had been infected is 3216 and the end fatality rate after all agents had recovered was 1089 dead, a fatality rate of 33.9 percent of those who were infected. This fatality rate, lower than the expected 36.4 percent is due to the vaccination of the population in this situation after three months of the simulation: because of the vaccination, many who were previously infected are now healthy and immune. Use of the vaccine instead of the quarantine saved 75 lives.

After the vaccine was implemented, the number of healthy and immune people bottomed out at 2577, as can be seen in the graph, while the number of carriers no longer increases after that time. From the graph, it is possible to notice the increases in the number of carriers, infected agents, and immune agents as they progress, defining the generations of infection. After the last generation becomes infected, defined by the time of vaccine, all of the values drop off after the generation progresses to the next stage of disease.

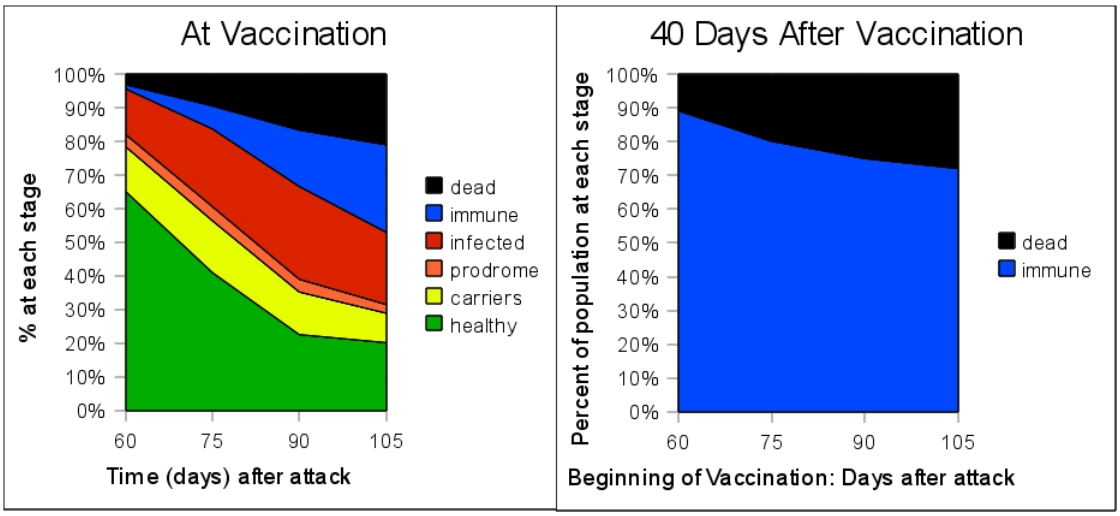


Figure 18: Results for Vaccine Simulation

The results from calculating several possible outcome times (60 days, 75 days, 90 days, and 105 days) ran 6 times to prevent outliers from significantly affecting the results are shown in appendix B.
The left graph shows the world immediately before the deploying of the vaccine, and the right graph shows the world 40 days after, long enough to ensure that the remaining infected agents will survive for the remainder of the simulation. Therefore, the infected agents will be labeled immune.

Fatality rates for vaccine simulations:	Infection rates for the simulations:
60 days: 540 (11%)	60 days: 1747 (35%)
75 days: 991 (20%)	75 days: 2951 (59%)
90 days: 1247 (25%)	90 days: 3873 (77%)
105 days: 1396 (28%)	105 days: 3991 (80%)

Figure 19: Fatality and Infection Rates for Vaccine Simulation

The average fatality rate for the Vaccine method varies: as the infection rate increases, the vaccination fatality rate decreases. This is because the vaccination immunizes everyone infected within 2 days and some infected within 4 days of the vaccine distribution, and greatly increases the chance of survival of those infected within 4 days and some of those infected within 7 days of the distribution of the vaccine.
Therefore, the fatality rate is lowest at the beginning of the simulation, because the few that have been recently infected make up a much larger percentage of the total number of people who had been infected. The measured fatality rate is 30.9 percent at 2 months, 33.6 percent at 2 and a half months, 32.2 percent at 3 months, and 35.0 percent at 3 and a half months. Compared to the 36.4 percent fatality rate of the quarantine scenario, the vaccination scenario saves many more lives.

4.3.5 Vaccine Data (Appendix 2)

4.3.6 Comparing Quarantine and Vaccination

Running multiple simulations for several lengths of program, the expected results of the simulation when the quarantine and vaccination are implemented are found: A quarantine is much easier to implement than creating and distributing a vaccine to a new disease, so the times of quarantine are earlier than those of vaccine distribution. In this particular scenario,

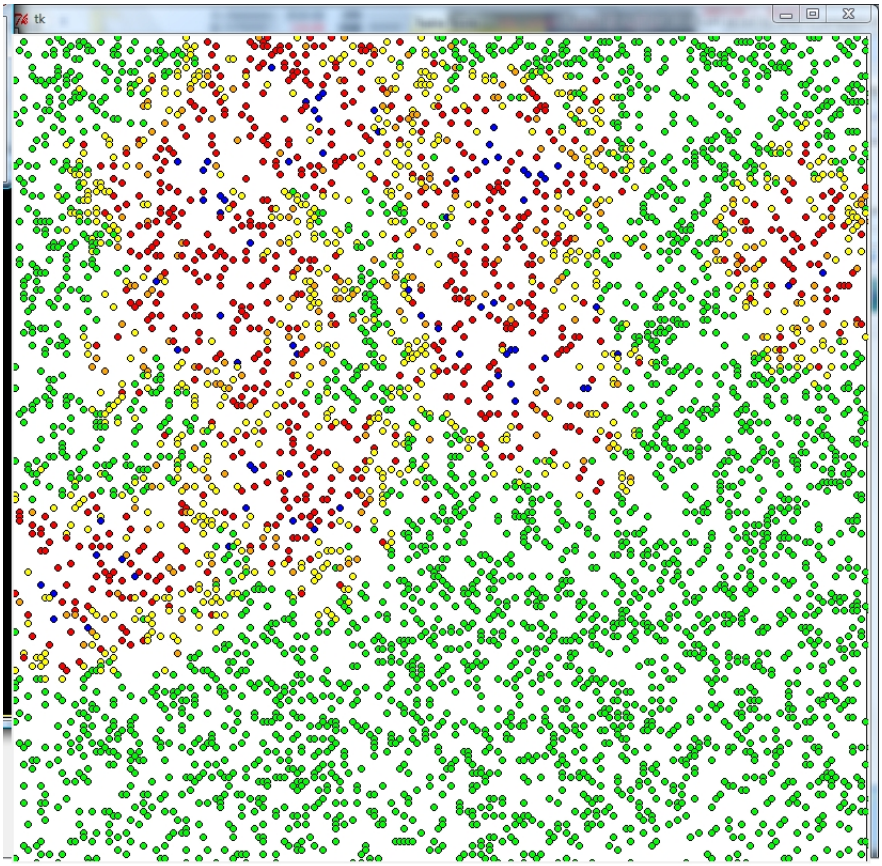


Figure 20: A world where no quarantine or vaccination has taken place.

a quarantine would be very possible, and, if a quarantine was implemented, would likely result in a death toll of around 750, with about 2000 people having been infected out of 5000: in a larger scenario, in which the infected travel to other areas, the expected fatality rate would be around 15 percent and the expected infection rate after two and a half weeks would be about 40 percent. In a vaccine situation, the fatality rate would be around 600 with 2000 people being infected: only a 12 percent fatality rate compared to the quarantine scenario's 15 percent.

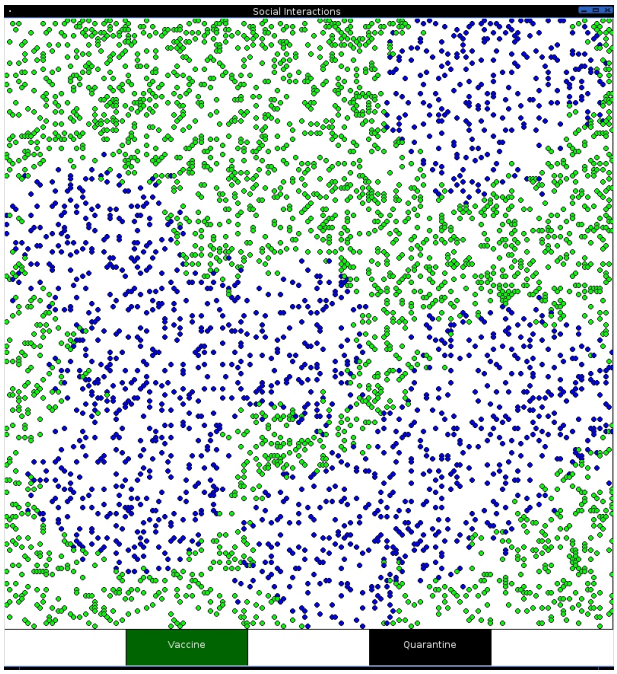


Figure 21: A world where a quarantine has taken place.

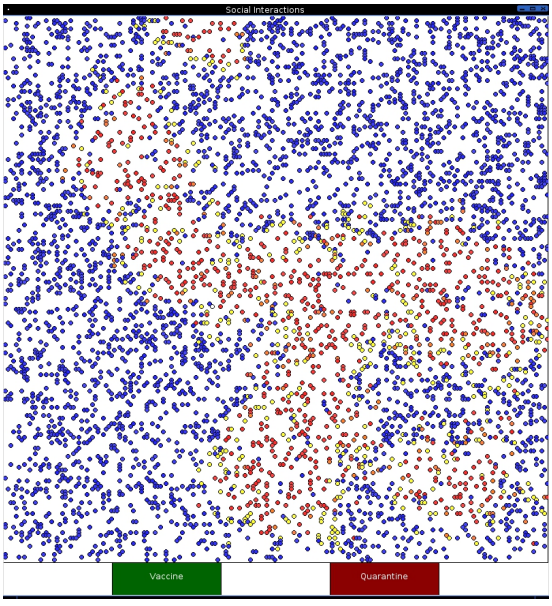


Figure 22: A world where a vaccination of the population has taken place.

4.3.7 Results

The quarantine simulation tends to simply end the simulation, and can easily be calculated without the simulation: on average, the number of people who have been infected *0.362 is a good estimate of the fatality rate of the simulation.
The vaccination scenario, on the other hand, varies with the time at which the vaccination began with regard to the start of the attack. Because those who have recently been infected are likely to recover, the fatality rate of a vaccine scenario is lower than that of the quarantine scenario IF they occur at the same time after the attack: in the situation described above, the difference would be 12 percent fatality rate to a 15 percent fatality rate, which is a difference of about 150 lives.
In order to have comparable fatality rates after two months, the quarantine must take place 6 days before the vaccine would be introduced in the scenario. However, a quarantine is much easier to implement and vaccine development is not very predictable, so the quarantine may still have the best dependability and the best results on the fatality rate in a real world situation.
This must, however, be compared to the moral dilemma of taking away the rights of the citizens who, while they may be infected, do not want to be controlled and refuse to forfeit their rights: the vaccination holds the moral ground, but the quarantine gets the job done quickly and efficiently. However, if the vaccine can be developed within 10 or so days of when the quarantine is developed, more lives will be saved from the vaccine.
This leads to questions that must be answered whenever a situation of this type arises: What is more important, the lives of the people, or the rights of the people? and Can we develop a vaccine fast enough, and is it worth the risk of waiting for it?

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